MAGNETIC FIELDS: OBSERVATIONS AND THEORY

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Abstract: Theoretical model calculations of magnetic elements in the photospheric layers of solar active regions are compared with the results of observations. Emphasis is placed on small scale magnetic elements and an attempt is made to provide an overview of the contributions that the current state of theory and observation can make to answering the following questions: What is the field strength and the magnetic field structure of a magnetic element? Are magnetic elements inclined with respect to the vertical? Do magnetic canopies exist and how can they be explained? What are the diameters of magnetic elements? What kinds of mass motions are present in magnetic flux concentrations and what role do they play for their structure and energetics? How high is the temperature in magnetic elements and what are the underlying heating mechanisms?

1. Introduction

The investigation of solar magnetic fields is particularly dependent on a strong interaction between observations and theory. Observations have so far been able to give us only an inadequate amount of information on the important small scales, due to the limitations imposed by finite spatial and temporal resolution, and often also due to the lack of "clean" diagnostics. Theoreticians have been hampered by having to deal with a complex, highly non-linear physical system. The respective limitations of theory and observations have in the past forced solar physicists of both breeds to restrict themselves to a simplified and idealized picture of the small scale structure of the magnetic field and of related structures and processes.

Today we stand at the threshold of a new age in the exploration of magnetic fields in solar active regions. We are witnessing the birth of truly self-consistent models of small magnetic elements which take a proper energy equation into account. For the observers new horizons have been opened with the installation of three new telescopes on the Canary Islands and with the advent of new diagnostic techniques and advances in radiative transfer. Now appears to be a good time to review the past before plunging into the exciting future.

For lack of space and due to my limited knowledge this does not pretend to be a complete review of the topic. Instead I shall concentrate on only a few selected areas in which the interaction between theory and observations has been particularly interesting and fruitful and which lie within my experience. Those interested in more details are referred to the host of often excellent reviews on the subject. Some examples of reviews on various aspects of photospheric magnetic field concentrations are: Harvey (1977, 1986), Nordlund (1986), Schüssler (1986, 1987), Solanki (1987), Spruit (1981, 1983), Spruit and Roberts (1983), Stenflo (1976, 1978, 1984). A few specialized reviews will be mentioned in connection with the topic which they cover. Often I shall not go into details concerning the techniques employed by both theoreticians and observers, but shall concentrate mainly on the respective results and on their comparison with each other.

2. Basic Picture

Hale (1908) first established that sunspots were magnetic phenomena. He measured their field strength and arrived at a value of 2900 G, which is quite acceptable today. Magnetic fields outside sunspots were also dicovered by Hale (1922a, b) in what he termed "invisible sunspots". The detected (average) field strengths were 200–300 G, a lower limit of 200 G being set by the limited sensitivity of his equipment. The increase in sensitivity resulting from the introduction of photoelectric detectors and the Babcock type magnetograph (Babcock and Babcock, 1952; Kiepenheuer, 1953) revealed that the non-sunspot field could have values as small as 2 G (averaged over 5–10″) (Babcock and Babcock, 1955). A major theoretical step towards the description of solar magnetic elements was undertaken by Parker (1955) when he assumed that the field strength B is related to the gas pressure by

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$$\frac{B^2}{8\pi} = P_e - P_i, \tag{1}$$

where P_e is the external and P_i the internal gas pressure of the magnetic element.

However, he initially applied this approximation to sunspots, at that time the only known structures with strong fields. The field outside sunspots was supposed to be mostly weak and homogeneous, a view supported by magnetograph observations with low spatial resolution. The idea that the field in plages and the network could exist in a more concentrated form was suggested by the observations of Sheeley (1966, 1967) and Beckers and Schröter (1968). It was firmly established when Stenflo (1973) showed that the field was concentrated into bundles of magnetic flux with field strengths of about 1 kG at the height in the atmosphere at which spectral lines are typically formed. Finally, Spruit (1976) presented a first model which attempted to give a reasonably complete description of a fluxtube and established gas pressure as the confining mechanism.

What are the main features of the basic picture we have today of the magnetic field structure in the photospheric layers of active regions? First we have the highly visible sunspots and pores, which are darker than their surroundings, i.e. cooler than the quiet photosphere at optical depth unity. These have observed field strengths of about 2000–3500 G in the umbra, 1000–2000 G in the penumbra, and 1500–2000 G in pores (e.g. Zwaan, 1978). Then we have the small and bright fluxtubes or magnetic elements, which have field strengths of approximately 1000–1500 G, cover a few percent ($\lesssim 25\%$) of the surface of an active region and contain at least 90% of the magnetic flux outside sunspots (Howard and Stenflo, 1972; Frazier and Stenflo, 1972). The surrounding medium is almost field free and the field is confined mainly by the external gas pressure [Eq. (1)].

With increasing height the external gas pressure decreases and the fluxtubes expand until neighbouring fluxtubes come into contact with each other and merge. A little above that height the magnetic field completely dominates over the rapidly decreasing gas pressure.

3. Magnetic Fields: Strength and Structure

3.1 Field Strength

Observationally, little has changed since Stenflo (1973) introduced the line ratio technique and discovered that the field has a true strength of approximately 1000 G, if we assume it to be horizontally homogeneous *within* a magnetic element. In the mean time other, partly independent, methods have been developed and have given values between 1000 and 2000 G in reasonable agreement with Stenflo's result (Harvey and Hall, 1975; Tarbell and Title, 1977; Wiehr, 1978; Koutchmy and Stellmacher, 1978; Robinson et al., 1980; Solanki and Stenflo, 1984, Stenflo and Harvey, 1985; Rachkovsky and Tsap, 1985; Stenflo et al., 1987b; Sun et al., 1987; Solanki et al., 1987). Part of the difference between the results of the various techniques stems from the fact that they measure the field at somewhat different heights in the atmosphere. Also, they have not always been applied to exactly the same structures. However, a part of the difference may also be due to a horizontal distribution of field strengths. Stenflo et al. (1987b) noted that each σ component of the Stokes V profile of the infrared $g = 3$ line Fe I 15648.5 Å is much broader than its mostly non-magnetic I profile. Radiative transfer calculations carried out by I. Zayer in Zürich have ruled out the possibility of the extra width of the V profile being due to velocity broadening. A horizontal distribution of field strengths (e.g. a Gaussian distribution peaking at 1500 Gauss with a half width of 500 G), on the other hand, can reproduce the V profile. Such a horizontal distribution of field strengths could either be due to a radial magnetic field gradient within each individual fluxtube or it could be due to a distribution of field strengths among different fluxtubes. In the former case fluxtubes would not satisfy the thin tube assumption even at relatively great depths in the photosphere, while in the latter case the range in field strengths may be the consequence of overstable oscillations (e.g. Hasan, 1985). Small pores have a strong radial variation of the field as has been measured by Steshenko (1967).

Let us turn to theory. Naïvely, i.e. considering only Eq. (1), the field can be supported in a stationary state at many values of the field strength. By evacuating the fluxtube we not only increase the field strength at a certain height according to Eq. (1), but due to the decreased gas pressure we see deeper down into the fluxtube, so that we see a layer with even stronger field. However, if we consider that the temperature increase towards the solar interior, and that the opacity (H$^-$ bound–free in the visible) increases dramatically with temperature, then we do not see so deep down after all and the increase in field strength at the *observable layers* of small fluxtubes remains within limits. All the same, we are still left with a considerable range of possible field strengths. We can select between the different possibilities either by investigating how stable a given field strength element is, or by seeing if there is any natural field strength which results when the formation of a fluxtube is modelled.

