PART III

OBSERVATIONS OF SUNSPOT AND ACTIVE REGION MAGNETIC FIELDS

ON MAGNETIC FIELDS IN SUNSPOTS AND ACTIVE REGIONS

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Abstract. This review is restricted to a few topics of the extensive problem under discussion; it refers to the literature since 1967 only. The literature prior to 1967 is reviewed in Zwaan, 1968; Howard, 1967; Lüst, 1965; Kiepenheuer, 1968; Jäger, 1964; and Bray and Loughead, 1964.

1. Comments on the Thermodynamical Structure of Sunspots

1.1. RECENT UMBRAL AND PENUMBRAL MODELS

The homogeneous hydrostatic equilibrium models for the umbra of a so-called 'typical sunspot' derived recently by Hénoux (1969), Hong Sik Yun (1971), Stellmacher and Wiehr (1970) agree rather well with one another (Figure 1). Hénoux's model has been derived from continuous radiation data and checked with the equivalent widths of medium strong lines. The model of Hong Sik Yun reproduces the wavelength dependence of the spot contrast up to 1.6 μ, its center to limb variation (see Mattig (1969a) and Wittmann and Schröter (1969)) and the wings of the NaD-lines. The Stellmacher-Wiehr model is a modified Hénoux model and capable of reproducing the line profiles of magnetically unsplit lines, as observed by the authors. A working model in the range of validity of these models seems capable of describing most of the available continuous radiation and Franhofer line data within observational errors. Deviations from hydrostatic equilibrium, at least in the upper layers where most of the lines originate, do not seem serious. These models refer to the

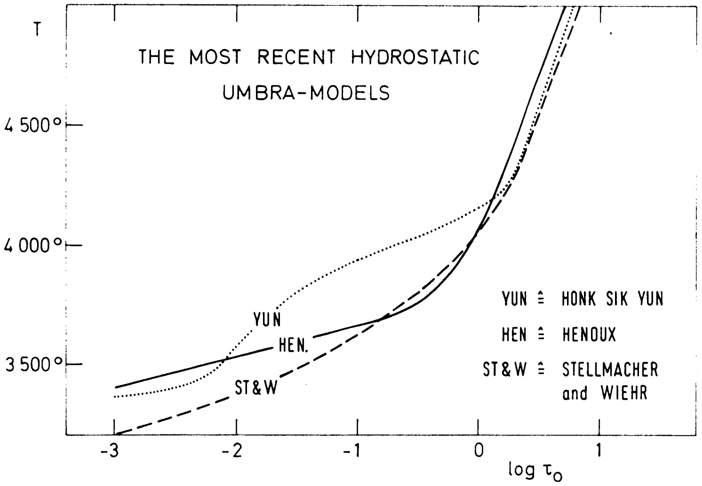

Fig. 1. Comparison of the three most recent homogeneous umbral models (hydrostatic equilibrium models).

Howard (ed.), Solar Magnetic Fields, 167–180. *All Rights Reserved.*

'mean averaged umbra' and not to the umbral region between the umbral dots. The relatively low umbral temperature gradient with its consequent departures from radiative equilibrium may be explained in terms of a lateral influx from the photosphere (cf. Zwaan, 1965 and Hong Sik Yun, 1971), in terms of a strong blanketing effect, caused by the thousands of molecular lines originating in the upper layers of umbrae, or is simulated by the umbral dots. Then the later have to be not of convective origin (Wilson, 1969) but non-radiative heated phenomena of the upper layers. Attempts to incorporate umbral inhomogeneities in inhomogeneous umbral models (Makita, 1963 and Obridko, 1968) are premature. High resolution spectral atlases of umbrae are under preparation at Kitt Peak and Göttingen (Wöhl *et al.*, 1970).

The penumbral homogeneous hydrostatic equilibrium model of Kjeldseth Moe and Maltby is also capable of well reproducing all available observational data (see e.g. Moe and Maltby, 1969 and Schleicher and Schröter, 1971). Its physical significance, however, is rather limited because of the strong inhomogeneity of the penumbra.

