STRUCTURE AND EVOLUTION OF A SUNSPOT

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1. INTRODUCTION :

Sunspots are dark areas on the solar photosphere which have sizes$\sim$10 to$\sim 10^3$ m. h. (m.h. = One millionth of the area of a solar hemisphere $\approx 3 \times 10^6$ km^2) and lifetimes varying from a few hours to several weeks depending upon the size. They are invariably present in sequences of phenomena called solar "activity", which include other interesting phenomena like flares and prominences of various types. The most important characteristic of the sunspots is their high magnetic fields eg. $\gtrsim 10^3$ G compared to < 10 G in the "quiet" regions. The number of sunspots on the solar surface and other parameters associated with solar activity vary from time to time following an approximate periodicity of $\sim$ 11 y. During each such cycle of activity, thousands of spots occur in each solar hemisphere.

Sunspots occur in groups of various types. About 80% of the sunspot groups are associated with bipolar magnetic regions ("B M R"s) whose axes make small angles with solar latitudes. At least one spot occurs in the leading (Western) component of each "BMR." The sunspot groups occur in a latitude zone of $\sim$ 30° S-30° N around the solar equator (See the cover photograph). This photograph was taken with the 6″ refractor on 10th April 1970 in white light. i.e., around an epoch of maximum solar activity. Notice the many groups of Sunspots distributed in a latitude zone $\sim$ 30°S - 30° N around the solar equator (North is at the top, East is on the right). The magnetic polarity of the leading component of a BMR is same as that of the general field in the same hemisphere. During an 11y cycle of activity, the magnetic fields in the "following" components of the BMRs seem to migrate towards the respective poles. During each cycle, small portions of these fields reach latitudes polewards of 40° and reverse the general magnetic field a few years after the "maximum."

In the following sections we attempt to summarize the present understanding of the structure and evolution of a sunspot.

2. OBSERVATIONAL INFORMATION :

2.1 The Two Dimensional Structure in the Photosphere : —

(a) INTENSITY STRUCTURE : White-light photograph of a typical sunspot (eg. Figure 1) shows a central dark region called "umbra" surrounded by a less dark annular area called "penumbra." The inner and the outer boundaries of the penumbra are fairly well defined though they appear irregular in high resolution photographs. Small spots, known as pores, (eg. of areas $\lesssim$ 25 m.h.) do not show any penumbra. For spots of areas $\gtrsim$ 50 m. h. the area of the umbra is roughly $\approx$ 17% percent of the area of whole spot.

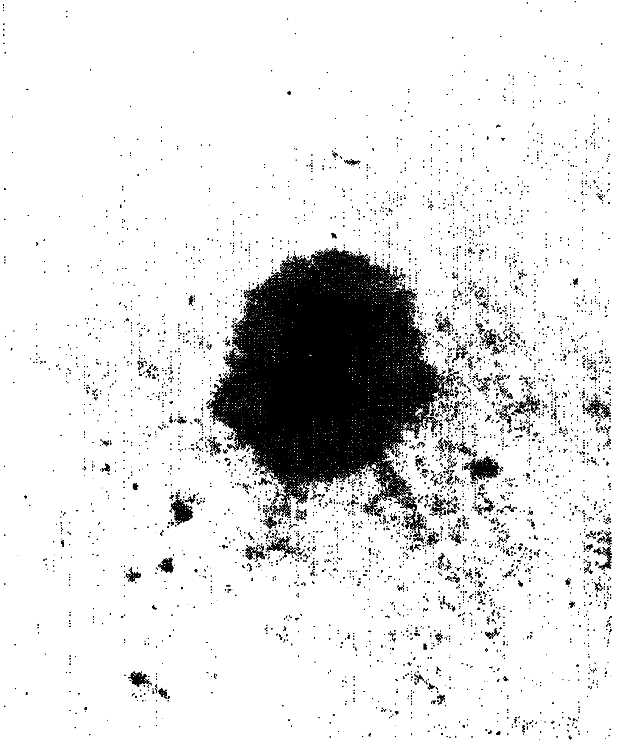

Fig. 1 A fairly large spot showing the dark umbra and the less dark penumbra. Radially oriented filamentary structures in the penumbra can be seen.

Within the umbra one often finds a number of bright dots with dimensions $\leqslant 0.5''$ (i.e. $\lesssim$ 300 km) and lifetimes $\sim$ 20 minutes. Some of these occasionally attain a maximum brightness comparable to that of the normal photosphere (Beckers and Schröter 1968; Krat et al. 1972).