The so called "convective collapse" mechanism for the concentration of the field has been very popular for explaining the creation of strong field magnetic elements. The following is a somewhat simplified sketch of the process. If we start with an initially relatively weak field then just below the photosphere the gas in the magnetic region may satisfy the criterion for convective instability. If the convection starts out as a downflow, then the magnetic element will become evacuated in its photospheric and slightly sub-photospheric layers as the temperature in the downflow drops below the ambiant value. The magnetic field suppresses lateral convective heat exchange and effectively insulates the downflowing material against the super-adiabatically stratified surroundings. The decrease in gas pressure in the magnetic element is due to the fact that the pressure scale height is approximately proportional to the temperature

$$H_p = \frac{kTR_\odot}{Gm_pM_\odot}, \tag{2}$$

where k is Boltzmann's constant, T is the temperature, $R_\odot$ is the solar radius, G is the gravitational constant, m_p is the mean particle mass (which is somewhat temperature dependent due to ionization effects), and $M_\odot$ is the solar mass. The external gas pressure will then force the field to contract, thus increasing the field strength. Since a stronger magnetic field greatly inhibits convection (e.g. Gough and Taylor, 1966), the new state (which has a lower energy than the old one) can be stable.

Convective collapse has been investigated by e.g. Parker (1978), Roberts and Webb (1978), Webb and Roberts (1978), Spruit (1979), Spruit and Zweibel (1979), and Unno and Ando (1979).

Spruit and Zweibel (1979) investigated if a critical field strength exists which can ensure the convective stability of fluxtubes. They find that fluxtubes are convectively stable for $\beta = 8\pi P_i/B^2 \lesssim 1.8$ if β is independent of depth. This corresponds to a minimal field strength of 1350 G at the solar surface. Spruit (1979) found that the collapsed state possesses a field strength in the range 1280–1650 G at the surface, which is in excellent agreement with the observations. The field strength of the end state depends on the strength of the initial field (with $\beta < 1.8$); a weaker initial field gives rise to a stronger final field. He also suggested that the end state may be one of overstable oscillations. Fully non-linear calculations have been carried out by Venkatakrishnan (1985) and Hasan (1984, 1985). Hasan's calculations, which include lateral radiative exchange, achieve a final state with a time averaged field strength of approximately 1250 G at a level 50 km below $\tau = 1$ in the external medium (initial field strength = 800 G). A fixed field strength cannot be defined, since the fluxtube oscillates overstably, with temperature and magnetic field oscillating along with the velocity.

Convective collapse has also been studied in three dimensions by Nordlund (1983, 1986). However, due to the limited horisontal resolution of his grid (corresponding to 190 km), he cannot follow the collapse to the fully concentrated state and the field strengths do not correspond to the observed ones when integrating over a realistic resolution element. The main reason for the limited grid is limited computer time. Nordlund's models actually start a step earlier than the other calculations of convective collapse, since they also show how the field is first swept together into the narrow downflow regions between granules before the final convective instability occurs.

3.2. Vertical Gradient of the Field and Fluxtube Expansion

Due to the decrease in gas pressure with height the field is expected to expand. The rate of expansion depends on a number of factors, mainly on the magnetic flux of the tube at some reference height. Since in the thin tube approximation the fluxtube expands to, for example, twice its surface radius at a certain height irrespective of initial radius, this means that the absolute expansion of larger fluxtubes is considerably more rapid. On the other hand, the larger the tube the greater will be the influence of magnetic tension, which tends to decrease expansion. However, for magnetic elements it generally plays a secondary role, as has been quantitatively shown by Pneuman et al. (1986) and Knölker et al. (1987). The expansion rate also depends on the temperature, which determines the pressure scale height, H_p [Eq. (2)]. If H_p in the magnetic elements is larger than in their surroundings, it determines the expansion of the field above a certain height. We shall return to this point later in this section in connection with canopies.

Observations of vertical field strength gradients are rare. They have been usually limited to comparing observations of field strengths in the transition region or the corona to strengths in the photosphere. In the transition region over sunspot umbrae Henze et al. (1982) have measured a field strength of up to 1200 G (UV data) and have deduced a vertical gradient of 0.4–0.6 G km^{-1} by comparing with photospheric field strengths at the footpoints. Hagyard et al. (1983), applying slightly different techniques on similar data, obtain gradients between 0.1 and 0.4 G km^{-1}. In general agreement, Akhmedov et al. (1982) derive a vertical gradient of 0.25 G km^{-1} from polarized radio data. Of course, such average gradients give only a rough picture of reality, since the true gradient will be a function of height. Outside sunspots radio observations (e.g. Habbal et al., 1986) give minimal field strengths between 50 and 200 G in coronal bright points. Another approach has been to compare the field strength deduced from lines in the visible spectral range with that from lines in the infrared (near 1.6μ). Due to a minimum in continuum opacity at these infrared wavelengths the latter lines are formed deeper in the atmosphere than the former. Stenflo et al. (1987b) find that the lines in the visible give approximately 1150 G (5250/5247 line ratio), while Fe I 15648.5 Å line in the infrared gives an *average* field of $\approx$ 1450 G which is also consistent with a decrease in strength with height. A quantitative gradient cannot be derived as yet due to the badly known heights of formation of the lines; particularly, since these heights also depend on the thermal structure of the magnetic elements in a complicated manner. Solanki et al. (1987) have combined observations of the 5250/5247 line ratio with the thin-tube approximation model to deduce the field strength in the lower layers of fluxtubes. They find that the thin tube approximation is compatible with the observations (although these are not very sensitive to magnetic field gradients). They deduce from it that the field strength near the $\tau = 1$ level inside the fluxtubes is close to 2000 G. In contrast to the other measurements of vertical magnetic field gradients in the photosphere Gopasyuk (1985) finds from a study of lines of different elements and with different excitations, strengths and Zeeman splittings, that the field initially increases with height before decreasing above a certain level.

Another indication for a strong vertical magnetic field gradient is provided by the observations of magnetic canopies in active regions (Giovanelli, 1980; Giovanelli and Jones, 1982; Jones and Giovanelli, 1983. See also Jones, 1985 for a review). The area over which a magnetograph signal is observed increases with increasing heigth of formation of the line. Giovanelli and Jones interpret these observations as showing that the field fans out very rapidly and becomes almost horizontal at a certain height in the atmosphere, with a magnetic 'canopy' overlying a non-magnetic atmosphere. In active regions such canopies are observed to lie close to the height of the temperature minimum.

Canopies were first proposed by Gabriel (1976), but much higher in the atmosphere, namely at the base of the transition zone. More detailed potential field calculations by Anzer and Galloway (1983) for whole network regions also produce a canopy near the transition region. Since their magnetic field fills the whole atmosphere, they define the canopy base as the height at which the magnetic energy begins to dominate over the thermal energy, i.e. $\beta \leq 1$. Finally, Pneuman et al. (1986) have calculated the heights at which individual fluxtubes merge for a given filling factor. They include magnetic tension up to second order in an expansion according to fluxtube radius. They find that as long as the temperature in the fluxtubes is not higher than in the surroundings at equal geometrical height the tubes merge above the temperature minimum for reasonable filling factors.

