THE THERMAL AND MAGNETIC STRUCTURE OF SUNSPOTS

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Abstract. The continuum intensity observations of sunspot umbrae and penumbrae in the visible and infrared are reviewed. The intensity in the darkest part of the umbra and the average penumbral intensity are known with relatively high accuracy in *large* sunspots. The importance of including infrared observations in the construction of semi-empirical sunspot models is emphasized.

Magnetic field measurements are discussed. Special attention is given to recent high-spatial-resolution observations that show large fluctuations in magnetic field inclination, suggesting that the sunspot magnetic field changes its inclination – but not its magnitude – between bright and dark penumbral features.

Key words: infrared: stars – line: formation – Sun: magnetic fields – sunspots

1. Introduction

Our empirical knowledge of sunspots is mainly based on observations in the visible part of the spectrum (*e.g.* Bray and Loughhead, 1964; Cram and Thomas, 1981; Obridko, 1985; Cox *et al.*, 1992). In this review we will emphasize the importance of the infrared observations for the determination of the thermal structure of sunspots, including the construction of semi-empirical sunspot models, *i.e.*, models that are in hydrostatic equilibrium and are adjusted to fit the observations.

In solar physics it is useful to make clear the nomenclature that will be used. The darkest part of the sunspot will be referred to as the umbral core. Sunspot umbrae are not uniformly dark but contain extensions of penumbral filaments and small, bright regions called umbral dots. For larger sunspots the bright umbral dots are usually located close to the rim of the umbra and may be called peripheral umbral dots (Krat *et al.*, 1972). In umbral cores the umbral dots show less contrast (Loughhead *et al.*, 1979) and to some observers the core gives the impression of being a featureless void (Livingston, 1991; Ewell, 1992). One should be aware, however, that examples of sunspots showing umbral dots distributed over nearly the whole umbra have been presented (Lites *et al.*, 1991). The penumbral structure has been studied in detail (see Muller, 1992). Here we shall limit the discussion to regarding the penumbra as consisting of dark and bright filaments, except when we need to underline that the filament appears to be broken up in fibrils.

Studies of the thermal structure of sunspots should be able to give information about the energy transport at different depths. In this paper we review the continuum intensity observations and show that the radiative flux decreases as a function of depth. Since the sunspot magnetic field will prevent ordinary convection, the problem is to explain why sunspots are as bright as observed. This brings us to the basic problem of how energy is transported to the surface in sunspots. If the energy is transported by oscillatory convection (*e.g.*, Weiss *et al.*, 1990), the monolithic flux tube picture of the sunspot may be used. One difficulty with this approach is that the convection cells will have to be very narrow in order to transfer energy laterally by radiation. This problem, combined with the observation that the umbral

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brightness is practically independent of the umbral diameter, led Parker (1979) to suggest that the sunspot consists of a cluster of narrow fluxtubes. In his model the energy is transported to the surface in field-free intrusions by ordinary convection. The cluster model requires a downdraft to keep the cluster of flux tubes together. There is, however, no observational support for this downdraft. In both models bright umbral dots are regarded as evidence for the way energy is transported to the surface. The possibility that the umbral core contains a region free of umbral dots, as suggested by some observers, may accordingly have important implications for our understanding of the energy flow in sunspots. In the following we shall concentrate on the continuum observations and the deepest observable layers.

Magnetic field observations in the infrared will be discussed. It is, however, necessary to include recent findings in the visible part of the spectrum to update our knowledge regarding the magnetic structure of sunspots. In particular, we shall draw attention to the importance of the fine structure in the magnetic field with spatial scale of the penumbral fibrils (*e.g.*, Title *et al.*, 1992). These new observations appear to solve the problem of understanding the conflicting results derived earlier from magnetic-field and from velocity-field measurements.

