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Recent Studies of Magnetic Canopies*

Harrison P. Jones

Laboratory for Astronomy and Solar Physics,
NASA/Goddard Space Flight Center.
Mailing address: Southwest Solar Station,
c/o National Solar Observatory, P.O. Box 26732,
Tucson, AZ 85726, U.S.A.

Abstract

Two current studies are described which stem from Giovanelli's seminal studies of the spreading of chromospheric fields near active regions and active-region network. First, improved observational techniques are described for obtaining magnetograms in the Ca II 8542 Å, Fe I 8688 Å, and C I 9111 Å lines which at least in principle allow for more accurate treatment of instrumental noise and allow better inference of field orientation. Second, a generalized response function is developed for calculating theoretical magnetograph signals from arbitrary line-of-sight variations of magnetic field, and initial applications to two-dimensional, potential-field models of network fields are described. Preliminary indications are that potential-field models can better explain the presence of low-lying, diffuse horizontal fields than can thin flux-tube models, but fail to predict a differential response between the different lines.

1. Introduction

Giovanelli (1980) pointed out that chromospheric magnetograms near active regions and active-region network when viewed near the limb show a widespread diffuse component, often with polarity reversals or 'fringes' characteristic of nearly horizontal field diverging from areas of intense photospheric concentration. In this and subsequent work with Jones (Jones and Giovanelli 1982, 1983; Giovanelli and Jones 1982), these fields were analysed in terms of magnetic canopy models. The lower interface of the overlying canopy was found to penetrate to much lower depths than predicted by thin flux-tube models (Spruit 1981). These studies were recently reviewed by Jones (1985) at the National Solar Observatory (NSO) Workshop on Chromospheric Diagnostics and Modelling, where several suggestions for further exploration were made. Two resultant projects are now in progress and will be discussed herein. The first concerns revised observational procedures and reduction techniques for better control of instrumental noise. The second is a preliminary study of how well potential-field models of chromospheric network can explain the observational data.

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2. New Observations

The original observations discussed by Giovanelli and later by Giovanelli and Jones were not explicitly designed for the study of diffuse fields. In particular, the study of the unipolar network (Jones and Giovanelli 1983) was based on regions selected from active-region magnetograms taken in support of the Solar Maximum Mission satellite and included only the Fe I 8688 Å and Ca II 8542 Å lines. Recently, I have begun to obtain limb-to-limb scans of other regions with the NSO/Tucson Vacuum Telescope and Diode Array Magnetograph (Livingston *et al.* 1976*a*, 1976*b*). The data include the C I 9111 Å line and are taken on several different days to allow improved inference of field orientation and include measurements of instrumental noise—scans formed exactly as the magnetograms themselves but with the Kerr Cell modulator deactivated. Reduction of this data is in progress, but some problems in both the data and analysis procedures are surfacing. Most importantly, the performance of the magnetograph has degraded over time, for a variety of reasons; this does not appreciably affect its usefulness for synoptic measurements of strong overall fields but is a serious problem when attempting to analyse the much weaker diffuse field measurements. Various efforts are underway to improve the instrumental performance, particularly electronically.

One annoying feature of the data which has always been present to some degree is 'streakiness' caused by variations in individual diode response during an observational scan. Various software corrections for the problem have been devised. The ones which Giovanelli and I applied in our analysis of unipolar fields generally involved forming pixel-by-pixel averages along the scan direction to find additive corrections which approximately eliminate the streaks. First analysis of the new data involved a more sophisticated technique involving subtracting median windows of the data taken along and perpendicular to the scan direction. This method can be very effective at removing streaks, but when applied to the noise data it introduced some spurious structure and increased the width of the histograms as well. Clearly it is important to do a more careful study of the effects of these procedures, particularly the ones applied in our previously published analyses. For example, if such an effect were present in our study of unipolar regions, it might help to explain why we saw no systematic statistical effects of the spatially averaged mean field strength on the character of the diffuse fields.