The easiest way of producing a low lying canopy is to increase the temperature inside the fluxtube. A higher temperature inside the fluxtube than outside at equal geometrical height will lead to a larger pressure scale height so that at a certain level $P_i \gtrsim P_e$ and the tube will "explode", i.e. neglecting tension the field will become practically horizontal here until it encounters the neighbouring fluxtubes, thus forming a canopy at this height. The variation of the merging height with the ratio of fluxtube to external temperature is illustrated in Fig. 1, taken from unpublished calculations of O. Steiner of Zürich, based on the fluxtube models of Steiner et al. (1986). The question therefore is, can a fluxtube become sufficiently hotter than its surroundings at equal geometrical height? This may be possible in the lower chromosphere but it would probably require considerable amounts of mechanical heating (cf. Hasan and Schüssler, 1985).

3.3. Inclination of Fluxtubes

Let us turn to the question: How vertical are fluxtubes? From a theoretical point of view Schüssler (1986) has discussed how strongly fluxtubes can be inclined by external photospheric flows. Assuming a horizontal flow velocity of 1 km s^{-1} he finds that the evacuated fluxtubes ($B = 1500$ G) are kept within 1° of the vertical by buoyancy. He argues that smaller fluxtubes may be more strongly inclined. Theoretical models of fluxtubes also generally presuppose vertical fluxtubes (e.g. Spruit, 1976; Deinzer et al., 1984b; Pneuman et al., 1986; Steiner et al., 1986). Zähringer and Ulmschneider (1987), on the other hand, find from non-linear wave calculations that over short periods of time fluxtubes can get considerably tilted higher in the atmosphere through the action of transverse or kink waves.

A number of authors have presented observational evidence, mostly of quite indirect nature, for inclined non-sunspot fields. Early indirect measurements were carried out by Stoyanova (1970) and Krat (1973). Later Schoolman and Ramsey (1976) and Tarbell and Title (1977) presented some indirect and inconclusive evidence for almost horizontal fields in what they called the 'dark component of the network'. From a comparison of magnetograms with Ca II plages Wiehr (1978) concluded that fluxtubes are inclined by 55° towards the west. Brants (1985), observing emerging flux regions, assumed that slanted fields are present when the unpolarized Stokes I profile has a large width, but the circularly polarized Stokes V profile has only a small amplitude. However, alternative explanations can be proposed which are equally valid. For example a partial cancellation of opposite polarities in the resolution element or a particularly large velocity broadening.

There are a few direct determinations of the magnetic field direction from measurements of 3 or all 4 Stokes parameters. Thus Deubner (1975) interpreted vector magnetograph data as suggesting an isotropic distribution of the inclination of field lines in faculae. In a regular sunspot House et al. (1975) have found the field to be highly inclined and not to deviate too strongly from the radial direction in the penumbra. Hagyard et al. (1984) have used vector magnetograph measurements to determine the amount of shear in an active region (the shear is defined as the difference between the asimuth of the measured field and a potential field). They find that flares tend to occur near places of maximum shear. Finally, Solanki et al. (1987) have found from a detailed analysis of Stokes V and (linearly polarised) Q profiles, involving radiative transfer calculations, that in 4 out of 8 observed active region plages the fields are inclined by at least 10°. Stenflo (1985) has pointed out the need to take proper field strengths into account if field inclinations are to be determined with any measure of accuracy (see also Solanki et al., 1987).

This is one area where theory and observations seem to contradict each other, and it requires further investigation. More measurements with full profile vector magnetographs should therefore be given a high priority.

4. Fluxtube diameters

Structures with concentrated magnetic fields seem to come in a wide variety of sizes, ranging from sunspots with diameters of tens of thousands of km down to the smallest magnetic elements which are smaller than the best presently achievable spatial resolution of approximately 0.25″–0.3″ (180–220 km). What does theory tell us about the diameters of magnetic elements? What details can observations reveal?

Piddington (1975) and Parker (1975) first pointed out that fluxtubes, with the field expanding with height, are liable to the interchange or fluting instability by which a given fluxtube fragments into smaller tubes. The stability of fluxtubes to interchange has been more quantitatively studied by Meyer et al. (1977) and Schüssler (1984).

Meyer et al. (1977) showed that buoyancy (for tubes expanding rapidly enough with height) can stabilize the fluxtubes. They derive a criterion stating that an axisymmetric fluxtube is stable if at its boundary the radial component of the field decreases upwards. But buoyancy works only for tubes with fluxes larger than $1\text{–}6\times10^{19}$ Mx (magnetic knots, small pores). The exact value of the limit depends on the details of the assumed model. Schüssler has shown that small fluxtubes with fluxes less than $1\text{–}5\times10^{17}$ Mx are also stable, provided they are surrounded by a whirl flow (inverse tornado flow) of approximately 2 km s^{-1}. Fig. 2 shows the region of instability of fluxtubes (to the left of the curves) as a function of flux and of whirl velocity. The two curves correspond to different models of the solar convection zone. As a result of the bathtub effect the presence of such a flow is probable due to the position of fluxtubes in the intergranular lanes, where they are surrounded by downflowing material (e.g. Nordlund, 1983). A minimal diameter of intense magnetic fluxtubes may result from the increasing inefficiency of the convective collapse mechanism with decreasing size of isolated weak magnetic field patches (e.g. Nordlund, 1986). As such a patch becomes so small that it becomes optically thin and achieves the same temperature as its surroundings by radiative exchange, it becomes increasingly resistent to the convective instability.

From an observational point of view only very few direct measurements of small fluxtube diameters exist. Ramsey et al. (1977) have obtained very high spatial resolution magnetograms. They see magnetic structures with sizes comparable to their effective resolution of 0.3″–0.5″. This means that the diameter of the smallest magnetic elements is $< 0.3''$.

The most common indirect method is to assume that photospheric bright points ("filigree") are fluxtubes (e.g. Dunn and Zirker, 1973; Mehltretter, 1974; Muller, 1983; Muller and Keil, 1983). Muller and Keil (1983) find an average size of bright points close to their resolution of 0.2″ outside of active regions, so that fluxtubes smaller than this may easily exist. Spruit and Zwaan (1981) have found sizes between their best resolution of 0.3–0.4″ (bright facular points) and 4″ (dark pores) in active regions. However, there is a gap in their observed distribution between 0.5″ and 1.4″. Whether there really are no fluxtubes with such diameters (in accordance with the predictions of theoretical stability analysis of Schüssler), or if fluxtubes in this size range have approximately the same continuum brightness as the quiet photosphere (as assumed by Spruit and Zwaan) we cannot decide.

We also wish to caution, that although Schüssler and Solanki (1987) have shown (from a comparison of fluxtube, average plage and quiet sun line profiles) that magnetic elements are on the average very bright and will therefore often (but not necessarily always) appear as facular bright points, we cannot say the reverse: not all bright points on the sun need have a magnetic origin, although Mehltretter (1974) did find a rough correlation between magnetic flux and the number of bright points in a given surface area.