Photographs of sunspots obtained under conditions of good seeing with spatial resolution approaching $\sim 1''$ show that the penumbra consists of alternately dark and bright filamentary structures ('penumbral filaments') of lengths $\sim$ 5000-10000 kms, breadths $\sim$ 300 kms, and lifetimes upto $\sim$ 30 minutes or sometimes more (Danielson 1961). These filaments appear as if arranged in a fanlike symmetry around the umbra.

The white light intensity in the darkest parts of the umbra is $\approx$ 0.1 relative to the normal photosphere (Zwaan 1968). The average relative intensity in the penumbra is $\approx$ 0.7 (Zwaan 1968; Ericksen and Maltby 1973; Moe and Maltby 1974). Relative intensities at different wavelengths in the dark and the bright filaments have been measured by Krat et al. (1972) and Muller (1973a, b).

(b) THE MAGNETIC FIELD: The intensity of the magnetic field in the darkest parts of the umbra is $\sim 3000 \pm 200$ G. As a function of distance r from the "centre" of the spot the intensity of the field and its inclination to the normal to the surface vary roughly as shown in Figure 2. (Cf. Gokhale and Zwaan 1972).

2.2 The Structure in Three Dimensions: —

(a) THE THERMODYNAMICAL STRATIFICATION NEAR THE PHOTOSPHERE: Line intensity measurements and broad-band photometry in various wavelengths and for various positions of the spot on the disc yield an empirical model for the depth dependence of temperature T on mean optical depth say τ_{5000} in the observable layers.

Zwaan (1974a, 1975) has pointed out the importance of the infrared data (1.5 μm - 4.0 μm) in that it is less affected by the stray light and that in this range the continuum is well defined and LTE is a safe assumption. He also showed that the models constructed from the observed intensities in the visible range cannot be extrapolated to predict the observed intensities in the infrared range and vice-versa. However by using an opacity-enhancement factor for $\lambda < 0.8\ \mu$ m which is probably due to the crowding of the atomic and molecular lines, he has constructed models for the dark umbral core in the range $10^{-2} \lesssim \tau_{5000} \lesssim 10$ which fit the data in both the visible and the infrared ranges. One of these models is roughly illustrated in Figure 3.

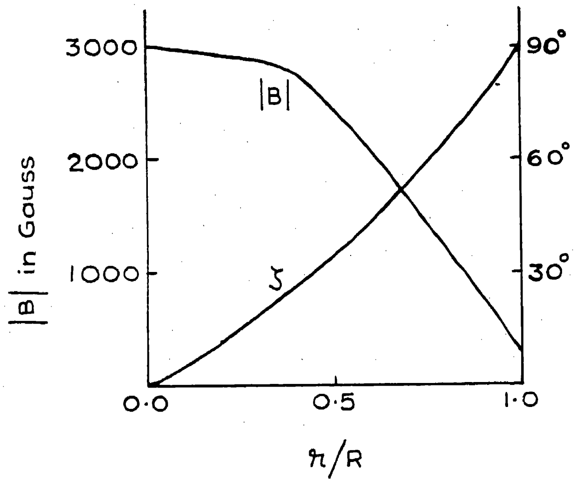

Fig. 2 A typical variation of (i) the magnetic field intensity | B | and (ii) in the angle ζ between the field direction and the normal to the photosphere, with the distance from the spot centre measured in units of the spot-radius R.

Similarly, models for the range $10^{-3} \lesssim \tau_{5130} \lesssim 10$ in the dark and bright filaments in the penumbra have been given by Moe and Maltby (1974).

Equivalent widths of the lines of natural atoms and molecules and the excitation and rotational temperatures derived from them may provide additional checks for such theoretical models. However observational data on the atomic and molecular lines is so far rather scanty (Cf. eg Zwaan 1968).