1.2. THE STRUCTURE OF A 'TYPICAL SUNSPOT'

So far spectroscopic observations of umbrae seem not to contradict the assumption of hydrostatic equilibrium (see also Tepliskaja and Turchina, 1969). A vertical section through a typical sunspot can be derived (see Figure 2) by taking the mean of the results from the investigations (Wittmann and Schröter, 1969; Wilson and Cannon, 1968; Wilson, 1968; Wilson and McIntosh, 1969; Jensen *et al.*, 1969; Mattig, 1969b; and Ruhm, 1969). In these investigations either the center to limb variation of the sunspot intensity profile (Wilson-effect) or the density scale height have been discussed. There is some controversy whether or not the depression vanishes for small optical depths. An almost force-free magnetic field in the upper layers and

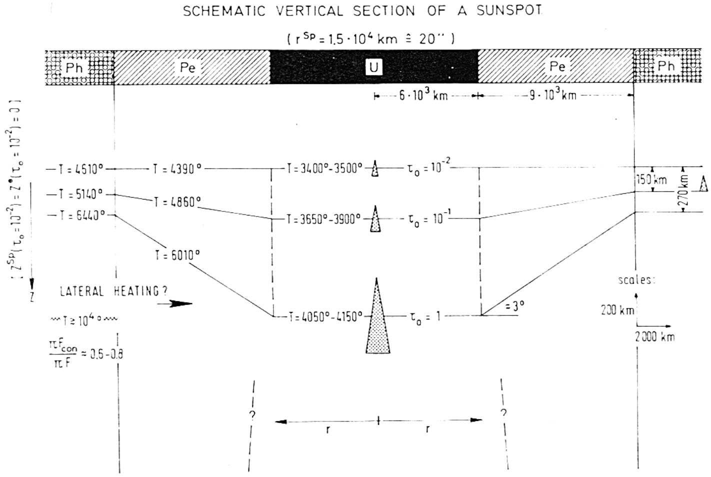

Fig. 2. A vertical section through a typical sunspot derived from Wittmann and Schröter (1969), Wilson and Cannon (1968), Wilson (1968), Wilson and McIntosh (1969), Jensen *et al.* (1969), Mattig (1969), and Ruhm (1969). ▲ indicates the density scale height.

an increasing prevalence of magnetic forces in deeper layers of umbrae are the consequences of this model. Wilson's conclusion that the diameters of umbrae increase with depth should be checked by more sophisticated observations.

2. The Average Magnetic Field of a Sunspot

It is well known that the magnetic field structure may vary in a complicated manner from one spot to another, especially when complex sunspot groups are considered (see e.g. Jayanthan, 1970). In order to understand some general aspects of the sunspot magnetic field the following discussion is restricted to single, symmetric, long lived sunspots.

2.1. THE RADIAL VARIATION OF THE MAGNETIC FIELD STRENGTH

Redeterminations of $H(\varrho)$ (where ϱ is the distance from the spot center in units of its radius) generally confirm previous results (Adam, 1969; Rayrole and Semel, 1967, 1970; Beckers and Schröter, 1969; and Deubner and Göhring, 1970) resulting in the conventional axial magnetic field pattern. Beckers and Schröter showed that the observed $H(\varrho)$ curve may be well represented by

$$H(\varrho) = H(0)\,[1 + \varrho^2]^{-1} \qquad 0 \leqq \varrho \leqq 1 \tag{1}$$

which leads to a magnetic field strength at the outer sunspot border one half of that at the center. This formula is to be compared with Broxon's and Mattig's formulae

$$\underset{\text{(Broxon)}}{H(\varrho) = H(0)\,[1 - \varrho^2]} \qquad \underset{\text{(Mattig)}}{H(\varrho) = H(0)\,[(1 - \varrho^4)\,e^{-2\varrho^2}]} \tag{2}$$

$$0 \leqq \varrho \leqq 1\,.$$

The $H(\varrho)$ curve as derived by Beckers and Schröter (1969) differs from previous results in two aspects: (a) the penumbral field was found to be considerably larger than assumed up to the present, (b) the magnetic field was found to tend sharply to zero at the outer penumbral border. Altrock (1969) and Mallia (1970) confirmed the high field strength in the penumbra, whereas Deubner and Göhring (1970) measured considerably smaller fields at the penumbral-photospheric border. Kossinskij (1967) found the magnetic sunspot radius to be larger than the spot intensity radius in contradiction to the measurements (b) by Beckers and Schröter (1969).