2. Continuum Observations

In the 1960's it was generally accepted that large sunspots were darker than small sunspots. However, this view was based on observations that were insufficiently corrected for scattered light (Zwaan, 1965). The stray light originates in the Earth's atmosphere and in the instrument and causes small amounts of light to be scattered from each position in the solar image to other positions. Since the sunspot is darker than the surroundings, the corrections for stray light become critical. In order to measure the amount of stray light, nearly simultaneous observations outside the solar disk have to be carried out. Observers who carefully correct their observations for scattered light have hitherto not found any evidence for a decrease in umbral brightness with increasing umbral diameter (*e.g.*, Rossbach and Schröter, 1970; Albregtsen *et al.*, 1984). This does not exclude the possibility that a systematic change in umbral brightness with umbral size may exist.

We emphasize the importance of a proper correction method for stay light (*e.g.*, Birkle and Mattig, 1965; Iuell and Staveland, 1975). One should be aware, however, that this correction method will not produce a complete restoration of the sunspot image. The method gives the corrected intensity in the center of the umbra as well as the corrected penumbral intensity as averaged over penumbral filaments. In observations of penumbral filaments image restoration methods have been applied (Grossmann-Doerth and Schmidt, 1981; Collados *et al.*, 1987). It seems likely that new algorithms like those for maximum entropy image restoration (Skilling, 1984) will be applied to sunspot observations in the near future. The observed fine structures in the form of bright umbral dots show dimensions comparable to the scale height, and knowledge about their thermal stratification may be important for understanding the energy transfer in sunspot atmospheres.

We note that an extension of the work on infrared imaging of sunspots (*e.g.*, Ewell, 1992) may be an important contribution for constructing two-component models with one hot and one cold component. A two-dimensional study of the sunspot atmosphere will require simultaneous observations with a series of two-dimensional detectors covering the wavelength region from 0.4 to 2.5 μm, properly corrected for stray light through the use of image restoration techniques.

2.1. UMBRAL CONTINUUM OBSERVATIONS

As relatively few intensity observations have been published recently, we have to rely on earlier observations, such as the sunspot intensity observations carried out for 10 months each year at the Oslo Solar Observatory between 1967 and 1986. The broad band pinhole photometers recorded intensities in a total of 11 wavelength regions in the spectral range 0.387–3.8 μm. Only measurements with an accuracy of 0.015 in the umbra/photosphere[1] intensity ratio were retained.

Let us consider the spectral distribution of the umbra/photosphere continuum intensity ratio in umbral cores, for sunspots with umbral radii larger than 4″. The results presented by van Ballegooijen (1984), Albregtsen *et al.* (1984) and Sobotka (1988, four largest sunspots) are in general agreement with the intensity values suggested by Albregtsen and Maltby (1981), after an evaluation of eleven papers published by different observers during the period 1968 to 1981. The extreme darkness observed in one sunspot by Bumba *et al.* (1990) is probably related to the fact that no correction for spectral line haze has been applied to that result.

Albregtsen *et al.* (1984) examined their data for connections between umbral temperature and sunspot parameters like the magnetic induction, size, age and the type of sunspot. No connection was apparent. Although the data do not show any systematic change of brightness temperature with sunspot size for large sunspots, such a relation could exist for smaller sunspots and has been suggested (see Sobotka, 1988).

Older data, not properly corrected for stray light, showed the umbral limb-darkening to be less than that of the photosphere, whereas more recent observers were unable to detect any center-limb variation in the umbra/photosphere intensity ratio. By observing the very same sunspot on several days during its passage over the solar disk, Albregtsen *et al.* (1984) found that all sunspots studied showed a real and significant decrease in the umbra/photosphere intensity ratio towards the limb. We note that the umbral limb darkening is easiest to detect in the infrared. Hitherto differences in limb-darkening between sunspots have not been detected.

A solar cycle variation in the umbra/photosphere intensity ratio was first detected in the infrared (Albregtsen and Maltby, 1978). Let the phase be measured as the time t elapsed since the last minimum in the cycle, the duration of which is t_0. After correction for limb-darkening the umbra/photosphere intensity ratio ϕ_u may be expressed as a linear function of the phase t/t_0 in the solar cycle, *i.e.*,

$$\phi_u(\mu = 1, \lambda, t/t_0) = c(\lambda) + d(\lambda)t/t_0.$$

At 1.67 μm the correlation coefficient between the umbra/photosphere intensity ratio and t/t_0 is 0.86 (−0.12, +0.07). The variation is caused by differences in umbral

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[1] Here "photosphere" refers to the quiet Sun.

intensity; the observed change in the intensity ratio is too large to be explained by a variation in the photospheric intensity.

