MAGNETIC FIELD MORPHOLOGY IN THE UPPER LAYERS

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ABSTRACT

We examine some basic properties of emerged magnetic flux concentrations, with emphasis on the interplay between the magnetic and thermodynamic structure in the region between the photosphere and the transition zone. The discussion is limited to the gross behavior of those phenomena that may be reasonably regarded as quasi-static, such as the longer-lived sunspots, pores, and some smaller magnetic flux tubes. Substructure and dynamic phenomena are not considered.

I. INTRODUCTION

In most regions of the solar surface, only a small fraction of the total area at deep photospheric levels is thought to be pierced by magnetic flux concentrations, yet the field is known to be essentially ubiquitous at coronal levels. In the important intervening region of the upper photosphere, chromosphere, and transition zone, then, the magnetic field evidently undergoes a rather drastic spreading with height. The physical factors which govern the magnetic topology of emerged flux concentrations are therefore of both theoretical and observational interest. In particular, the upper layers of emerged magnetic structures may be heated by both acoustic and magnetic waves, and the relative proportion of heating stemming from these and other sources is related to the fraction of the atmosphere threaded by magnetic fields at the relevant height. Theoretical models of the heating processes thus depend upon the assumed background magnetic structure, as does our interpretation of observations of solar and stellar emission from the upper layers.

Our discussion of the field morphology in the upper layers stresses two main points. First, understanding of the magnetostatic structure of solar flux concentrations stems from the relation among three factors: force balance, energy balance, and the way in which the observations are interpreted. The balance of gas pressure, magnetic, and gravitational forces directly determines the equilibrium geometry (or shape) of the magnetic configuration. However, the energy balance regulates the thermodynamic properties, which in turn influence the force balance. The energy transfer processes, of course, depend upon the geometric and magnetic properties of the structure. Thus in a real solar feature, force balance and energy balance cannot in general be legitimately discussed separately. Similarly, the observational properties of such structures are in most cases intimately related to their presumed thermodynamic and magnetic properties, i.e., the interpretation of the measurements are highly model-dependent, except in certain circumstances.

Second, we emphasize the importance of scale size -- the physical dimensions of the flux concentration -- on all three factors. At least in some aspects, the larger features (e.g. the centers of large, homogeneous sunspots) are simpler to understand on a theoretical basis and offer the best opportunities for making unambiguous observations on the sun. Small features like network elements, on the other hand, are inherently more complicated: the energy and force balance is strongly coupled and the observational inferences are closely tied to operational assumptions regarding the structure of the feature.

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Finally, much of the emerged magnetic flux on the sun is manifestly bipolar in nature, i.e., the flux elements connect to some nearby point on the solar surface. Such structures are inherently three-dimensional (3-D) and hence pose a tough theoretical challenge. Nevertheless, because the bipolarity should have perceptible impact upon the the field morphology in the upper layers, techniques for generating truly 3-D magnetostatic models suitable for quantitative analysis are of obvious importance. We briefly touch upon relevant developments in this direction at the end of the paper.

II. THE SPREADING OF EMERGED FLUX -- GENERAL PRINCIPLES

Magnetic flux evidently erupts from the interior of the sun because the buoyancy associated with the reduced gas densities inside a submerged flux rope eventually forces it to the surface. At photospheric levels, the buoyancy is thought to be strong enough to cause the footpoints of the erupted flux concentration to be nearly vertical. The structure spreads with height because the overall gas pressure falls off more rapidly than does the field. However, the flux tube interior and the surrounding exterior fluid are subject to different heating mechanisms and the resulting lateral gas pressure gradients may alter the rate and extent of the expansion. In sunspots and pores, for example, the cool interior is at lower pressure than the exterior gas at the same height (the Wilson depression), causing the exterior gas to squeeze in and oppose the spreading described above. A similar sort of confinement occurs in smaller flux tubes, though they are evidently at more nearly the same temperature as the undisturbed photosphere. In groups of spots and pores, however, where the flux ropes reconnect to the surface in a compact and complex pattern, the individual strands may deviate strongly from the vertical. Nevertheless, the basic rationale that there must be spreading with height still holds, even if the expansion is modified by strong tension forces.