The saturation effect in Zeeman split lines as discussed by Maltby and Kjeldseth (1968), Hénoux (1968), Beckers and Schröter (1968a), Göhring (1969) and Staude (1970) may lead to an incorrect interpretation of the $H(\varrho)$-curve and of the height gradient when strongly saturated lines (such as λ 5250 Å) are used for the observations. This effect leads to a much larger separation of the maxima of the Stokes parameter V when compared with the true field if $\gamma \neq 0$ (γ is the inclination angle of the field to the line of sight). Since no discontinuous changes in $H(\varrho)$ at the umbra-penumbra border are observed, one concludes that either the umbral depression at those depths where the lines originate is negligible or that the model of an inclined depression within the penumbra (see Figure 2) is correct.

2.2. THE INCLINATION OF THE AVERAGE SUNSPOT MAGNETIC FIELD

Redeterminations of the zenith angle $\alpha(\varrho)$ of the magnetic field across a symmetrical sunspot (Adam, 1969; Beckers and Schröter, 1969; and Deubner and Göhring, 1970) generally confirm the classical Hale and Nicholson law $\alpha = \pi/2 \times \varrho$.

However, when comparing the results from different observers in detail (see e.g. Figure 9 in Beckers and Schröter, 1969) one finds: (a) a very large scatter in the various determinations, (b) only those observations based on the classical 'neutral line' method, which are observations of the location of the transversal effect within the sunspot during its disc passage, lead to zero values of α in the spot center; all other methods (intensity ratio of the σ-to-π-component, magnetographic and lambda-meter measurements) result in non zero values of α in the spot center, (c) the zenith angles measured by the latter methods are systematically larger than those obtained from the 'neutral line' method.

Retardation in solar instruments, generally neglected, may well be responsible for these effects. Almost all solar telescopes use mirrors at high angles of incidence (coelostats or Coudé-mirrors) which produce not only linear polarization but also light retardation caused by phase changes.* Only a few observers have considered the effect of instrumental retardation on their magnetic field measurements (e.g. Adam at Oxford, Jäger and Oetken at Potsdam).

Assume that this retardation makes the instrument behave like a $\lambda/4$ plate for a small fraction p of the incident light and that it does not change the polarization state of the remaining fraction $(1-p)$. The axis of the instrumental polarization ellipse will rotate during the day. For simplicity consider this axis to be parallel to the analyzing plate.

Then a fraction $(1-p)$ of the Zeeman light-pattern is analyzed with a $\lambda/4$ plate and a polaroid and the remaining fraction p through a $\lambda/2$ plate and a polaroid.

The simple Unno formulae for large splitting are a reasonable approximation for umbral magnetic fields. Using these formulae (multiplied by p) for a $\lambda/2$ plate + polaroid arrangement and multiplied by $(1-p)$ for a $\lambda/4$ plate + polaroid arrangement one obtains:

$$r_{\sigma_1,\,\mathrm{obs}} = f(\theta)\,\frac{\frac{1}{4}\eta_\lambda (1-\cos\gamma)^2}{1+\frac{1}{2}\eta_\lambda(1+\cos^2\gamma)} \times$$

$$\times \left\{1 - p\,\frac{\sin^2\gamma\,\sin 2\varphi - 2\cos\gamma}{(1-\cos\gamma)^2}\right\} \hat{=} f(\theta)\,\frac{\frac{1}{4}\eta_\lambda(1-\cos\hat{\gamma})^2}{1+\frac{1}{2}\eta_\lambda(1+\cos^2\hat{\gamma})}$$

$$r_{\sigma_2,\,\mathrm{obs}} = f(\theta)\,\frac{\frac{1}{4}\eta_\lambda (1+\cos\gamma)^2}{1+\frac{1}{2}(1+\cos^2\gamma)} \times$$

$$\times \left\{1 - p\,\frac{\sin^2\gamma\,\sin 2\varphi + 2\cos\gamma}{(1+\cos\gamma)^2}\right\} \hat{=} f(\theta)\,\frac{\frac{1}{4}\eta_\lambda(1+\cos\hat{\gamma})^2}{1+\frac{1}{2}\eta_\lambda(1+\cos^2\hat{\gamma})}$$

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* If the incident light is linearly polarized, one will generally measure elliptically polarized light at the exit.