3. Generalized Magnetograph Response Function

Jones and Giovanelli (1982) presented a formalism for computing the response of an ordinary longitudinal-field magnetograph to fields which are uniform only in a finite segment along the line of sight. While adequate for the models they discussed, many more elaborate field models can be calculated which involve arbitrary variations along the line of sight. Beckers and Milkey (1975) discussed response functions to small variations in opacity, and Landi Degl'Innocenti (1977) has discussed similar linearization of the Stokes transfer equations about solutions departing slightly from the Milne–Eddington condition that the ratio of continuous to line absorption coefficients be constant along the line of sight. Below, we present a similar but quite simple generalization of our canopy-field response function which is expressed in a form well posed for numerical evaluation and which, within the limits of its basic assumptions, is not restricted to any particular form of unperturbed atmosphere.

To begin, we consider, as in our earlier work, magnetic fields strong enough to separate Zeeman substates in energy beyond quantum 'level-crossing' effects, but weak enough that the Zeeman separation is small compared with a Doppler width. In addition, we assume that the populations of the Zeeman states are controlled by collisions and that the parent energy level populations are effectively the same as for a gas with the same thermodynamic state but no field. Landi Degl'Innocenti (1983) has given a more comprehensive discussion of the various regimes for the transfer of polarized radiation in the solar atmosphere, but the above assumptions are mostly well justified for the present purposes. Under these conditions, a first-order Taylor expansion of the Mueller absorption matrix in the Stokes transfer equations leads to

$$\kappa^{\pm}(\lambda,\, s) = \kappa(\lambda,\, s) \pm \lambda_H(s)\, \partial\kappa(\lambda,\, s)/\partial\lambda\,, \tag{1}$$

$$e^{\pm}(\lambda,\, s) = \tfrac{1}{2}\{\, e(\lambda,\, s) \pm \lambda_H(s)\, \partial e(\lambda,\, s)/\partial\lambda\}\,. \tag{2}$$

Here the $\pm$ superscripts refer to opposite states of circular polarization, κ and e are the absorption coefficient (per unit length) and emission coefficient respectively, s is the geometric distance along the line of sight (for an observer at $s = +\infty$ and photosphere at $s = 0$), λ is the wavelength from line centre, and λ_H is the Zeeman shift for the line-of-sight component of the field. Functions without superscripts denote the corresponding physical quantities in a field-free atmosphere of the same thermodynamic state. To this order, the opposite states of circularly polarized radiation do not interact with the other Stokes parameters and thus obey simple transfer equations of form

$$\frac{\partial I^{\pm}(\lambda,\, s)}{\partial s} = e^{\pm}(\lambda,\, s) - \kappa^{\pm}(\lambda,\, s)\, I^{\pm}(\lambda,\, s)\,, \tag{3}$$

where I is the specific intensity in the direction of increasing s at a given position along the line of sight.

Equivalently, one may express equations (3) in terms of the total intensity I and the difference between the two states of circular polarization (Stokes V) by the transformation

$$I^{\pm}(\lambda,\, s) = \tfrac{1}{2}\{\, I(\lambda,\, s) \pm V(\lambda,\, s)\}\,. \tag{4}$$

The *coupled* transfer equations for I and V then become

$$\frac{\partial I}{\partial s} + \kappa I = e\,, \tag{5}$$

$$\frac{\partial V}{\partial s} + \kappa V = \lambda_H(s)\left(\frac{\partial e}{\partial\lambda} - I\,\frac{\partial\kappa}{\partial\lambda}\right), \tag{6}$$

where functional dependence has been suppressed for compactness. We note that in this representation the transfer equation (6) for V involves I, but that equation (5) is simply the ordinary transfer equation for unpolarized light and may be solved separately by conventional methods.

By noting that

$$I\frac{\partial\kappa}{\partial\lambda}=\frac{\partial\kappa I}{\partial\lambda}-\kappa\frac{\partial I}{\partial\lambda},$$

and making appropriate substitutions from equation (5), one may rewrite equation (6) for V as

$$\left(\frac{\partial}{\partial s}+\kappa(\lambda,\ s)\right)V(\lambda,\ s)=\lambda_H(s)\left(\frac{\partial}{\partial s}+\kappa(\lambda,\ s)\right)\frac{\partial I(\lambda,\ s)}{\partial\lambda}. \tag{7}$$