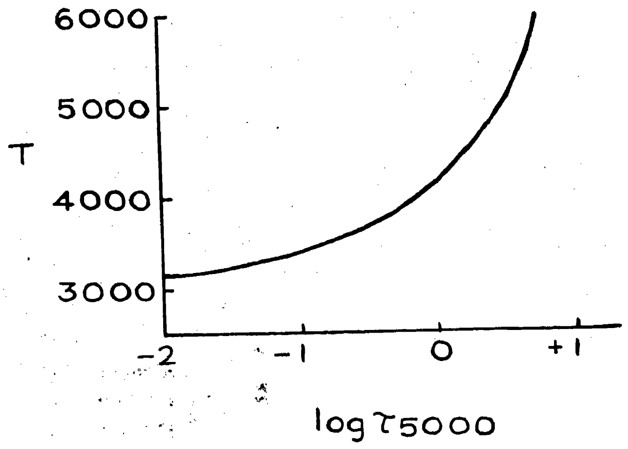

Fig. 3. An empirical model for the dependence of temperature T on the mean optical depth τ_{5000} in the darkest parts of a sunspot umbra. (Cf. Zwaan 1974).

Once the functional relation T (τ_{5000}) is known, the assumptions of hydrostatic equilibrium and LTE may be used along with the theoretical formulae for opacities, to calculate the pressure and temperature as functions of the geometrical depth (Cf. eg. Zwaan 1965). Such an empirical model for the sunspot structure can serve as a boundary condition for theoretical models of the sunspot structure in deeper layers.

(b) THE WILSON DEPRESSION: For spots away from the centre of the solar disc, the penumbral region closer to the centre of the disc is foreshortened more compared to the penumbra nearer the limb. The difference in the apparent breadths of the two portions goes on increasing as the spot approaches the limb (see Figure 4). For spots very near the limb, the penumbra towards the centre almost disappears. This has been interpreted as a saucer type shape for the photosphere (the level where optical depth $\tau_{5000} \approx 1$) in the sunspot. This depression is presumably due to the larger transparency of the sunspot plasma compared to the plasma at the same geometrical depth in the normal photosphere. The larger transparency is due to the lower temperatures and pressures within the spot. The observational estimates for the Wilson depression vary from $\sim$ 400 to 800 $\sim$ km. The variations in the estimates are due to the observational uncertainties and do not seem to be related to the size of the spot (Gokhale and Zwaan 1972).

The value of Wilson depression serves as a useful constraint on the three dimensional models of the sunspot structure below the observable layers.

(c) THE CHROMOSPHERE OVER SUNSPOTS: Comparison of the sunspot photographs in various wavelengths in the $H\alpha$ - line shows that the umbra-penumbra boundary gets more and more diffuse with increasing height above the photosphere. Photographs in lines corresponding to successively larger heights above the photosphere are characterised by an increasing number of dark fibrils much longer than their photospheric counterparts.

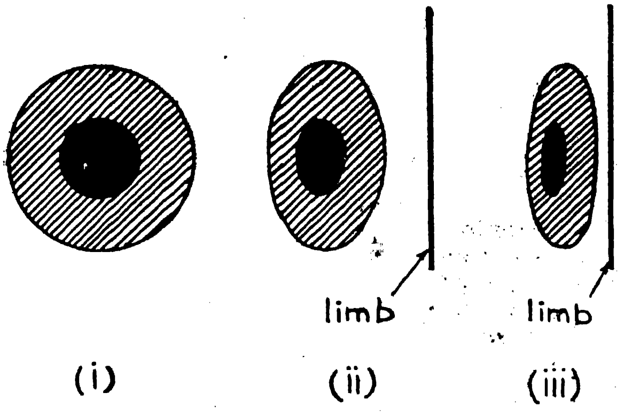

Fig. 4 A schematic diagram showing the difference in the foreshortening rates for the disc-side and the limbside penumbral portions as a spot moves from a position (i) near the centre of the disc to a position (ii) near the limb and further to a position (iii) very near the limb.

At the height of formation of the line centre, the fibrils are so numerous that they seem to form an "enlarged version of the white light penumbra" which has been described by Loughhead (1974) as a 'superpenumbra."

The Ca^{+} K line spectra of sunspots show that the K_{232} profile of the umbra differs from the profile of the surrounding plage regions. Engvold's (1967) observations show that in the umbra the K_2 - emission and the K_3 absorption are both definitely present. However the latter is so weak that the double reversal is detectable only with difficulty. The double reversal gains in strength as one proceeds from umbra to the plage regions.