$$r_{\pi,\,\mathrm{obs}} = f(\theta)\,\frac{\frac{1}{2}\eta_\lambda \sin^2\gamma}{1+\eta_\lambda \sin^2\gamma} \times$$

$$\times \{1 + p\sin 2\varphi\} \triangleq f(\theta)\,\frac{\frac{1}{2}\eta_\lambda \sin^2\hat{\gamma}}{1+\eta_\lambda \sin^2\hat{\gamma}}$$

where $f(\theta) = (1 + \beta_0 \cos\vartheta / 1 + \beta_0)$, γ the true and $\hat{\gamma}$ the 'observed' inclination angle of the magnetic field to the line of sight and φ the azimuth angle of the field. Since $p\sin 2\varphi > 0$ in the range $0 < \varphi < 90°$, the π-component is strengthened by instrumental retardation (it is unchanged for $\varphi = 0°, 90°$). For small angles γ:

$$\sin^2\gamma\sin 2\varphi + 2\cos\gamma > 0 \quad \text{and} \quad \sin^2\gamma\sin 2\varphi - 2\cos\gamma < 0\,.$$

Hence, the stronger σ_2-component is weakened and the weaker σ_1-component is strenghtened considerably ($(1-\cos^2\gamma)$ is almost zero) by instrumental retardation.

The effect is least for $\gamma = 90°$; generally the Zeeman components will show 'inconsistent' intensity ratios.

Therefore, when deriving $\hat{\gamma}$ from the intensity ratios σ_1/π, σ_2/π, σ_1/σ_2 and neglecting retardation in the instrument, one will obtain $\hat{\gamma} > \gamma$.

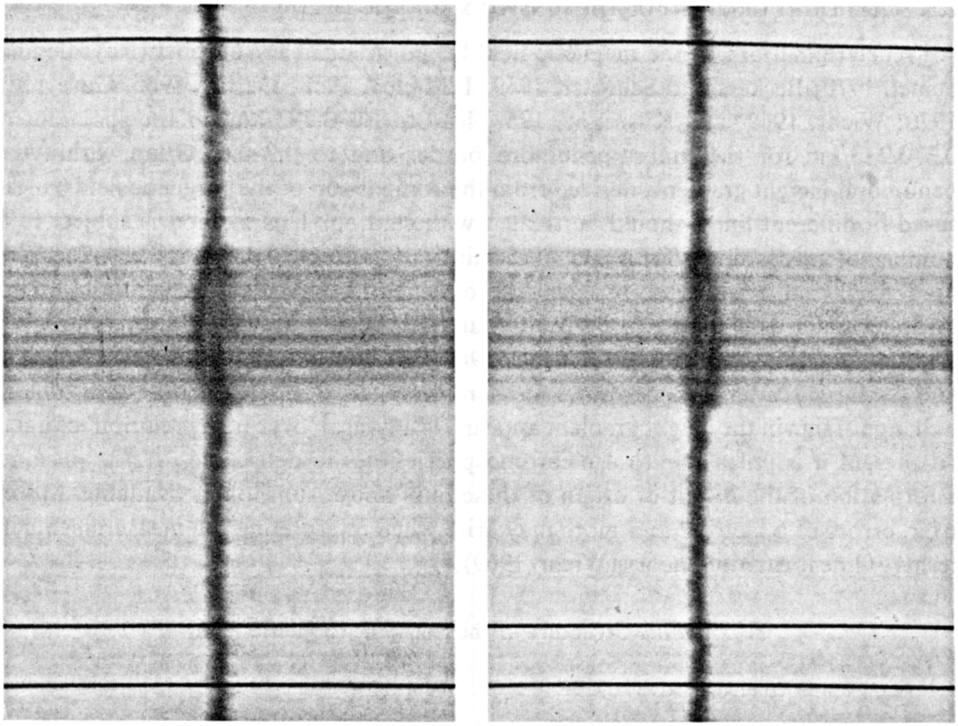

Fig. 3. The magnetically sensitive Fe-line λ6173.3 Å in a sunspot penumbra, observed through a Wollaston prism and polaroid (Sacramento Peak Big Dome coelostat and spectrograph). Note the inconsistency of the Zeeman pattern in the two spectra due to retardation in the instrument; e.g. the π-component does not vanish (as it should) when both spectra arc subtracted from each other.

Computations show, that if $\gamma = 10°$ (the smallest observable true inclination angle in the spot center because of the spot's disc position), $\hat{\gamma} \sim 25° - 35°$ when $p = 0.1$ and $\eta_0 = 10$. The retardation parameter may vary from instrument to instrument; Adam (1969) measured $p = 0.07$; at Locarno $p \sim 0.05$ was found.