Equation (7) has the compact formal solution for the emergent V of

$$V(\lambda,\ \infty)=\int_{-\infty}^{\infty}\lambda_H(s)\frac{\partial}{\partial s}\left(\exp\{-\tau(\lambda,\ s)\}\frac{\partial I(\lambda,\ s)}{\partial\lambda}\right)\mathrm{d}s, \tag{8}$$

where

$$\tau(\lambda,\ s)=\int_{s}^{\infty}\kappa(\lambda,\ s')\,\mathrm{d}s'$$

is the monochromatic optical pathlength along the line of sight. The final magnetograph signal is then computed by integrating equation (8) over the bandpass of the monochromator of the magnetograph. The result is divided by the emergent intensity (integrated over the same bandpass) and is normalized by unit response at disc centre (see Jones and Giovanelli 1982). Equation (8) is in a form where the required integrations involve perfect differentials of complicated functions, which allows simple

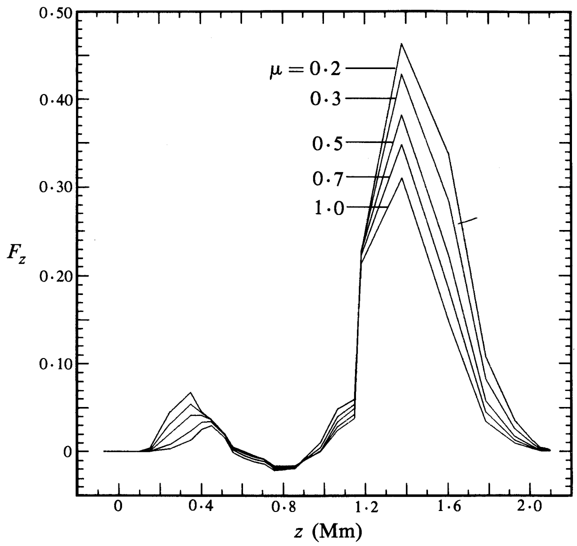

Fig. 1. Response function F_z for depth-varying magnetic fields for the 8542 Å line of Ca II in the VAL model C atmosphere at various values of μ. Wavelength integration and normalization are appropriate for the NSO/Tucson Vacuum Telescope with the 'synoptic' exit slit (see Section 3 for further discussion).

quadrature approximations involving differences without introducing serious loss of accuracy or stability. We note in passing that if $\lambda_H(s)$ is constant over some segment of the line of sight, the earlier result of Jones and Giovanelli is recovered trivially. With the exception that λ_H must remain small compared with a Doppler width, no restrictions have been placed on the variations of field or other atmospheric properties in deriving equation (8). Fig. 1 shows the result of applying equation (8) to model C of Vernazza *et al.* (1981; hereafter referred to as VAL) for the 8542 Å line of Ca II as observed with the NSO/Tucson Vacuum Telescope and Diode Array Magnetograph. The response function plotted is a discrete version of the portion of the integrand in equation (8) which multiplies the Zeeman shift (integrated over wavelength and normalized as above). The different curves correspond to different values of μ, the direction cosine of the line of sight with respect to the local solar vertical. We note that the primary response of the line is to fields of order 1·0 Mm (10^6 m) above the photosphere ($\tau_{5000} = 1$).

4. An Application to Potential Fields

The earlier work of Giovanelli and Jones did not seriously consider potential-field theory to be applicable to chromospheric magnetic fields above network and surrounding active regions because it ignores the interaction of gas pressure and magnetic forces in the very region where the transition from plasma- to field-dominated regimes is taking place. Our feeling was that, like thin flux-tube models, potential-field theory would not explain the diffuse fields seen in relatively low-lying lines. However, Anzer and Galloway (1983), among others, have shown that at least in active regions, potential fields can lie low enough to be compatible with diffuse-field observations. On the other hand, they felt their computations of network models to be incompatible with the results of Jones and Giovanelli (1983) for unipolar network.