Another indirect method is to search for a lower limit to the magnetic flux. Wiehr (1979) has found some evidence for such a lower limit of 2.4×10^{18} Mx, which corresponds to a diameter d: 390 km $\leq d \leq$ 550 km if we assume the true field strength to be 1000 G $\leq B \leq$ 2000 G. More recently, Wang et al. (1985) have carried out similar observations. They follow elements of magnetic flux which are disappearing through interaction with elements of opposite polarity. In general the observable flux reaches a minimum shortly before complete disappearance. They find minimum values between 1.0×10^{16} and 1.4×10^{17} Mx, which corresponds to sizes of 35–130 km. Such investigations are rather unreliable (as is illustrated by the different results in the two investigations) due to the following reasons. They are carried out at the very limits of the instruments' capability (noise!). They do not take into account line weakenings and different continuum levels in the magnetic elements, which distort the measured flux values considerably (cf. Grossmann-Doerth et al., 1987). Furthermore, Wang et al. only consider bipolar regions, so that a too small flux may be seen due to the limited spatial resolution. A similar technique is to look for a "quantization" in the magnetic flux. Livingston and Harvey (1969) found some evidence for such "quantization", but this has never since been reproduced, and must be considered to be spurious.

5. Temperature, Heating Mechanisms, and Internal Mass Motions

There are basically two mechanisms for heating fluxtubes to the observed temperatures: radiation and mechanical heating. Mechanical heating itself can be of quite different types and one of the main open questions is to deduce the relative importance of the different mechanisms, i.e. to find the relative importance of the various possible terms in the energy equation for fluxtubes as a function of height in the atmosphere, radius of the fluxtube, field strength, etc.

Both radiative and mechanical heating are challenging to calculate. In the former case we can use the diffusion approximation in the deeper layers of fluxtubes, but have to solve the proper radiative transfer equation higher in the atmosphere. Since fluxtubes cannot be considered to be plane parallel, the radiative transfer must be carried out in at least 2-D cylindrical geometry. The discussion of radiative heating is further complicated by the fact that the magnetic elements also affect their environment, so that, strictly, the radiative transfer cannot even assume a plane parallel atmosphere (e.g. quiet sun) outside the fluxtubes. It is therefore not surprising that only greatly simplified treatments of the radiative heating in fluxtubes have so far been published. The situation is not much better as far as mechanical heating mechanisms are concerned (i.e. wave heating, convection, stationary flows). For example, wave heating often involves energy dissipation by shocks, which are notoriously difficult to treat properly, or by radiative damping which poses the same problems as direct radiative heating.

I first briefly review the theoretical models which do not consider waves or stationary flows within the magnetic elements and shall compare these with empirically determined fluxtube properties, mainly the temperature. Then a connection is sought between the observations of mass motions in fluxtubes and the theoretical picture we have of such mass motion.

5.1. Stationary Fluxtube Models with an Energy Equation

A first comprehensive model of magnetic elements was constructed by Spruit (1976). The magnetic field was assumed to be a potential field with a bounding current sheet and pressure balance was only approximately satisfied. All energy transport (radiation and convection only) was supposed to be diffusive and the change in convection near the magnetic elements was treated in a rather ad-hoc manner. Despite these simplifications and assumptions this model was by far the most sophisticated one to have been proposed until then and it has had a profound influence on the development of the field. It showed, for example, the important role played by the hot walls in determining the continuum intensity of the fluxtube.

Spruit (1977b) improved on his initial model, in particular how he treated the convection near the obstructing fluxtube, and considered some effects in greater detail. Foremost of all the effect of the presence of a small fluxtube on its surroundings. He showed that since the $\tau = 1$ surface in a fluxtube lies deeper than in the surroundings, it serves as a heat leak and the surroundings are consequently cooled.

Another model considering energy transport in fluxtubes has been published by Ferrari et al. (1985) and Kalkofen et al. (1986). They study very thin fluxtubes and neglect their influence on their surroundings. They solve the radiative transfer for a grey opacity in the two stream approximation. Radiation is assumed to be the only energy transport mechanism in the fluxtube. As intuitively expected for such very thin structures, for which the photon mean free path inside the fluxtube is large compared to the fluxtube radius, the internal temperature is almost equal to the external temperature at equal *geometrical* depth. At equal *optical* depth the fluxtube is 2000–2500 K hotter than the surroundings ($\tau = 1$). In their second paper they consider the effect of changing the radius of the tube on the axis temperature and also in a rough manner the variation of the temperature across the fluxtube cross-section. Interestingly they find that for these very thin fluxtubes the axis temperature increases with increasing radius. A possible reason is that their approximation of very thin fluxtubes breaks down quite soon. E.g. the mean free path of photons in the external atmosphere at $Z = -100$ km (i.e. near $\tau = 1$ in the fluxtube) is 700 m, and even in the fluxtube it is not more than 30 km (Schüssler, private communication).

The most comprehensive two dimensional fluxtube models are those of Deinzer et al. (1984a, b) and Knölker et al. (1987). They solve the full non-linear MHD-equations for a compressible medium. The radiative energy transport, however, has remained in the diffusion approximation (although a proper radiative transfer has been developed and is at present being implemented), while the convection is treated with the mixing length formalism. The models are in slab geometry. Although the capability of solving fully dynamical problems is present, so far only stationary solutions have been presented. Detailed $T(\tau)$ and $T(Z)$ structures for fluxtubes of various sizes have been calculated. One of the important results is that as expected intuitively T decreases with increasing radius of the fluxtube, thus showing the transition from bright magnetic elements to dark pores to be mainly a direct effect of the increase in the diameter and in its ratio to the Wilson depression. Another interesting results of this model is the presence of a baroclinic flow surrounding the magnetic elements. It is driven by the gradient in pressure near the magnetic element, which is itself a consequence of the decreased pressure scale height (i.e. temperature) due to the influx of heat into the fluxtube. The more realistic treatment of the surroundings in this model also leads to a considerably lower temperature of the fluxtube walls than in Spruit's model.

Other very comprehensive models are those of Nordlund (1983, 1985, 1986). These are further developments of his granulation models (see Nordlund, 1982, 1984 for details). They are three dimensional, time dependent, treat convection by solving the complete MHD equations, and include radiative transfer explicitely. Unfortunately, the resolution of the grid is of approximately the same order as the expected diameter of the magnetic elements. Therefore, these models are not suitable for studying the internal structure of flux concentrations, but are extremely useful for the illustration and comprehension of the interaction of magnetic flux with the convection.

5.2. Empirical Models

Some of the more recent empirical models of the temperature in the photospheric layers of magnetic elements are those of Hirayama (1978), Chapman (1979), Stellmacher and Wiehr (1979), Solanki (1986) and Walton (1987). Each of these models is based on different types of data and makes slightly different assumptions and approximations. For more details see also the review by Solanki (1987). The models of Solanki have the advantages that they are the only ones of the above models based on Stokes V data, which contain information exclusively on the magnetic concentrations even when these cover only a small fraction of the observed areas. They are compatible with well over a hundred Fe I and II Stokes V profiles observed at various postions on the solar disk (cf. Pantellini et al., 1987). They also satisfy the constraints set by the best presently available continuum contrast observations near disk centre (Muller and Keil, 1983 for the network, Frazier and Stenflo, 1978 for active region plages) and take the velocity broadening of the Stokes profiles into account, as well as the difference between the properties of network and active region plage fluxtubes. We shall therefore use these empirical models to compare with the theoretical ones.