In the K line filtergrams the bright structures in the umbra are coarse in appearence compared to the complex fine structures seen in the H α - filtergrams. The structure around the umbra seen in K and Hα are similar only to the extent that they show similar outline for the superpenumbral region. Instead of the individual fibril structures seen in H α we see bright emission in K apparently due to the real increase in the K line source function. Near the penumbral boundary there are suggestions of the fibril structures in the K line, but they are mostly lost in the dark columns of K_3 absorption (Zirin 1974). EUV spectroheliograms from the Apollo Telescope Mount show that the chromosphere corona transition region directly above a sunspot is brighter than the surrounding region by an order of magnitude (Foukal et al. 1974)

Chromospheric observations of sunspots also reveal "umbral flashes" and "penumbral waves" which are described separately (Sections 2.3b and 2.3c).

2.3 Other Interesting Properties of Sunspots :—

(a) EVERSHED EFFECT : Doppler effect observations show the presence of a mass flow almost radially outward across the penumbra with velocity increasing linearly with distance from small values at the inner boundary to about $\sim$5 km s^{-1} at the outer boundary. This effect was discovered by Sir John Evershed at the Kodaikanal Observatory. (Endowed with a superior skill, he detected the minute displacements in the spectral lines with the small scale images (16″/mm) obtainable with the equipment commonly used in those days.) Beyond the outer boundary of the penumbra the velocity of the flow abruptly reduces to values indistinguishable from the surrounding flow patterns in the supergranular cells. There is some evidence that the flow is channelized along dark filaments and that there is practically no widening of the channel (eg. Krat et al. 1972).

(b) VELOCITY OSCILLATIONS AND WAVES : Oscillatory vertical motions with velocity amplitudes $\sim$ 1 km s^{-1} and periods$\sim$180 s have been observed in the umbral photosphere (Beckers and Schultz 1972).

The periods of similar oscillations in the penumbra vary from $\sim$300 s at the inner boundary to $\sim$1000 s near the outer boundary. Just outside the outer boundary the periods drop to normal photospheric value $\sim$ 300 s. Unlike the normal photosphere the velocity oscillations in sunspots do not seem to be associated with the line depths, line widths or continuum intensity (Beckers and Schröter 1972; Bhatnagar et al. 1972).

In the chromospheric observations eg. H_α observations, the velocity oscillations have amplitudes $\sim$ 3 km s^{-1} and periods $\sim$ 165 ± 20 s in the umbra. The oscillating structures have dimensions 2-3″. Transverse waves developing just within the umbral boundary and propagating outward with velocities $\sim$ 20 km s^{-1} have been observed by Giovanelli (1972) and by Zirin and Stein (1972). These waves start with amplitudes $\sim$ 1 km s^{-1} near the umbral boundary and become gradually invisible near the outer penumbral boundary. According to Giovanelli, this fading may be either due to dissipation or due to the increase of the alfven velocity.

(c) UMBRAL FLASHES : In H and K lines above the sunspot umbrae, bright regions of diameters $\sim$700-2000 km with life times $\sim$50 s and a tendancy to repeat every $\sim$ 145 s were discovered by Beckers and Tallant (1969) who termed these inhomogeneitics as "umbral flashes." In these flashes they found mass motions with upward velocities $\sim$ 6 km s^{-1}. Downward motions with velocities$\sim$ 1-5 km s^{-1} were also observed for small durations just before each "repeatation." The flashes themselves seem to move towards penumbra with velocities $\sim$ 40 km s^{-1}. The flashes were observed to have magnetic fields $\sim$ 2100 G which decreased at a rate of $\sim$ 12 G s^{-1} during the flash life. Zirin (1974) has observed flashes in Hα also. These do not seem to coincide in position with the K-line flashes. However this does not exclude the possibility of a dynamical correspondence between the flashes at the two levels.

2.4 Evolution of Sunspots :—

(a) FORMATION : Formation of first sunspot in an active region is preceeded by strengthening of the longitudinal component of the magnetic field, appearence of some transverse fields near the neutral line of the longitudinal field, brightening and spreading of K_{232} emission and appearence of transverse structures in $H\alpha$ which are called 'arch filamentary systems' (Bappu et al. 1968; Frazier 1972). In the photosphere the intergranular space at the sight of formation becomes darker than usual and within about half an hour a small pore is formed. Most pores decay before they develop into a sunspot with a penumbra.

All spots are born as 'pores' near the corners where boundaries of three or more supergranules meet (Bumba and Howard 1964).