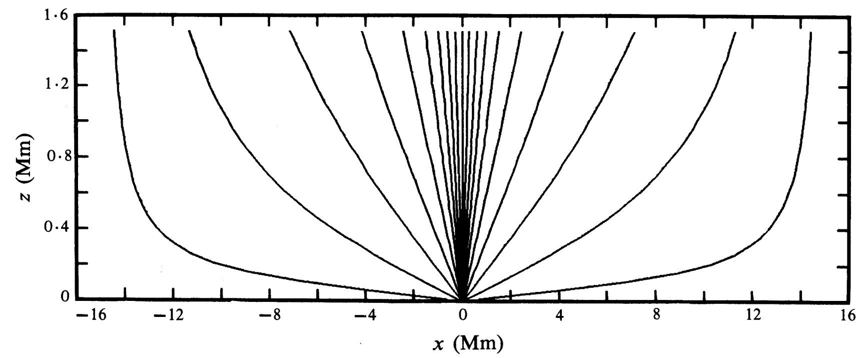

Fig. 2. Magnetic lines of force for a two-dimensional periodic model of network fields using potential-field theory. The spatially averaged field at height $z = 0$ is 15 G, the 'network' width is 0·05 Mm, and the period, or 'cell' diameter, is 30 Mm.

At the NSO workshop it was pointed out that the Anzer and Galloway conclusions were based on the height of the 'equipartition' surface (where gas and magnetic pressures are equal), which bears no necessary relation to the canopy base height of the discrete interface models. It was also suggested that it would be relatively easy to compute the

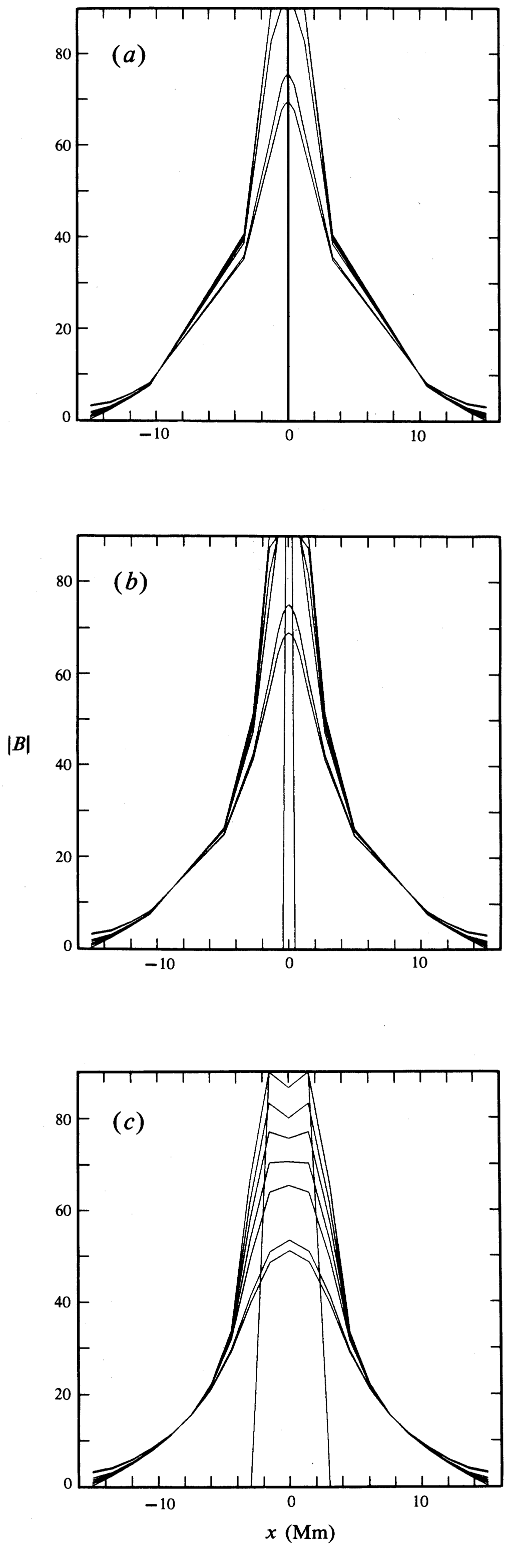

Fig. 3. Absolute field strength against horizontal position at several heights. Cell diameter and mean field are as in Fig. 2. Network widths are (*a*) 0·05 Mm; (*b*) 0·5 Mm; (*c*) 5·0 Mm.