It is well known that the average heliographic latitude of sunspots varies throughout the solar cycle. The correlation coefficient between the umbra/photosphere intensity ratio and the heliographic latitude is -0.63 (-0.12, $+0.16$) at 1.67 μm. Hence, the umbral intensity is better correlated with t/t_0 than with the sunspot heliographic latitude.

The hypothesis (*e.g.*, Adjabshirzadeh and Koutchmy, 1983) that a variation in the relative number of umbral dots from one sunspot to another may account for the observed difference in the umbra/photosphere intensity ratios has been investigated. Whereas the hypothesis would give the largest change in the visible, the observations show the largest change in the infrared. Suggestions as to the nature of the observed relation between the umbral temperature and the solar cycle have been presented (Schüssler, 1980; Yoshimura, 1983; Nordlund and Stein, 1990). The point to note here is that the observed relation may have implications for the relationship between sunspots and the solar dynamo.

According to Kusoffsky and Lundstedt (1986), the half-life time of "normal" umbral dots is about 60 min. It is often assumed that the umbral dots have almost photospheric temperature and sizes of 100–200 km. However, considerably lower dot temperatures are observed in the core of the umbra (Loughhead *et al.*, 1979; Grossmann-Doerth *et al.*, 1986) and some sunspots show cores without umbral dots (Livingston, 1991; Ewell, 1992). Possibly one may unite these conflicting results by introducing a hypothesis that only umbrae with radii larger than a certain value, say $4''$, have an umbral core without umbral dots (Maltby, 1992).

2.2. PENUMBRAL CONTINUUM OBSERVATIONS

Observations by Grossmann-Doerth and Schmidt (1981) and Collados *et al.* (1987) agree well with the results given by Maltby (1972) for the wavelength dependence of the average continuum penumbra/photosphere intensity ratio, *i.e.*, as averaged over penumbral filaments. No corrections for spectral line differences between the penumbra and the photosphere have been applied to these observations. Within the accuracy of the observations it has not been possible to detect any center-limb variation in the penumbra/photosphere intensity ratio.

Although the average penumbral intensity only changes slightly from one sunspot to another, differences in penumbral intensities between different sunspots are observed and found to be real (Ekmann, 1974). Sunspots with a darker than average umbra usually have a relatively dark penumbra. The correlation coefficient between penumbral and umbral intensities is 0.90 at a wavelength of 1.67 μm.

A description of the morphology of the penumbra is given by Muller (1992). Here it is sufficient to regard the penumbra as consisting of bright and dark filaments. Grossmann-Doerth and Schmidt (1981) and Collados *et al.* (1987) have studied the intensities in bright and dark penumbral filaments. It is apparent that the bright (dark) filaments within the very same sunspot are not equally bright (dark). This led Grossmann-Doerth and Schmidt (1981) to argue that their results were in conflict with those of Muller (1973). Collados *et al.* (1987) confirm the spread in brightness between the filaments, but find that their results are in general agreement with those of Muller (1973).

3. Semi-Empirical Models

In semi-empirical models the atmosphere is assumed to be either in hydrostatic or in hydrodynamical equilibrium and the temperature-optical depth relation is adjusted until the calculated intensities account for the observations.

In this paper the emphasis will be on the core model that fits the observations for an *average* large sunspot. Next, we shall take into account the presence of umbral dots and mention a few aspects of two-component umbral models. In penumbral semi-empirical models one has to consider that a non-vertical magnetic field may introduce a lifting force. Furthermore, the marked filamentary structure of the penumbra calls for two or more components in the horizontal plane.