To illustrate the general principles involved in the spreading of emerged magnetic flux, let us consider the theoretical idealization depicted in Figure 1a (top). Here we view a vertically-oriented, cylindrically symmetric bundle of field lines that are fanning out with height about the axis. We assume the field lines are fixed (rooted) in place at some level $z = 0$ in the atmosphere and that the gas pressure at any given height z along the axis differs from that at the same height far from the axis. Let us also stipulate that the structure is magnetostatic (no flows) and twist-free. That is, gas pressure forces balance the Lorentz force in the horizontal direction, hydrostatic equilibrium obtains along field lines, and there are no field-aligned currents. Hence the field lines lie entirely in the plane of the Figure.

Let us now define some basic parameters governing the expansion. As measured at the base, we have

ΔP $\equiv$ net horizontal gas pressure differential

$B^2/8\pi$ $\equiv$ magnetic field pressure on the axis

R $\equiv$ horizontal scale (radius) of flux concentration

H $\equiv$ vertical scale of atmospheric ΔP variation.

By averaging the equation of horizontal force balance over a cylindrical volume of radius and height R about the axis and above the base ($z = 0$), it can be shown (Pizzo, 1986) that when

$$\frac{\Delta P}{B^2/8\pi} \lesssim \frac{R}{H} , \tag{1}$$

the spreading of the field lines does not deviate significantly from a free, potential expansion, i.e., the solution to the boundary problem is little affected by the gas pressure forces. (By free, potential expansion we mean one in which there are no currents above the $z = 0$ surface.) Conversely, where the above