However, before proceding with this we wish to point out that these models also have disadvantages, the main of which are that they are one-dimensional (plane parallel atmospheres) and the lines are all calculated in LTE. Also, the reliability of even the best continuum contrast measurements is not beyond doubt, due to the extremely small size of the magnetic elements and the probable presence of a dark ring around them. Finally, such models give some kind of (spatial and temporal) average of the properties of the fluxtubes in the resolution element and individual fluxtubes may differ considerably from this average at a given time.

The problem of whether 1-D (plane parallel) radiative transfer is adequate for the diagnostics of solar magnetic elements has been addressed by e.g. Owocki and Auer (1980), Van Ballegooijen (1985a,b) and Solanki and De Martino (1987). Using profiles calculated in a plane parallel atmosphere not only has an influence on the determined magnetic field, the filling factor and to a smaller degree the angle of inclination of the field, but it also tends to give incorrect results for the fluxtube temperature. In general, the assumption of a plane parallel atmosphere for the fluxtubes will underestimate the fluxtube temperature. The error in the temperature increases considerably towards the limb.

The influence of NLTE on the diagnostics of fluxtubes has been investigated in detail by Stenholm and Stenflo (1978) and Solanki and Steenbock (1987), while the more basic problem of a consistent NLTE description of the radiative transfer of polarized light has been addressed by e.g. Domke and Staude (1973a, b). The former two investigations are complementary to each other. Stenholm and Stenflo (1978) have been most interested in how the cylindrical geometry of fluxtubes can change line profiles. They use a full 2-D radiative transfer code, but consider only a 2-level atom and a rudimentary temperature model of fluxtubes. They show that the field strength, as determined by the line ratio technique, is independent of the magnitude of NLTE effects. Solanki and Steenbock, on the other hand, consider only 1-D radiative transfer, but a very extensive iron model atom (79 Fe I levels, 20 Fe II levels and the Fe III continuum) and a number of different temperature models, including the empirical models of Solanki (1986). They concentrate on the influence of departures from LTE on the determination of velocity and temperature in fluxtubes. These two investigations show that NLTE effects, although not invalidating previous investigations, cannot be ignored. Both, the presence of hot walls and of a higher temperature in the interior of the fluxtubes (at equal optical depth) lead to NLTE induced line weakenings of the often used Fe I lines, due to the over-ionisation of iron. This is the same effect as is responsible for departures from LTE of Fe I in the quiet photosphere (Athay and Lites, 1972), but is considerably stronger in the typical fluxtube atmosphere. Fig. 3 illustrates this difference.

Let us now return to comparing theoretical with empirical models: Fig. 4 shows T vs. $\log \tau$ (the logarithm of the continuum optical depth at 5000 Å) for two empirical (plage and network models of Solanki, 1986) and two theoretical models (models A and C of Deinzer et al., 1984b). The agreement between the two is quite gratifying if we consider all the simplifying assumptions made. The very thin fluxtubes of Ferrari et al. (1985), on the other hand, are considerably hotter than the empirical models. It appears that such very thin fluxtubes do not provide a significant contribution to the observed radiative flux in active regions and the enhanced network. This may have to do with the effect described by Van Ballegooijen (1985b) whereby fluxtubes with a very small diameter are less visible, except when looking almost straight down the throat of the fluxtube.

5.3. Mass Motions in Magnetic Elements: Theory and Observations

Stationary motions in magnetic elements are restricted mainly to the direction parallel to the magnetic field lines so that we can roughly speak of upflows and downflows. The widely observed downflows within fluxtubes (e.g. Harvey, 1977; Giovanelli and Slaughter, 1978; Wiehr, 1985) have always been problematic for theoreticians to explain, since they seem to contradict the conservation of mass (density increases more strongly downwards than the fluxtube cross-section decreases, and diffusion across the field lines is very small) so that it becomes a problem to replenish the downflowing material in the upper atmosphere. Durrant (1977) has argued against their presence, as have Hasan and Schüssler (1985). The latter authors have used new and realistic diffusion coefficients to show that diffusion at the temperature minimum is insufficient to replenish a downflow stronger than approximately 10 m s^{-1} at the $\tau = 1$ level. A downflow of 0.5–1 km s^{-1}, as sometimes observed, would drain the corona within a matter of minutes. As pointed out by Webb and Roberts (1978) and others a downflow may well be a transient feature of the birth of fluxtubes, associated with their convective collapse.

Observational evidence has lately been increasing that the observed downflows are spurious. Recent measurements which are inconsistent with strong downflows have been published by Stenflo and Harvey (1985), Brants (1985), Solanki (1986), and Stenflo et al. (1987a). Furthermore, Solanki and Stenflo (1986) have been able to show that the observations showing downflows are compatible with the newer ones showing no downflow, if we take into account that the downflow observations have much lower spectral resolution. The spectral smearing induces a spurious downflow signal. We can therefore safely conclude that *stationary* downflows are not a major heating source in the photosphere.

Waves have been the non-stationary motions within fluxtubes studied in greatest mathematical detail, usually in a linearized approach and often neglecting atmospheric stratification (no gravity). Waves involving the bulk of the fluxtube are generally divided into three catagories illustrated in Fig. 5. In addition, surface waves at the boundary of the fluxtube are also possible (e.g. Edwin and Roberts, 1983).

Recent reviews on the subject of fluxtube waves have been given by Roberts (1984, 1986), Thomas (1985), and Ulmschneider and Muchmore (1986). I shall not attempt to review the considerable literature on wave calculations in fluxtubes, and refer to these reviews for more details. The heating of the chromosphere and transition region by the dissipation of waves (among other mechanisms) has been recently reviewed by Hammer (1987). Heating of the lower chromospheric layers of thin fluxtubes by longitudinal tube waves and acoustic tube waves (which are the same as longitudinal tube waves, but with rigid fluxtube walls) has been investigated by Herbold et al. (1985). They carry out a non-linear calculation which explicitely takes shocks into account. They start with an atmosphere with asymptotically constant temperature at large heights, and can produce a qualitative temperature increase corresponding to a chromosphere with their calculations at the cost of reducing the temperature deeper down in the atmosphere.

Let us now turn to the observations. Until recently the evidence for non-stationary mass-motions in magnetic elements was restricted to low amplitude 5-minute oscillations (Giovanelli et al., 1978; Wiehr, 1985). However, such observations, which look for periodic motions in the Stokes V profile, are only sensitive to oscillations and waves which are in phase in the majority of fluxtubes in the resolution elements. Due to the limited spatial resolution this is usually a large number, ruling out the discovery of waves excited locally in individual fluxtubes. Therefore, only line broadening observations can presently give us information on the velocity amplitudes in fluxtubes. Solanki (1986) has analysed the line widths of a few hundred line profiles at disk centre (derived from Stokes V, cf. Solanki and Stenflo, 1984, 1985) and finds that rather large amplitude (vertical) mass motions are required to reproduce the observations. If the velocity is described by a mixture of macro- and micro-turbulence then we have rms amplitudes ranging from 1 km s^{-1} to 3.5 km s^{-1}. For medium strong lines these velocities are considerably larger than on the quiet sun. Possible sources of such line broadenings are motions along the field lines, like overstable oscillations and longitudinal tube waves. Stationary velocity *gradients* along the line of sight can also produce line broadenings, but the profiles they produce come into conflict with other observations, namely the absence of a shift in the zero-crossing wavelengths.