3.1. UMBRAL CORE MODEL

In semi-empirical umbral core models the atmosphere is assumed to be in hydrostatic equilibrium along a vertical magnetic field such that the field does not influence the stratification. The easiest way to construct a model for the umbral core is by scaling the quiet-Sun model. This approach has been used by several authors, most recently by Sobotka (1988) who sets $\Delta\theta =$ constant, where

$$\Delta\theta = 5,040\ (1/T_{\mathrm{u}} - 1/T_{\mathrm{ph}})$$

and T_{u} and T_{ph} are respectively the temperature of the umbra and the photosphere. The advantage of this method is that the $\Delta\theta$ value characterizes the entire model. The disadvantage is that the model does not fit the observations (see below).

We shall consider umbral core models presented by van Ballegooijen (1984), Maltby *et al.* (1986), Obridko and Staude (1988) and Sobotka (1988). Since these models have been calculated with different computer codes and input parameters, differences other than those caused by the different temperature-optical depth relations may occur. In order to minimize these other effects the models have been recalculated using the same computer code.

A comparison between calculated continuum intensities and the observed continuum intensities at the center of the solar disk is presented in Figure 1. It is apparent that all four models may account for the observations in the visible and near infrared part of the spectrum up to approximately 1 μm. Hence, observations in the infrared are required to differentiate between the models. We note that the model by Sobotka (1988) with $\Delta\theta = 0.45$ shows considerably lower intensities than those observed in the far infrared. The model by Obridko and Staude (1988) predicts intensities that are too low at wavelengths above 1.6 μm. Both the models by van Ballegooijen (1984) and by Maltby *et al.* (1986) may account for the observations shown in Figure 1. A recent model by Ming-de and Cheng (1990) was not included in Figure 1; the model is quite similar to the model by Sobotka (1988).

A reasonable fit to the center–limb observations is obtained with the models by van Ballegooijen (1984) and by Maltby *et al.* (1986). The deviations between

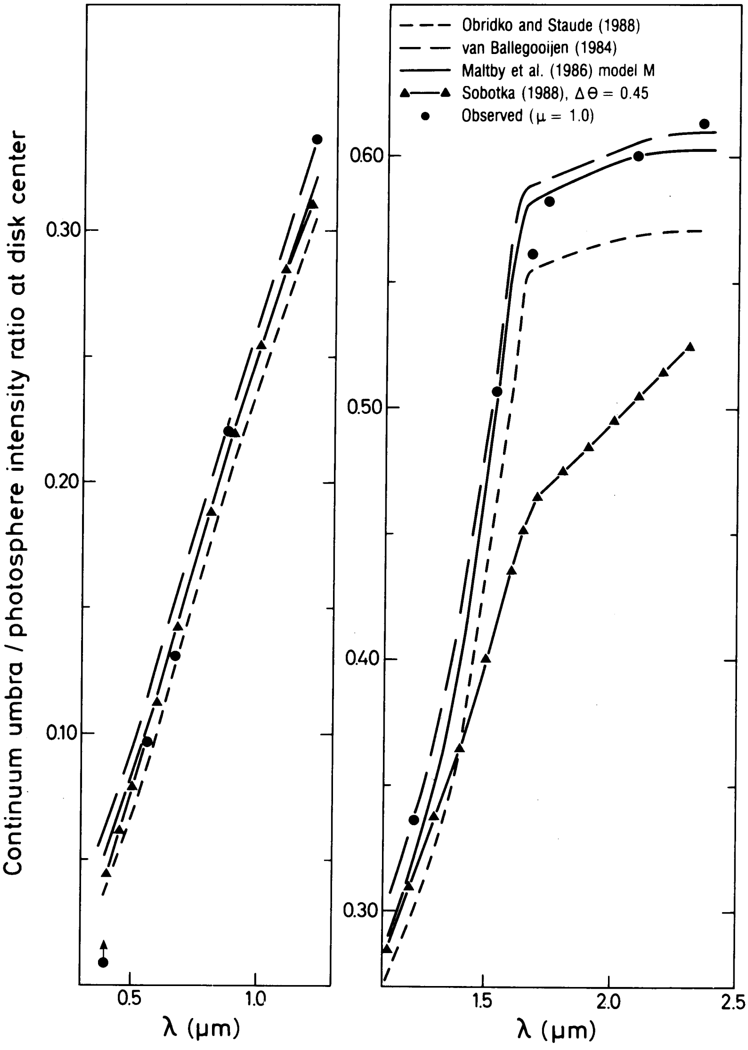

Fig. 1. Observed continuum umbra/photosphere intensity ratios at disk center compared with the predicted intensity ratios for four different umbral core models. The same computer code was used to obtain the four sets of intensity ratios.