The instrumental retardation (or the inconsistency of the Zeeman pattern) will generally escape detection in the lambdameter and magnetographic techniques and can best be recognized when the Stokes parameters of the entire line profile are measured. The scatter of the various determinations of $\alpha(\varrho)$, especially for small α, has to be interpreted in terms of (a) different values of p, (b) different positions of the instrumental retardation axis (at the time of observations) for the various instruments used, and (c) the dissimilar influence of instrumental retardation on the many analysing techniques employed. Since the effect of instrumental retardation is negligible for $\gamma = 90°$ and $\hat{\gamma} > \gamma$ when $\gamma < 90°$, the larger values for α obtained from methods other than the 'neutral line' method are well understood. Since retardation is present in almost all solar telescopes and has almost been ignored, earlier observations leading to a non vertical field in the spot center (Bumba, 1962; Bray and Loughead, 1964) are inconclusive.

2.3. THE HEIGHT GRADIENT OF THE SUNSPOT MAGNETIC FIELD

All redeterminations of the magnetic field height gradient in sunspots (Rayrole and Semel, 1970; Beckers and Schröter, 1969; Ikhsanov, 1968; Dubov, 1965, Guseynov, 1970; Wiehr, 1969; and Kusnezov, 1968) lead to 1.0–0.5 G/km for the spot center, 0.3–0.2 G/km for the umbra-penumbra border and to 0.2–0.05 G/km within the penumbra. Height gradients derived from the comparison of the magnetic fields, measured in different lines, should be treated with caution. This method is subject to a number of misleading effects and uncertainties (scattered light if ionized lines are used, LTE and NLTE; the problem of contribution curves and heights of origin; saturation effects as discussed by Maltby and Kjeldseth Moe (1968), Hénoux (1968), Beckers and Schröter (1968), Göhring (1969), and Staude (1970). Because of this, and the large scatter in Guseynov's measurements (1970) his result that occasionally a change of sign in the height gradient appears, is a typical 'over-interpretation' of data. At present it is unfeasible to use chromospheric lines to determine $\partial Hz/\partial z$ since no information of the height of origin of these lines above sunspots is available. Moreover, errors of a factor 2 and more may arise when interpreting the measurements in terms of line formation theory (Wiehr, 1969).

3. The Fine Structure of the Sunspot Magnetic Field

3.1. THE UMBRAL FINE STRUCTURES

A number of properties of the bright umbral fine structures, the umbral dots, have been studied by Beckers and Schröter (1968b). Many questions regarding the relationship of these features to the umbral magnetic field remain. Are umbral dots permanent phenomena in umbrae or do they occur only in certain stages of sunspot evolution?

Do they have the same magnetic field as the umbra or a zero field or even perhaps one of opposite sign? This is unknown, since all attempts to measure the magnetic field in umbral dots have failed. Are umbral dots of convective origin? If so, how is one then to explain their life time being considerably longer than their radiative cooling time? Are they non-radiative heated phenomena of the umbral upper layers (Wilson, 1969)? Do they occur in all spots with the same spatial density and the same intensity contrast, or do these vary from spot to spot?

The existence of a fine scale structure of the umbral magnetic field had been suggested by the Crimean observers several years ago (see e.g. Severny, 1965) who concluded this from the observed large rotation of the polarization plane with depth.

Mogilevskij *et al.* (1967) and later Beckers and Schröter (1968a) ascribed the splitting of the π-component of a Zeeman triplet into two opposite circularly polarized components to the magnetic field in umbral fine structures (Figure 4). The π-component splitting has also been observed and measured recently by Deubner and Liedler (1969) and Mehltretter (1969). This splitting leads to an opposite polarity (if interpreted in terms of magnetic splitting) when compared with the ordinary splitting and corresponds to 200–500 G. It should be emphasized that this effect which appears in

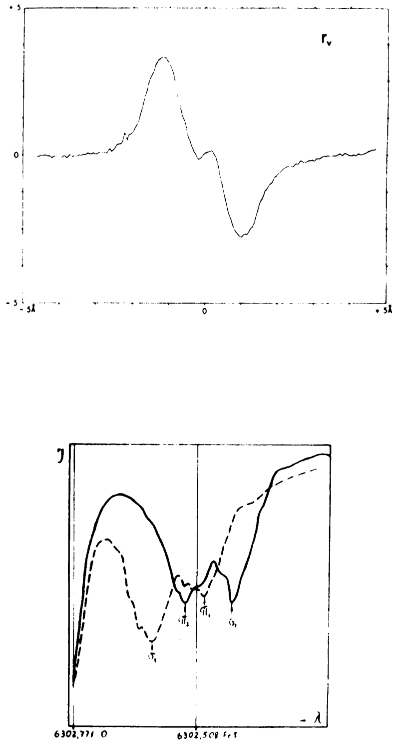

Fig. 4. The splitting of the π-component of λ6173.3 Å and λ6302.5 Å into two opposite circularly polarized components (a) after Beckers and Schröter (1968a), (b) after Mogilievsky *et al.* (1967).