We can also test for the presence of horizontal motions by observing near the limb. Pantellini et al. (1987) extended the analysis of Solanki (1986) to the solar limb. Surprisingly, the velocity amplitude does not decrease when approaching the limb, rather it even increases slightly.

Fig. 6 shows the macroturbulence velocity as a function of line strength, derived from about 150 Fe I lines. Stars and the dashed curve represent the macroturbulence for regions with $\mu > 0.6$ (μ = cosine of the heliocentric angle, θ) while the open circles and the solid curve represent the macroturbulence for regions with $\mu \leq 0.3$. The Simmons and Blackwell (1982) quiet sun microturbulence relation is used.

At first sight these strong horizontal motions may appear contradictory to physical intuition, since one would expect flows, oscillations etc. to be mainly parallel to the field lines. However, a little more consideration shows a number of possible mechanisms to explain these observations. Transverse waves are obvious candidates, as are Alfvén waves. Not so obvious are longitudinal waves, since their main velocity component is along the field lines. However, the associated "breathing" of the fluxtubes, also results in a small transverse component. Finally, the mechanism by which transverse waves may be excited, the jiggling of the magnetic elements by the surrounding granulation is itself a possible source of at least a part of the observed line broadening. Parker (1983, 1986) roughly estimates the magnitude of this jiggling to be 0.5–1.0 km s^{-1}. This estimate appears realistic in the light of the finding from Spacelab 2 (SOUP, Title et al., 1987a) that the centres of individual granules have an average horizontal velocity of approximately 1 km s^{-1}.

6. Concluding Remarks

A brief overview has been given of a few aspects of the theoretical and empirical study of solar magnetic elements. Emphasis has been laid on the comparison of theory with observations, so that the many theoretical studies of highly idealized situations, which are quite basic to our understanding of the physical phenomena associated with solar magnetic fields, have not been included. There are also a host of highly interesting topics which, due to lack of space, could not be dealt with here. An example is the influence of magnetic elements on the solar convection, where exciting new results from white light movies (SOUP on Spacelab2, Title et al., 1987a), from magnetograms (Title et al., 1987b) and also from conventional line bisector studies (Brandt and Solanki, 1987; Immerschitt and Schröter, 1987) have recently become available. Another exclusion is the discussion of recent advances in the radiative transfer of polarized light which will have a profound influence on our empirical knowledge of magnetic structures in the future.

When writing this review I was struck most of all by how much more strongly theory and observations interact today than say a decade ago. The reason lies partly therein that observers have improved techniques and instrumentation to observe quantities not earlier possible, but I think mainly in the giant strides which the community of theoreticians has been making in producing models which can be directly compared to observations. This increasing cooperation and interaction should make us confident of future strides in our knowledge of the fine scale structure of the solar magnetic field.

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Figure Captions

Fig. 1: Merging height as a function of the ratio of internal to external pressure scale heights. Three models of Steiner et al. (1986) are shown. Their radii at $\tau_{\text{ext}} = 1$ are given in the figure. $\alpha = 0.1$ for all three models. (Steiner, private communication.)

Fig. 2: Magnetic flux Φ as a function of whirl velocity v_B. To the left of the curves (one for the convection zone model of Spruit, 1977a; the other for the model of Meyer, Schmidt and Weiss, 1977) the fluxtubes are interchange unstable. Since v_B is realistically expected to be 1–2 km s^{-1}, small tubes may be stable. (After Schüssler, 1984.)

Fig. 3: NLTE effects: $\Delta \log \epsilon = \log gf\epsilon_{NLTE} - \log gf\epsilon_{LTE}$ vs. equivalent width W_λ. $\Delta \log \epsilon$ is a measure of the strength of ionization departures from LTE. Upper figure: for a quiet sun atmosphere (HSRA, Gingerich et al., 1971). Lower figure: for a network model of Solanki (1986) with a particularly high continuum contrast: $I_c^{Magn.}/I_c^{Quiet} = 1.63$. Dots: Fe I lines with $\chi_e \leq 3.5$ eV, circles: Fe I lines with $\chi_e > 3.5$ eV, crosses: Fe II lines. Fe II departures in NETW2 are of the same order as in the HSRA. Note the generally larger NLTE effects in the fluxtube model. (From Solanki and Steenbock, 1987.)

Fig. 4: Comparison between two empirical models (solid lines, from Solanki, 1986) and two theoretical models (dashed and dot-dashed, from Deinzer et al., 1984b). Temperature vs. logarithmic continuum optical depth at 5000 Å. A quiet sun model (HSRA) is also plotted for comparison. (After Schüssler, 1987.)

Fig. 5: Wave modes in a thin cylindrical fluxtube. n denotes the order of the Bessel function solution for the radial dependence of the wave. (After Thomas, 1985.)

Fig. 6: Macroturbulence velocity in magnetic elements ξ^V_{mac} (derived from Fe I lines) vs. line strength S_I. Stars and dashed curve: average curve for regions with $\mu > 0.6$ circles and solid curve: average values for regions with $\mu \leq 0.3$. (From Pantellini et al., 1987.)