the calculated and observed values are significant for the two other models, most apparently for the model by Sobotka (1988). Maltby (1992) compared the calculated radiative flux density, integrated over wavelength, as a function of optical depth at the reference wavelength (0.5 μm) for the umbral models. Whereas both the photospheric model and the umbral model by Maltby *et al.* (1986) vary relatively smoothly with depth, the models by van Ballegooijen (1984) and Obridko and Staude (1988) show more complicated variations. The transition from radiative to another form of energy transport occurs close to the solar surface.

The semi-empirical umbral and photospheric models give the stratification in the umbra and the photosphere, respectively. In order to make a comparison between semi-empirical and theoretical sunspot models meaningful, a value for the Wilson depression is needed. Although analytical magnetostatic models (Osherovich and Garcia, 1989) are of interest, the focus has shifted to numerical solutions (Jahn, 1989; Pizzo, 1990).

3.2. TWO-COMPONENT UMBRAL MODEL

The two component model by Obridko and Staude (1988) combines one hot component with temperature close to that of the photosphere with an umbral core component. Several questions arise in connection with the two-component umbral models, in particular since the intensity of the bright component is uncertain. Furthermore, it is unlikely that the fraction covered with bright emission remains constant with height. We know that umbral dots in the central part of large sunspots show less contrast than peripheral umbral dots. It is possible that the distribution of umbral dot intensities is such that the bright component changes in temperature from one umbral dot to another and from one sunspot to another.

Since some umbral cores are free of umbral dots the energy flow in deep layers must be distributed laterally before reaching the visible layers. In order to get some insight into the time needed to distribute energy laterally by radiation we have calculated the cooling time for a hot filament embedded in a cold gas. For a hot filament with diameter 100 km, situated at an optical depth of 10 in the umbra, the cooling time is 50 s, increasing to 800 s for a diameter of 400 km. Hence, in order to account for the brightness of a featureless umbral core a fine structure is needed in subphotospheric layers.

3.3. PENUMBRAL MODELS

The penumbra is much closer in temperature to the photosphere than is the umbra. The temperature of the penumbra may, in a first approximation, be described by a single parameter value of $\Delta\theta$ = constant, where now

$$\Delta\theta = 5,040\ (1/T_{\mathrm{p}} - 1/T_{\mathrm{ph}})$$

and T_{p} and T_{ph} are respectively the temperature of the penumbra and the photosphere, as averaged over penumbral filaments and granules. The average value for penumbrae is $\Delta\theta = 0.055$. The one-component penumbral models of Yun *et al.* (1984) and Ding and Fang (1989) are primarily aimed at modeling the penumbral chromosphere; we note that these models are too cold in deeper layers to account for the continuum observations.

In the penumbra the filament structure is so evident that it is tempting to construct a two-component model. The model should agree with the observed intensities in dark (d) and bright (b) filaments. As a check on the model, the calculated spectral intensity as averaged over penumbral filaments may be compared with observations. A two-component model with $\Delta\theta_b = 0.010$, $\Delta\theta_d = 0.093$ and the ratio of the areas covered by bright and dark filaments equal to 0.75 was presented by Kjeldseth-Moe and Maltby (1974), based on observations of penumbral filament intensities by Muller (1973).

Evidently the intensity may change from one bright penumbral filament to another within the same penumbra so that the two-component model must be used with care. The construction of a two-component model also brings up the question of keeping the two atmospheres in balance in the horizontal direction over an extended height range. This implies that the sum of the gas pressure and the magnetic pressure must be the same in bright and dark filaments. The gas pressure stratification in the filament may be influenced by a variation in curvature of the magnetic field lines with depth. It is interesting that large fluctuations in inclination angle for the penumbral magnetic field have been reported (see section 4.4).