(b) GROWTH RATES AND DECAY RATES : Cowling (1953) found that the time-dependence of the area of a sunspot to be as illustrated in Figure 5. In general the decay of a spot is much slower than the growth. From plots of areas of sunspot groups Bumba (1963) inferred that stable spots may show a phase of 'slowest' decay at a rate $\frac{dA}{dt} \sim 10^{11}$ cm^2 s^{-1} which is independent of area. Zwaan (1974b) showed that only some regular spots and even fewer irregular spots pass through the phase of the slowest decay. The more rapid decay is associated with the presence of bright structures like umbral dots and/or light bridges.

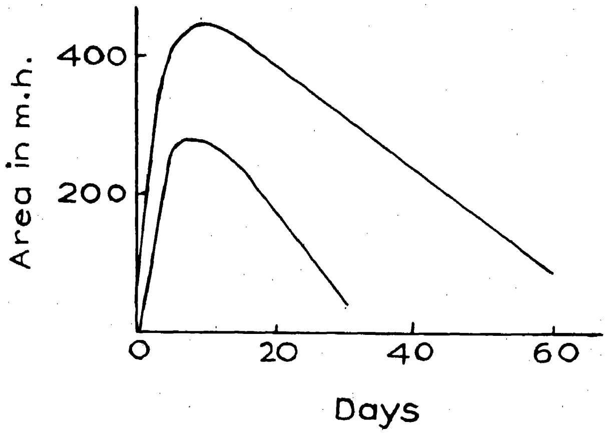

Fig. 5 Typical variation of the spot area with the age of a spot as shown by two curves, one for spots of life ~ 60 days and the other for spots of life ~ 30 days (Cf. Cowling 1946).

(c) EVOLUTIONARY SIMILARITY : Except for the smallest spots (of areas $\lesssim$ 25 m.h.), the following quantities remain approximately same :

(i) the ratio of the umbral area to the spot area,

(ii) the effective temperature in the darkest parts of the umbra (~ 4000 K),

(iii) the magnetic field structure scaled to the radius of the spot and (iv) the Wilson depression (~600 km).

Thus the spot maintains a radial, 'evolutionary similarity' (Gokhale and Zwaan 1972) in which various quantities are functions of r/R(t) where R(t) is the instantaneous radius of the spot and r is the distance from the axis of symmetry.

(d) THE MOAT AROUND A SPOT AND THE MOVING MAGNETIC FEATURES : Surrounding a medium or a large spot there often exist radially outward horizontal flows with valocities ~ 1 km s^{-1} extending to distances comparable to the spot dimensions (Sheeley and Bhatnagar 1971). Thus the spot lies at the centre of an unusually large supergranule which is called a 'moat' (Harvey and Harvey 1973). During the decay of a spot (or pore) magnetic structures of storng fields and dimensions $\lesssim 2''$ have been found to appear just beyond the outer edge of the spot (or pore) and to move approximately radially outward with velocities ~ 1 km s^{-1} until they disappear or reach the nearest supergranular boundaries (Sheeley 1969; Vrabec 1971). Most of these moving magnetic features ('MMF's) often appear in pairs of opposite polarity but the polarity of the net flux carried outward is that of the decaying spot and the rate of transport of magnetic flux equals the rate of reduction of the spots magnetic flux (Harvey and Harvey 1973).

3. THEORETICAL PROBLEMS :

Theoretical understanding of the sunspot phenomenon is extremely inadequate compared to the wealth of the observational data. The main theoretical problems are: (1) the mean thermodynamical and magnetic structures of the spot below the observable layers (ii) various modes of energy transport and the overall energy balance in the spot and its surroundings (iii) the processes responsible for the formation and the decay of spots (iv) individual details like the umbral and penumbral inhomogeneities, Evershed flow, oscillations and waves, etc.

These problems are all mutually interrelated and eventually they will need a synthesized treatment. However up till now they have been treated more or less separately.

3.1 The Mean Thermodynamical Structure :—

By neglecting the curvature of field lines in a depth dependent magnetic field, Chitre (1963) showed that one can obtain a reasonable model for the thermodynamical structure of the umbral column provided there is a non-radiative energy transport which may be less efficient than the convection outside the spot. Similar models were computed by Deinzer (1965) for magnetic fields satisfying a geometrical constraint called similarity. Yun (1970) constructed a series of umbral models by using effective temperature, total magnetic flux and the field direction at the spot edge as free parameters. He obtained reasonable agreement with the observed values for the Wilson depression, the surface field strengths the vertical field gradient at the centre, and the spot area.