the Stokes parameter V has no connection with the saturation effect appearing in the Stokes parameter I as studied by Maltby and Kjeldseth Moe (1968), Hénoux (1968), Beckers and Schröter (1968a), Göhring (1969) and Staude (1970). Surkov (1969), observing Doppler-shifts of the split π-components, came to the conclusion that this effect could be explained well in terms of Faraday-rotation. Beckers (1969) found this explanation unlikely, though possible. It has not yet been checked whether or not the π-component splitting occurs in all spots or only in some umbrae. It is very unlikely that this effect is caused by light scattered into the umbra from adjacent magnetic knots of opposite polarity. At the present there are two alternate explanations:

(1) In certain umbrae, the magnetic field of 2000–4000 G has a fine structure of 200–500 G of opposite polarity embedded in it. (Note: the intensity of the split π-components has been estimated to be $\sim$0.1 of the σ-components and this is of the same order of magnitude as the contribution of the umbral dots to the composed umbral spectrum.)

(2) The effect is caused by a strong variation of the magnetic field azimuth with depth (Rachkovsky and Beckers, 1969). This, however, leads to the strange conclusion that, independent of the hemisphere, all spots with north polarity must have an anti-clockwise rotation of the field with increasing depth whereas all spots with south polarity must have magnetic fields rotating clockwise.

Steshenko (1967) gave direct evidence of the umbral magnetic field inhomogeneity. He observed a small umbral element ($\lesssim 2''$) showing a magnetic field strength of > 5000 G, embedded in an umbral field of 2400 G.

A new fine structure phenomenon of the upper-most layers of umbrae, the umbral flashes', has been detected by Beckers and Tallant (1969) (see also Wittman, 1969). The correlation of these Ca$^+$K-line features with Hα umbral fine structures and with umbral dots is unknown. Havnes (1970) succeeded recently in interpreting most of the properties of umbral flashes in terms of a magnetic-acoustic wave model.

3.2. THE FINE STRUCTURE OF THE PENUMBRAL MAGNETIC FIELD

Recent observations regarding the penumbral magnetic field fine structures lead to:

(1) a downward motion in dark interfilamentary regions with respect to the bright filaments (Mattig and Mehltretter, 1967 and Beckers and Schröter 1969,);

(2) a weaker longitudinal field in bright filaments according to Beckers and Schröter (1969) and Mamadazimov (1969), but a stronger one according to Mattig and Mehltretter (1967). This controversial result is apparently caused by insufficient spatial resolution achieved up to now;

(3) the observed local magnetic field fluctuations are $\sim$30% of the average field and may in reality be considerably larger. (Do observations of the average penumbral field and its fluctuations repudiate a penumbral fine structure model in which small field-free regions exist?);

(4) the field in dark interfilamentary regions being more horizontal as compared with the surroundings (Beckers and Schröter, 1969);

(5) extensions of the penumbral filaments into the umbra are showing considerably weaker and more horizontal fields compared to the umbral surroundings;

(6) umbral light bridges definitely showing a much smaller magnetic field ($\Delta H > 300$ G) than their surrounding umbra (Beckers and Schröter, 1969; Abdussamatov, 1970; and Bumba, 1967a). A larger zenith angle of the field in light bridges is indicated.

Grigorjev (1969a) showed that the finite resolution falsifies local fluctuations in $H_{\parallel}$ more than those in $H_{\perp}$. Stenflo (1968) made the first attempt to interpret the penumbral magnetic field observations in terms of a filamentary magnetic field model. Several observers report to have found the $H_{\parallel}=0$ line not to coincide with the neutral line of Doppler shifts when observing the penumbral magnetic and velocity field during the sunspot's passage across the disc. They attributed this discrepancy to the fact that both magnetic fields and motions are strongly inhomogeneous within the penumbra.