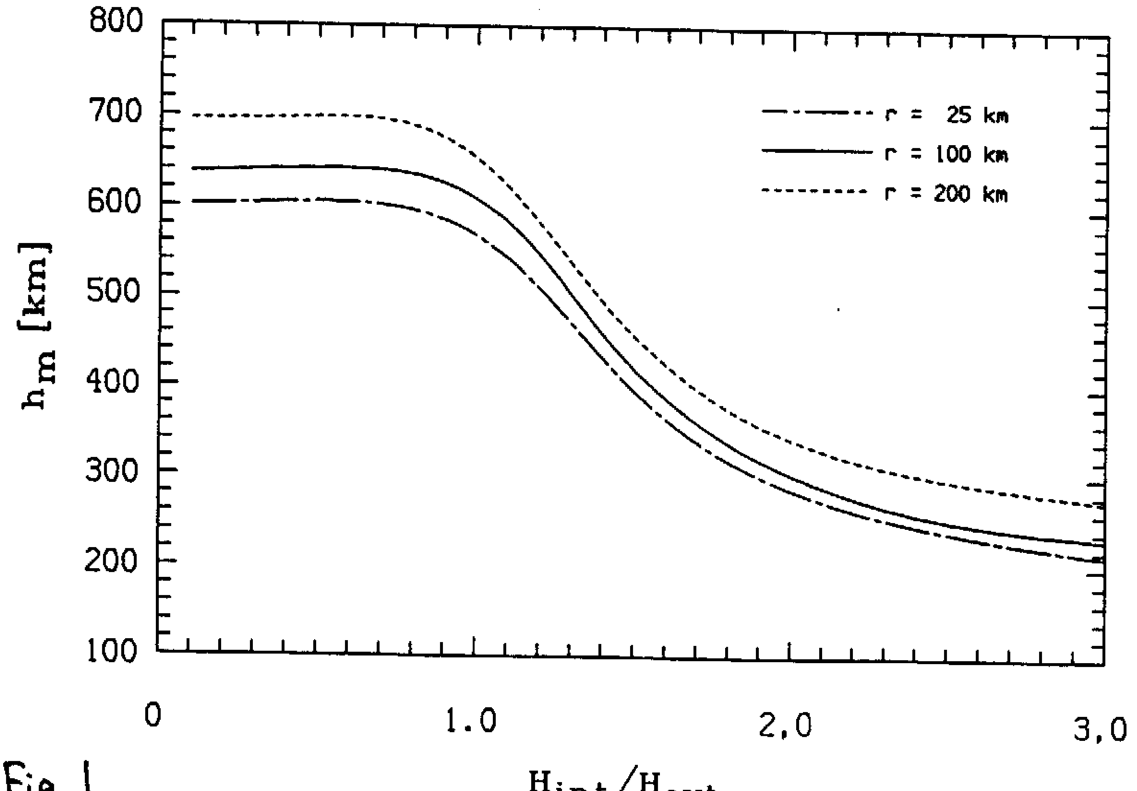

Fig. 1

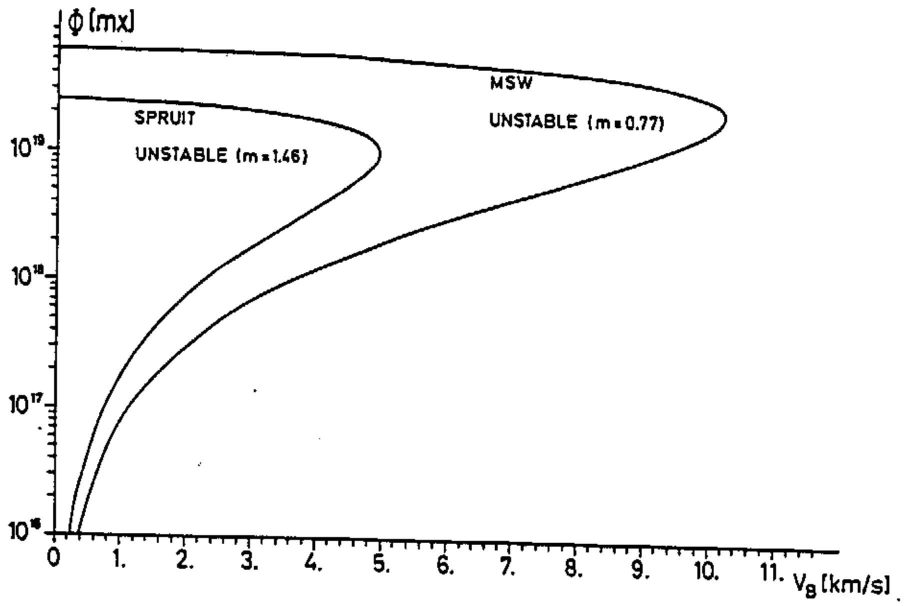
Φ (mx)
MSW
UNSTABLE (m = 0.77)
SPRUIT
UNSTABLE (m = 1.46)
10^{19}
10^{18}
10^{17}
10^{16}
0
1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.
V_B [km/s]

Fig. 2.

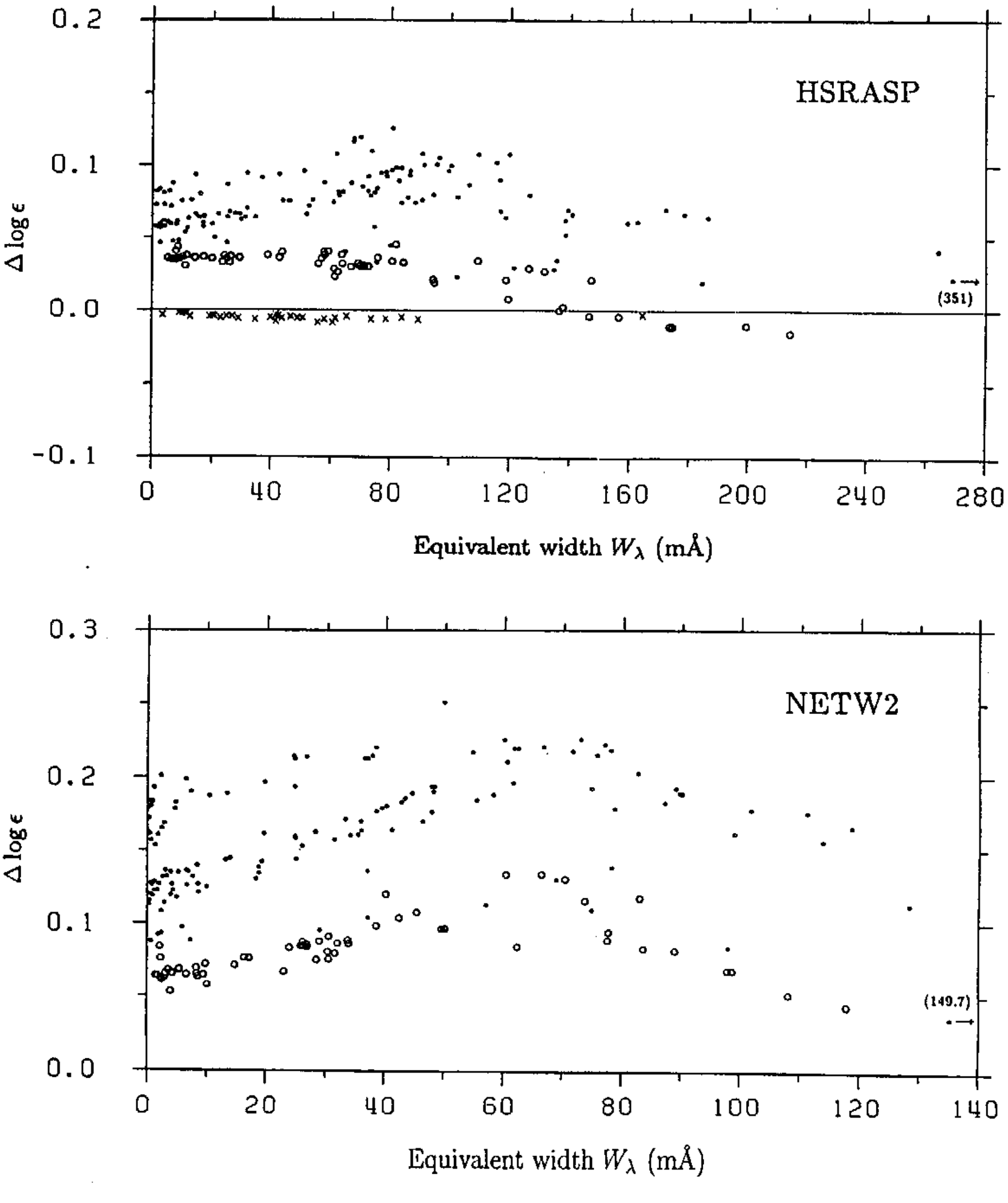
HSRASP
Δ log ε
0.2
0.1
0.0
-0.1
(351)
0
40
80
120
160
200
240
280
Equivalent width W_λ (mÅ)
NETW2
Δ log ε
0.3
0.2
0.1
0.0
(149.7)
0
20
40
60
80
100
120
140
Equivalent width W_λ (mÅ)