Mullan (1971) has shown that a fully radiative model for sunspots is possible. However his treatment of convection is based on Opik's (1970) model of convection which leads to a convection-zone of thickness ~ 10^4 kms only, which cannot be reconciled with the present models of the solar interior (e.g. Spruit 1974).

3.2 Energy Transport and the Energy Balance :—

The average intensity of a sunspot corresponds to a deficit of about one-third the normal photospheric intensity (i.e. the deficit $\approx 2 \times 10^{10}$ erg cm^{-2} s^{-1}) (Cf.

Zwaan 1968). Only $\sim 1\%$ of this deficit may be traced to the excess emission in the 'faculae' surrounding the spot, if at all that much energy is somehow channelized from the spot to the faculae. The kinetic energy of the Evershed flow might account for another 10% or so of the deficit. A major portion of the missing energy may however be escaping upward, downward or sideways as hydromagnetic waves. According to Savage (1969) and Parker (1974, 1975a) a substantial amount of energy goes upward or downward as alfven waves* generated by overstability in the first 10^3 km or so below the umbral photosphere. According to Wilson (1975) almost all the energy carried by alfven waves must be going downward. In an alternative model Wilson (1972) suggested that a refrigeration cycle, run at the cost of the magnetic energy, carries energy horizontally outwards in first few thousand Kms below the photosphere. This suggestion has several conceptual difficulties (Gokhale 1974). Thus there is considerable uncertainty about the modes of energy transport and energy balance in the sunspots. However it seems that by combining the energy transport problem with another problem viz. that of the decay one might make a substantial progress towards the solution of both the problems (see the end of Section 3.3b).

3.3 Formation and Decay :—

(a) FORMATION : Biermann (1941) suggested that a sunspot occurs due to the suppression of convection by strong magnetic fields. Dicke (1970) demonstrated that the physical conditions in a spot may be determined by the strong hydromagnetic stress distribution in the observable layers of the spot. However such explanations lead to the question as to what causes the concentration of the field to the required high values (eg. $\sim 10^3$ G). According to the concept of magnetic buoyancy (Parker 1955), strong fields arrive at and above the photosphere from deep layers in the convection zone. But the observations suggest that during the process of rising the fields do not remain concentrated on the scales of sunspots even in the photospheric layers. Therefore further concentration is required even after the fields have reached quasiequilibrium at and above the photosphere. The observation that sunspots are born as pores which are always found at the corners of supergranules indicates that the reconcentration of the fields is provided by convective (eg. supergranulation) flows. This seems to be further supported by Vrabec's (1974) observation of the inward moving magnetic features during the growth of a sunspot.

According to a latest theory of sunspot formation (Parker 1974a, 1974b), the generation of alfven modes in the magnetic fields leads to the cooling of the mangetic regions and therefore to a lateral compression of the magnetic fields till an energy balance reached.

(b) DECAY : Cowling (1946) showed that the decay of a sunspot cannot be explained on the basis of the ohmic dissipation on the scales of the whole spot. Gokhale and Zwaan (1972) showed that the decay of the sunspot area at a constant rate may be explained by assuming the presence of a thin electric current sheet around the boundary of the sunspot fluxtube, which maintains the evolutionary similarity as a result of an assumed lateral inward flow in deep layers. However the current sheet is required to be too thin (eg $\sim 10^4$ cm) if we use the ohmic diffusivity obtained from the kinetic theory.

Meyer et al (1974) have attempted to explain the sunspot decay in terms of the 'effective' magnetic diffusivity as enhanced by a 'turbulene' of characteristic lengths $\sim$ 2000 km and of characteristic velocities $\sim$ 20 m s $^{-1}$ which may be present inside and around the sunspot fluxtube. However the applicability of such a "turbulent diffusion" is doubtful since the kinetic energy density in the turbulence is $\sim 10^{-3}$ times the magnetic energy density.