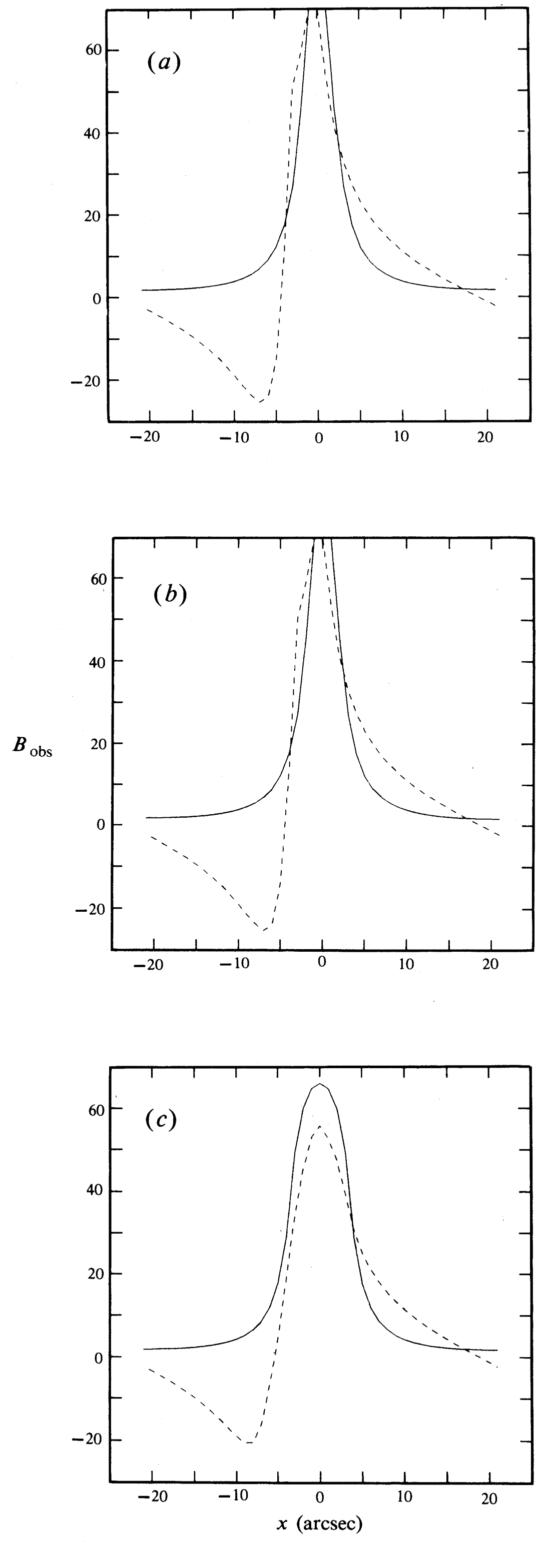

Fig. 4. Simulated magnetograph signal B_{obs} against horizontal position for $\mu = 1\cdot 0$ (solid curves) and $\mu = 0\cdot 5$ (dashed curves) for network widths of (*a*) 0·05 Mm; (*b*) 0·5 Mm; (*c*) 5·0 Mm.

magnetograph response for a given reference atmosphere since potential fields do not interact with the plasma; thus the radiative transfer calculations need to be performed only once. To this end, Galloway has provided the potential-field codes which he and Anzer used for their network models. As a test of the methodology before attempting to use the full three-dimensional code, a simpler two-dimensional potential field was considered with the boundary condition that the field at zero height be vertical and concentrated into periodic uniform strips ('network') of width d in x, of infinite extent in y, and with period in the x-direction ('cell size') of L. The analytic solution of Anzer and Galloway (1983) for this problem was used in conjunction with the above response theory to compute sample theoretical magnetograph results for the 8542 Å line.

Fig. 2 shows lines of force for one such model with a spatially averaged field strength at zero height of 15 G and a very small width of 0·05 Mm. One notes immediately that there is in fact a horizontal field in the cell interior quite low in the atmosphere.

A more quantitative view of the field variation is given in Figs 3*a–c* which show the absolute value of the field strength as a function of horizontal position for several heights in atmospheres with network widths of 0·05, 0·5 and 5·0 Mm; all three models have the same mean field strength of 15 G, and the field strength scale is chosen to be identical in the three graphs. A notable feature of Fig. 3 is that, exterior to the strips of flux concentration, the field is remarkably independent of both height and strip width—a simple consequence of the fact that in the domain of interest, for comparison with observation, both height and network width are small compared with typical cell size. In all cases appreciable areas exterior to the strip have field strengths comparable with the mean field.