Fig. 3

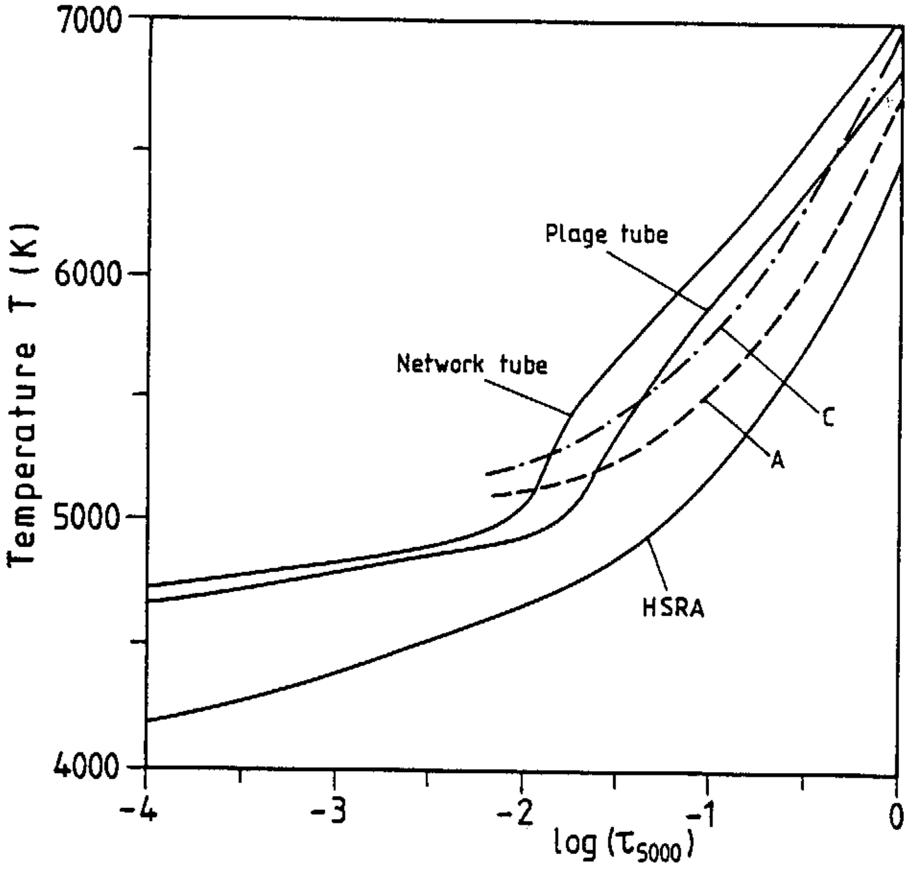
7000
6000
5000
4000
Temperature T (K)
-4
-3
-2
-1
0
log (τ_{5000})
Plage tube
Network tube
C
A
HSRA

Fig. 4

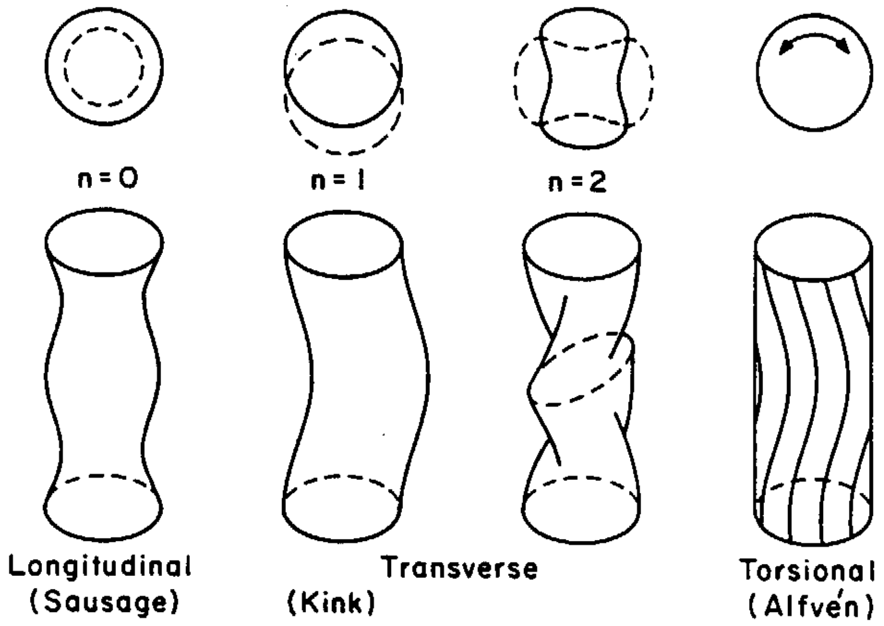
n = 0
n = 1
n = 2
Longitudinal
(Sausage)
Transverse
(Kink)
Torsional
(Alfvén)

Fig. 5

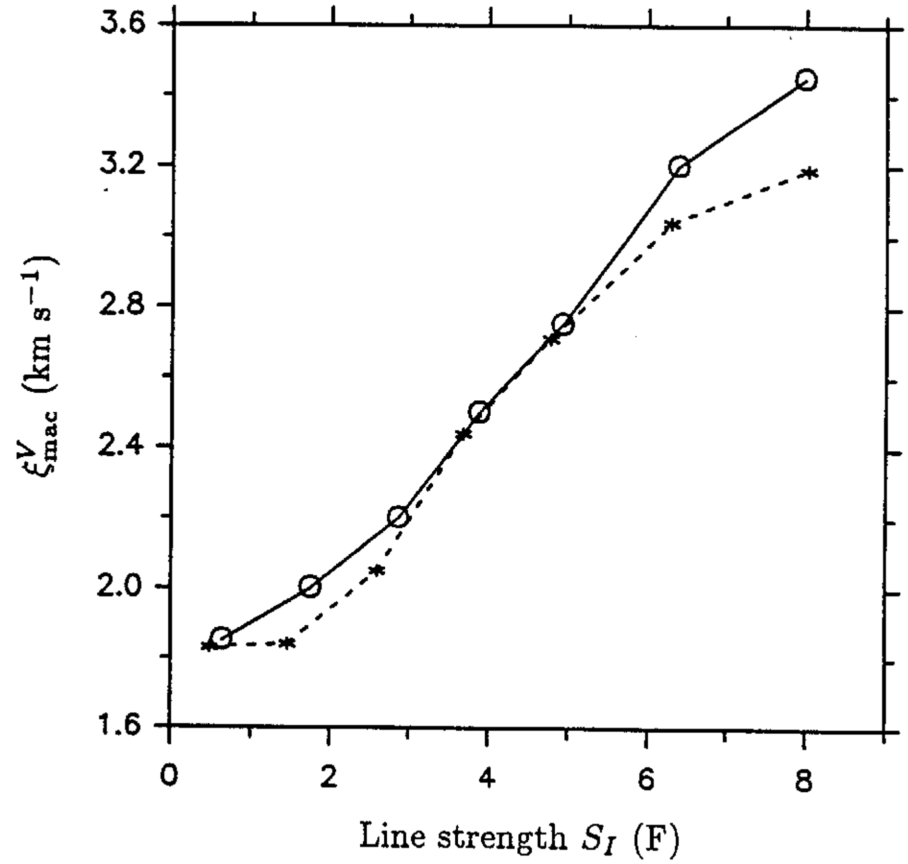

Fig. 6