4. The Magnetic Field in Pores and in the Photosphere around Sunspots

4.1. The magnetic field in pores

Observations by Steshenko (1967), Bumba (1967), Beckers and Schröter (1968c) showed the magnetic field in pores and small spots to be never less than 1200 G. A rather flat distribution of the magnetic field strength across pores has been observed (Steshenko, 1967) which, in fact when corrected for seeing, may lead to an almost constant field strength across a pore.

4.2. Fine scale magnetic fields around sunspots

Strong magnetic fields (500–1400 G) in tiny photospheric areas ($\lesssim 2''$) around sunspots have been observed recently by a number of observers (Steshenko, 1967; Bumba, 1967a; Sheeley, 1967; Beckers and Schröter, 1968c; Grigorjev, 1969b; and Abdussamatov and Krat, 1969). All observers agree that generally these features ('gaps', 'magnetic knots', 'micro-pores') coincide with photospheric long lived dark intergranular regions, bright Hα flocculi and the Ca^{+}K-network. It may be suspected, but has not yet been proved definitely, that they occur at the boundaries of supergranules (see e.g. Grigorjev, 1969b). Roughly 10 knots per 100 granules occur near spots and 1 knot per 100 granules far away from active regions (Beckers and Schröter, 1968c and Sheeley, 1967). Since their number in an active region is quite large, they play an important role in the balance of the magnetic flux and it can be concluded that magnetic knots are an essential part of a solar active region and not occasional phenomena around single spots. According to Grigorjev (1969b) these features appear in continuous dark regions when the field is almost vertical (magnetic knots?) and in continuous bright points when the field is almost horizontal (constituents of faculae?). The hydromagnetodynamic stability of these 'micro-pores' has been studied by Zwaan (1967). Livingston and Harvey (1969) claimed to have found evidence for a quantization in the fine scale photospheric magnetic flux. In view of the finite resolution achieved this claim is premature.

5. Dependence of the Spot Magnetic Field on Area and Temperature

Recent results regarding magnetic fields in knots, pores and small spots suggest that there may exist a threshold value of 1200–1500 G for the magnetic field required to form a visible (dark) pore or sunspot like phenomenon. (Note, that $H^2/8\pi$ is of the same order of magnitude as the photospheric gas pressure at $\tau \approx 1$). Until a few years ago one could argue that the magnetic field increases with area (Ringness and Jensen, 1960; Ringness, 1965), the spot intensity decreases with area, and hence the spot temperature depends on the magnetic field strength. In fact, such a relation $T_{\text{eff}} = f(H)$ has been used in the theoretical sunspot models of Yun (1968) and Stankiewicz (1967) based on the idea that the inhibition of convection increases continuously with H. Both relations $I = f(A)$ (Rossbach and Schröter, 1970; Makarov, 1968) and $H = f(A)$ where A is the spot area, are now subject to strong doubt. Kopecký (1969) tried to explain both the recent and earlier observations in terms of a rather artificial two-component sunspot magnetic field.

5.1. TEMPORAL VARIATIONS OF THE SUNSPOT MAGNETIC FIELD

Several attempts have been undertaken to remeasure time variations of the magnetic field in sunspots in connection with the latter's development and with the occurrence of flares (Kolpakov, 1968; Künzel, 1967; Ikhsanov, 1967a, b). Image motion and image blurring influence strongly magnetic field measurements (see Severny and Deubner, 1968); changing seeing conditions may well simulate temporal magnetic field variations. One should therefore consider the above results with caution. A typical number for $\mathrm{d}H/\mathrm{d}t$ in a normally developing active region is found to be ~ 10 G/h in good agreement with the values given years ago by Cowling. Occasionally, changes up to 200 G/h can be observed in certain very active parts of a region, often associated with flares. In order to avoid interpretation difficulties due to seeing, simultaneous observations of temporal field changes in the same active region with magnetographs at three (or more) sites should be carried out. Only those changes which have been observed by at least two observers simultaneously should be accepted. Such an attempt has been undertaken recently by the observatories of Pulkovo, Potsdam and Schemecha.