Figs 4*a–c* show the theoretical magnetograph signal for the Ca 8542 Å line produced by the above potential fields and the VAL model C atmosphere at disc centre ($\mu = 1 \cdot 0$, solid curves) and moderately near the limb ($\mu = 0 \cdot 5$, dashed curves). As might be expected from the previous discussion, the 'diffuse' field exterior to the network strip is nearly identical in the three cases, and the 'observed' fields are of the same order as the mean field when observed near the limb (dashed curves).

As a final comparison with observation, the synthetic magnetograph signal for the case of $d = 0 \cdot 05$ Mm has been analysed as though it resulted from a magnetic canopy, and the resulting cumulative distribution of canopy heights is plotted in Fig. 5. In fact, the result is only modestly higher (by approximately 0·1 Mm) than the histograms obtained from actual observations for comparable mean field strengths by Jones and Giovanelli (1983). Thus, at least in the preliminary computations reported here, the expectation that diffuse fields in potential-field network models lack sufficient strength low in the atmosphere to be compatible with observations is not substantiated.

However, there are two ways in which potential-field models appear to conflict with the data. First, the lack of depth dependence in the diffuse horizontal field suggests that similar results should be obtained in all three of the observed lines despite their discordant heights of formation. If verified in subsequent calculations, this is certainly at variance with observations in strong active-region network. In addition, the potential-field results scale directly with mean field strength in contrast to the lack of such dependence seen by Jones and Giovanelli (1983). However, this latter result is not easy to understand from any point of view and may yet prove to be an artifact of data reduction.

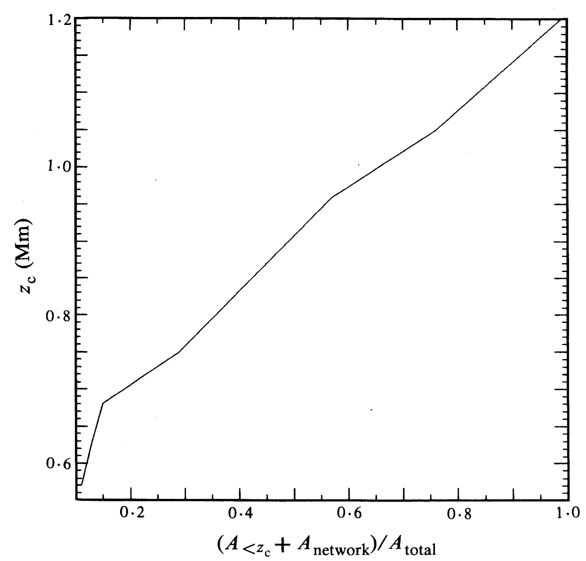

Fig. 5. Cumulative areal distribution of 'canopy heights' obtained when the simulated magnetograph signal for the case of $d = 0 \cdot 05$ Mm at $\mu = 0 \cdot 5$ is interpreted using the canopy model of Jones and Giovanelli (1982). Here $A_{<z_c}$ is the non-network area for which the computed base height z_c is less than the corresponding value of the ordinate.

5. Discussion and Summary

The projects discussed above are part of an ongoing effort to understand how the intense concentrations of photospheric magnetic fields spread through the chromosphere into large-scale coronal structures and how this affects the thermodynamic state of the gas and macroscopic flow patterns. Observationally, it seems imperative to include a careful treatment of the statistical effects of noise in the data reduction, as well as to understand better the effects of destreaking procedures. The preliminary calculations suggest that in some respects potential fields may be more compatible with magnetograph data than previously supposed. The results emphasize the need for both computation and observation in a variety of lines spanning an appreciable range in heights of formation, particularly near the heights of suspected canopy bases.

Finally, one puzzle presented by observations of a diffuse horizontal field in relatively low-lying lines is the observed persistence of spatially compact network emission (which is presumably driven by concentrations of field) in high chromospheric and transition-region lines. Although the potential-field models combined with a mean reference atmosphere are inherently incapable of explaining lateral structure in the emission or absorption characteristics of spectral lines, they do suggest that magnetic configurations are possible in which the central field in the network features remains reasonably concentrated with height even in the presence of an appreciable diffuse field.

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