4. The Magnetic Field

The magnetic field observed on the Sun emerges from the solar interior and has already been broken up into separate flux tubes when reaching the visible surface. It is well known that the sunspots occur within activity belts. One third of all sunspots are members of "sunspot nests", *i.e.* sunspots that appear with practically the same coordinates in latitude and in longitude (Brouwer and Zwaan, 1990). Per unit area at the solar surface the probability is more than 25 times larger for emergence of new active regions within an already existing active region than it is for emergence elsewhere in the then available activity belt (Harvey, 1992). In a large bipolar active region at maximum development the typical distance between the centroids of opposite polarities is 150 Mm, a distance comparable to the depth of the convection zone. In fact, it has been suggested that the toroidal magnetic field system responsible for the sunspots is located at the interface between the convective zone and the radiative interior (*e.g.*, Schüssler, 1983; Zwaan, 1992). In the following we shall focus on the observable parts of the magnetic field in *single* sunspots, leaving aside magnetic elements that move radially in the sunspot moat. Studies of the network and intranetwork magnetic fields are also outside the scope of this review.

4.1. ZEEMAN AND PASCHEN–BACK EFFECTS

The magnetic field in sunspots are most commonly inferred from measurements of the polarization in spectral lines split by the Zeeman effect (see Zeeman, 1913). It may be of some interest to know that the splitting of the D_1 and D_2 lines of Na by a magnetic field was first found by Fievez (1885) a decade before the effect was discovered by Zeeman in 1896.

The fact that not all lines follow the Zeeman line splitting pattern was detected by Paschen and Back from investigations of the Li I 6708 Å resonance line. The reason is that for strong magnetic fields the magnetic splitting is comparable to the doublet separation. The splitting of the Li I resonance doublet by the sunspot magnetic field is discussed by Maltby (1971). A discussion of the Paschen–Back splitting of the Mg I line at 12.32 μm is given by Chang in this volume.

4.2. LINE FORMATION THEORY

The interpretation of the magnetic field measurements should be based on an understanding of the theory of spectral line formation in the presence of a magnetic field. The line formation theory in terms of Stokes parameters was formulated originally by Unno (1956) and extended by Rachkovsky (1962). Considerable effort has been devoted to the solution of the Unno-Rachkovsky equations; for a review see Semel *et al.* (1992). Although more general non-LTE formulations, including quantum interference and partial redistribution, exist (Landi degl'Innocenti, 1983), the practical applications are usually limited to electrical dipole transitions, LS-coupling, no quantum interference between the Zeeman states, complete redistribution on scattering, and steady state atmospheres.

Another limiting factor in the line formation theory is the lack of good correction methods for molecular and atomic blends as well as for depressions in the continuum caused by line haze. As an example, consider the Fe I 5250.22 Å line that has been extensively used for magnetic field measurements. One of the σ-components contains a blend from FeH at 5250.31 Å in the umbral spectrum (Wöhl *et al.*, 1983). The blend in the π-component in the umbra was identified by Kjeldseth-Moe (1973) as the 5250.24 Å $P_1(71)$ line of TiO belonging to the (0,0) band of the α-system. His calculations showed that estimates of the inclination of the magnetic field vector will easily yield values 20° to 30° in error if the molecular blend is neglected. This suggests that the observed line haze in the spectra of umbrae may seriously influence the results of magnetic field measurements. Umbral spectra are so crowded with lines that care should be taken in all three cases of polarimetry measurements; *i.e.*, broad-band, magnetograph and high spectral resolution observations. The broad-band polarization observed in sunspots (*e.g.* Leroy, 1962) has, so far, had limited diagnostic value. A better theoretical calculation of the spectrum, taking into account the blends present may improve the situation.