6. Some Comments on the Development of Solar Active Regions

The following aspects regarding the development of solar active regions (SAR) have come to the forefront during the last few years:

(1) recent investigations by Bumba and Howard, 1965; Bumba and Howard, 1969; Ness and Wilcox, 1966; and Bumba *et al.*, 1969, show that SAR preferably occur in certain long-lived zones of about 10° in longitude. These zones rotate with a synodic period of 27 days; their magnetic field structure determines the structure of the interplanetary magnetic field (see the numerous papers by Wilcox, Schatten and others);

(2) new activity is caused by the interaction of new ascending magnetic fields with

the old background field. Bappu *et al.*, (1968) found the new active region to occur near the border of the old magnetic region;

(3) it is well established that supergranulation plays an essential role in the interaction between the new and old magnetic fields. Motions in granules and supergranules redistribute the magnetic flux of a SAR by a random walk over a large area (endproduct: background field). At the boundaries of the supergranulation cells the first disturbance of this background field by the new fields occurs. Observations indicate that even spots may occur only at the boundaries of supergranules;

(4) changes in the background field, indicating new activity, may occur two or three days prior to the first appearance of sunspots (Bappu *et al.*, 1968). The onset of new activity is always indicated by a brightening of the chromospheric network (especially the K_{232}-network);

(5) almost all observers find small and large scale downward motions in regions of spot formation. Bhatnagar (1970) observed a conspicuous descending motion over all active regions of 0.6–0.8 km/s. Hence, the appearance of new magnetic flux is generally accompanied with descending material in layers where the lines originate;

(6) Bappu *et al.* (1968) observed the first changes in the old background field pattern to consist of the appearance of 'magnetic hills' of the longitudinal component, coinciding with the K_{232} emission regions. One is immediately reminded of the photospheric small scale magnetic fields as knots, gaps, micropores (Sheeley, 1967; Beckers and Schröter, 1968c; Grigorjev, 1969b; and Abdussamatov and Krat, 1969). That the magnetic hills of Bappu *et al.*, 1968, are of a larger size and show a smaller maximum field is not necessarily an implication against such a comparison, since the spatial resolution for magnetographic observations is worse than that achieved by Sheeley (1967), Beckers and Schröter (1968c), Grigorjev (1969a), and Abdussamatov and Krat (1969).

The new activity may be suspected to consist of the penetration of the new strong magnetic field (within knot-like features) into the old weak background field at the boundaries of adjacent supergranules. Bappu *et al.* observed the appearance of new small scale fields of opposite polarity within one supergranule boundary in the prespot phase of the SAR and this is in favour of the above interpretation.

Subsequently, more magnetic knot like features appear within the background field lifting the constituents of a large subphotospheric magnetic flux tube into the photospheric and chromospheric layers. In chromospheric layers the K_{232}-prespot network is built. If the spatial density of the new penetrated small-scale fields reaches a critical value, the individual small-scale flux tubes are merged into a larger magnetic pattern, thus forming a spot.

A rough estimate strengthens the presumed close correlation between magnetic knot-like photospheric field regions and the bright Ca^+K emission areas as observed in the prespot phase of a SAR.

Assume the diameter of a photospheric magnetic knot to be 800 km, its magnetic field to be 1000 G. The magnetic flux is then 5×10^{18} Mx. The size of the bright Ca^+K emission features in the prespot phase is roughly 3 s of arc (or ~ 2000 km). Attributing the photospheric flux to this area one obtains for the average magnetic field in these features $H \sim 40$ G, in accordance with observations. Assuming further that this Ca^+K emission occurs 2000–3000 km above the photosphere one arrives at a height gradient of the magnetic field of 0.5–0.3 G/km, again in agreement with the results of Section 3.3.

More observations along the lines of Bappu *et al.* and extended by additional simultaneous high resolution magnetic field measurements (Sheeley, 1967; Beckers and Schröter, 1968; Grigorjev, 1969a; and Abdussamatov and Krat, 1969) are needed to test whether or not fine-scale magnetic structures like 'gaps', 'magnetic knots', and 'micro-pores' are the first agents in the formation of a new solar active region.

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Discussion

Wilson: With regard to the depression of the level $\tau = 1$ in the umbra of a sunspot, I would like to point out that we find that the surface ($\tau = 0.01$ say) is depressed by ~ 500 km but that the level surface $\tau = 1.0$ is somewhat more depressed to 600 km below the corresponding level in the photosphere.

Schröter: According to Jensen *et al.* the difference of depression between the 'surface' and optical depth units (in an umbra) amounts roughly to 600 km. According to Wittmann and Schröter the depression vanishes for very small depths. Therefore – in my scheme – I left $\tau = 10^{-2}$ undepressed and $\tau = 1$ to be depressed by 600 km. The large scale height for $\tau = 1$ and the 'photospheric' scale height (~ 100 km) in the upper layers (as found by Mattig and others) favors this model.