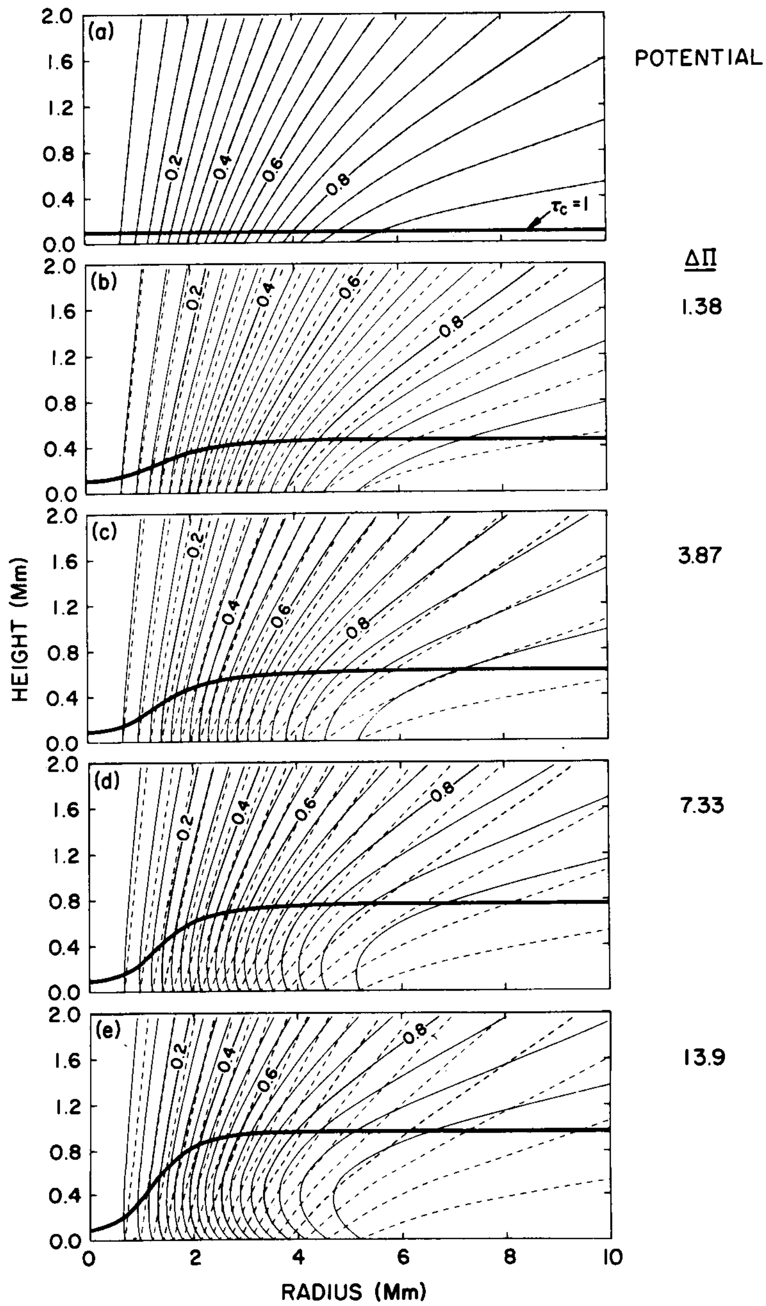

Fig. 1 -- Series of equilibria for a smoothly varying magnetic flux concentration in which the normalized horizontal gas pressure differential $[\Delta\Pi \equiv \Delta P/(B^2/8\pi)]$ increases from (a) to (e). Topmost panel (a) shows field lines for a purely potential ($\Delta P = 0$) solution which appears in each of the subsequent plots as dashed lines. The ΔP variation is generated by vertical displacement of an umbral model atmosphere (Avrett, 1981), which is presumed to obtain along the axis, against a quiet photosphere atmosphere (Spruit, 1977), which is presumed to obtain at large horizontal distances. The $\tau_c = 1$ surface is denoted by the heavy horizontal line to aid in visualizing the Wilson depression. Base axial field strength in all cases is held constant at B = 2.2 kG, and the size of the tube is fixed at R = 3.0 Mm. Labels on field lines indicate fraction of total flux interior to each line. (From Pizzo, 1986.)

condition is violated, the interior-exterior pressure differential will play a significant role in confining the flux tube in the atmosphere.

The physical basis for relation (1) can be traced in Figures 1 and 2. In each panel, the vertical coordinate (z) records height above the lower boundary (z = 0), which is set at some arbitrary level in the atmosphere just below the τ_c = 1 visible surface (indicated by the heavy horizontal line); the horizontal coordinate (r) denotes distance from the symmetry axis (r = 0). Both are given in units of 1000 km. The lines fanning out portray the field lines for a magnetic flux concentration in which the normal component of the magnetic field along the lower boundary is given by a gaussian with an e-folding scale of R = 3000 km. (The lateral and top boundaries of the computational regime used to generate the solutions in Figs. 1 and 2 have been removed to very large distances to approximate a free expansion.)

The top panel of Figure 1 shows a purely potential solution, i.e., there are no horizontal pressure gradients (ΔP = 0) and the magnetic field is force-free. The succeeding panels in Figure 1 demonstrate the effects of progressively increasing interior-exterior gas pressure differential on the equilibrium. As ΔP increases relative to the nominal base magnetic pressure, the field lines are squeezed in towards the axis more and more. Eventually (bottom panels), the constriction is so great that the field lines are bent into an hourglass shape. In these cases, equilibrium is rather graphically provided by the tension forces associated with the curving field lines acting in opposition to the encroachment of the external gas; but it is of paramount importance to recognize that throughout the Figure -- including the potential solution at the top -- magnetic tension plays a major role and lateral total pressure balance is not a prerequisite for equilibrium.

While this behavior is fairly straightforward, the effects of horizontal scale size are more subtle. In Figure 2, the interior-exterior pressure differential is held constant, while only the horizontal scale of the field R is varied. Scanning up from the bottom, we see that flux concentrations of the largest scale are the least affected by a given gas pressure deficit, while those of the smallest scale are most affected. What is happening here is that in the absence of gas pressure gradients, the magnetic field falls off vertically with a natural scale of order R. Hence the vertical distance over which the field pressure remains substantial is also of order R. The gas pressure differential, meanwhile, is falling off with a characteristic scale commensurate (in this particular case) with that of the exterior atmosphere, or H $\approx$ 350 km. For the examples towards the bottom of Figure 2, where R greatly exceeds H, the layer in which the gas pressure forces are significant is so shallow that only minor deviation from a potential solution results (note, the field responds globally to an external force, so the stress across the thin layer is distributed in varying measure to the whole configuration). In the panels towards the top, where R approaches H, the layer is relatively thick and the interaction correspondingly strong. Ultimately, in the limit where the field is of such small scale that R $<<$ H, the field wants to fan out so rapidly with height that the presence of even weak gas pressure differentials is going to have major effects, particularly in the upper levels of the configuration.

Although relation (1) is to be viewed as primarily functional in nature and is of limited quantitative value, it nonetheless offers some important insights, which can be summarized as follows:

1. Big structures, such as the larger leader and follower spots, require gas pressure differentials of enormous magnitude and depth to have much effect on the spreading above the photosphere; for credible solar values (e.g. Maltby, 1977), we might expect to find direct manifestation of the gas pressure confinement only near the edges of the structure (e.g., in the penumbra). Hence, with regard to establishing the overall shape of the structure, the thermodynamic properties in the region in and above the photosphere (where we can measure them) are relatively unimportant.