Krause and Rüdiger (1975) have shown that the decay of sunspot fluxtube may be explained by assuming two-dimensional (horizontal and depth-independent) random motions which may not be suppressed even by the strong magnetic forces in the sunspot if the latter are balanced by the pressure-gradients. It can be shown (Gokhale 1976) that if the sunspot fluxtube is a bundle of elementary fluxtubes (eg of flux $\sim 10^{-18.5}$ Mx), as indicated by some observations, then the motions assumed by Krause and Rüdiger may lead to a diffusion of the bundle by imposing random walk on the individual elementary fluxtubes. It can also be shown that within a bundle of "$10^{18.6}$ Mx-tubes" such motions may indeed exist and the laterally propagating fast mhd modes produced by these motions may account for the energy balance in the sunspots provided the sunspot is a region of enhanced energy transport as suggested by Parker (1974, 1975a). This model also provides a natural explanation for the observed MMF's and may also account for the evolutionary similarity without making the "boundary current sheet" as thin as in the model of Gokhale and Zwaan (1972).

Parker (1975b) has raised the question of the hydromagnetic stability of the sunspot flux tube and has tentatively suggested that a redistribution of cooling in the umbra might prevent the break-up of a sunspot fluxtube by the strong flute instability.

3.4 Theories for Individual Details :—

(a) EVERSHED FLOW : Theories for Evershed flow are at best tentative since they depend upon the assumed magnetic and thermodynamical structures and also upon the model for the overall energy balance.

Altschuler et al (1968) showed that diffusing magnetic fields would exert forces on the plasma which lead to a flow similar to the Evershed flow. Chitre (1968) showed that a steady laminar flow along the boundary between the umbral and penumbral magnetic fields will lead to a flow like the Evershed flow, if the laminar flow originates near the "sunspot base" with velocities comparable to the convective velocities. A similar explanation follows from the thin current-sheet model (Gokhale and Zwaan 1972), in which the upward laminar flow is maintained by the inward laminar flow which maintains the evolutionary similarity.

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* Beckers (1976) has measured the widths of Ti I (λ 5713.90) and Fe I (λ 5691.50) absorption lines in sunspots and has shown that these widths may be interpreted as due to the mass motions associated with alfven waves. He concludes that the observed values for the widths are consistent with the suggestion that alfven waves are responsible for maintaining the coolness of a spot.

(b) OSCILLATIONS AND PENUMBRAL WAVES : Moore (1972) and Mullan and Yun (1973) have attributed umbral flashes and the running penumbral waves to overstabilities in the first several hundred kms below the umbral photosphere. Similarly, calculations of overstability below the penumbral photosphere yield fairly good agreement with the observed variation of the period of velocity oscillations across the penumbra (Chitre and Gokhale 1976). These calculations reveal that both the fast and the slow mhd modes become overstable in these layers and that the periods of the slow mode agree with the observed periods at various distances from the inner boundary of the penumbra. Across the outer boundary of the penumbra, the slow mode becomes the convective (normal granulation) mode in the normal photosphere and the fast mode becomes the accoustic (five-minute oscillation) mode.

(c) UMBRAL DOTS : Earlier Empirical models of the umbral dots by Zwaan (1965) and Fricke and Elsaser (1966) were criticised by Wilson (1969) who showed that these dots may not have a convective origin. Later on (Wilson 1971) he pointed out that alfven waves in the umbra may provide adequate energy for these dots. Roberts (1976) has shown that a superadiabatic temperature gradient may excite alfven waves in a vertical magnetic flux tubes. According to Roberts, this may account for the sizes and intensities of the umbral dots besides explaining the coolness of the spots according to Parker's (1974) theory and the velocity oscillations in the umbra.

(d) PENUMBRAL FILAMENTS : Danielson (1961) showed that penumbral filaments may be essentially convective roles in a horizontal magnetic field. Detailed calculations by Chitre and Gokhale (1976) without using Boussinesq approximation lead to a similar conclusion. It will be interesting to investigate if the penumbral filaments are just the '$10^{18.5}$ Mx-fluxtubes' fanning out from a 'bundle' (that presumably constitutes the sunspot fluxtube - Cf. Section 3.3 b) and becoming alternately dark and bright as a result of some typical mode of energy transport.

4. CONCLUDING REMARKS :

Here we have considered sunspot mainly as an individual phenomenon. Statistical properties of sunspots, their role in the 11y - cycle of the solar activity and their relations to other phenomena in the activity are simply mentioned in Section 1. Despite the long history of the sunspot observations our present theoretical knowledge about them (even as an individual variety of phenomena) is far from satisfactory. Nevertheless it will be clear from Section 3 that there is ample scope for further investigation and at the same time ample hope for a much better understanding of the phenomenon in near future.

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