4.3. THE MESOSCALE MAGNETIC STRUCTURE

The magnitude of the magnetic field near the centre of the sunspot is between 2000 and 4000 G. The magnetic field strength is nearly independent of sunspot size (Brandt and Zwaan, 1982); a slow increase in B with increasing area has been found. Several authors (see review by Skumanich, 1992) have presented measurements of the magnetic induction $B(r)/B(0)$ as function of the distance r from the centre of the sunspot, measured in units of the penumbral radius. Recent studies suggest a steeper gradient and accordingly a smaller value of B at the rim of the penumbra than the relation $B(r) = B(0)/(1+r^2)$ derived by Beckers and Schröter (1969). The recent papers suggest an inclination of 60–70° close to the rim of the penumbra, whereas earlier papers found the field to be nearly horizontal in the outer parts of the penumbra. Improved accuracy in sunspot magnetic field determinations have been attained by using the magnetically sensitive infrared line at 1.5648 μm line (Solanki *et al.*, 1992) and the Mg I line at 12.32 μm (Deming *et al.*, 1988). Since sunspots in general do not show circular symmetry, there is an apparent need for infrared observations of the magnetic field distribution along different position angles within the sunspots, using detector arrays.

The field measurements at photospheric heights have also been studied with the intention to determine the vertical gradient of the magnetic field (*e.g.* Hofmann and Rendtel, 1989). A review of the extrapolation of photospheric magnetic fields into the corona is given by Semel *et al.* (1992).

4.4. HIGH SPATIAL RESOLUTION MEASUREMENTS

One problem we face comparing medium spatial resolution observations of the magnetic field with the direction of the gas flow in the penumbra is the following: the high electrical conductivity in the sunspot atmosphere makes it very likely that the flow is along the magnetic field lines. Whereas the flow is nearly horizontal at photospheric heights, the magnetic field measurements (see section 4.3) suggest an inclination of 60–70° close to the rim of the penumbra. High spatial-resolution observations of both the magnetic field and the flow field by Title *et al.* (1992) give insight into this problem and we would like to draw attention to two new findings: (1) There is a variation in inclination of the magnetic field in the penumbra of ±15–20° with a spatial scale of the penumbral fibrils. (2) The more horizontal magnetic fields occur in the regions of the Evershed flow.

Since there is a tendency for the Evershed flow to occur in darker penumbral structures, where the magnetic field is more horizontal, the new findings appear to be consistent with gas flow along the magnetic field lines, as expected from theoretical arguments. Observational arguments in favor of the rapid fluctuation in magnetic field inclination with position angle in the sunspot are given by Kalman (1991). We note that thin X-ray loops are observed to terminate in the penumbra (Golub *et al.*, 1990). The orientation of the loops suggests an inclination close to 45° for the magnetic field. The high inclination found for some field lines in the sunspot region makes it easier to understand the observed velocity field in the chromosphere and transition region. The observed variation in inclination of the magnetic field in the penumbra with a spatial scale of the penumbral fibrils raises questions about the structure of magnetostatic atmospheres; for a general formulation see Low (1991).

5. Concluding Remarks

In this review attention has been given to the fact that the detection of the solar cycle variation of the sunspot intensity was based on observations in the infrared. By comparing different semi-empirical umbral models we have illustrated how continuum observations in the infrared have contributed considerably to our present understanding of the temperature structure of sunspots.

Using semi-empirical models one may determine the lateral pressure difference between the umbra and the photosphere. The largest contribution to the lateral gas pressure difference comes from the magnetic field, which acts both through the magnetic pressure, $B^2/2\mu$, and through the magnetic tension. Further comparisons with numerical models (Jahn, 1989; Pizzo, 1986) may be valuable.

The semi-empirical models indicate that the sunspot regions are in radiative equilibrium in the upper layers, but other energy transport processes take over close to the solar surface. In both the monolithic flux tube model and in the cluster model the umbral dots are regarded as evidence for the way energy is transported to the surface. If the umbral core is observed to be without umbral dots the energy must be distributed laterally by radiation in deeper layers. In order to account for the brightness of a featureless umbral core a fine structure is needed in subphotospheric layers.

The sunspot brightness is primarily determined by the energy transport processes, but the energy equation is mathematically coupled to the momentum equation. Along the magnetic field lines the gas is nearly in hydrostatic balance, but not quite since flows are observed. We have drawn attentional to recent observations of the magnetic field and the velocity field. These high-spatial-resolution observations show that the physical picture may change considerably when improved observations become available and suggest that infrared observations of the magnetic field with high spatial resolution would be valuable (see Rabin 1993, in this volume).

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