2. Small structures, in contrast, are inherently sensitive to gas pressure differentials and therefore to the details of the energy balance. In this case, the thermodynamic properties of

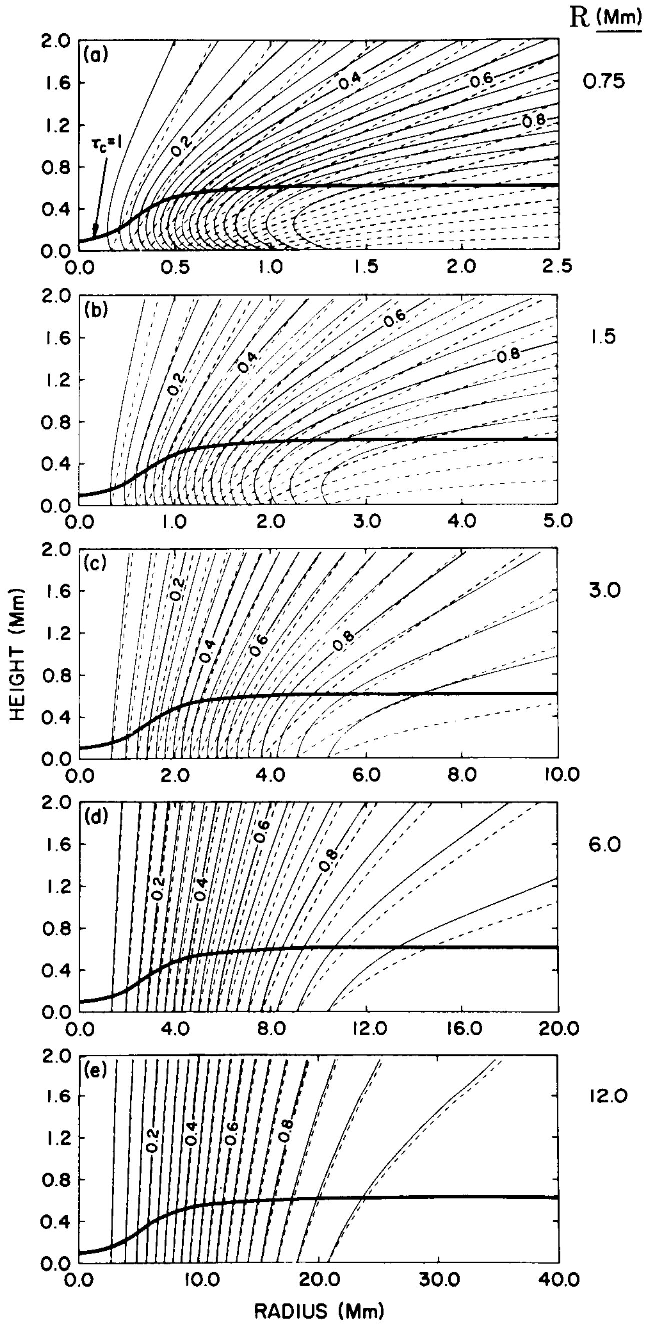

Fig. 2 -- Series of equilibria in which the tube radius R is varied between 0.75 Mm (a) and 12.0 Mm (e), while all else is held fixed. The vertical scale is the same as in Fig. 1, but the horizontal scale in each plot is proportional to R. (From Pizzo, 1986.)

both exterior and interior gas largely determine the expansion of the flux tube into the atmosphere.

Finally, it is to be emphasized that this dependence on scale size is a geometric property of the equilibrium and does not hinge upon details of the energy transfer or fine structure of the magnetic configuration. Although the behavior implicit in (1) was derived on the basis of smooth distributions of magnetic flux and gas pressure, as were the examples illustrating that relationship, the fundamental principles are not vitiated by the presence of current sheets or thermodynamic discontinuities. Such complexities will only wreak quantitative changes in the relationship and result in local modifications of the equilibrium structure.

III. PRACTICAL APPLICATION TO SUNSPOTS

The functional relationship (1) suggests a simple but telling test of the theoretical concepts sketched out above. Namely, it says that the centers of large sunspots (R $>$ several thousand km) ought to be thoroughly insulated from the crush of the surrounding atmosphere and therefore only the most minor deviations from free, potential expansion are to be anticipated. Accordingly, the observed magnetic field structure in the upper layers of a large spot should compare favorably with the predictions of a potential calculation based on the observed normal photospheric field. Though simple in the extreme, the importance of conducting such an experiment cannot be overstated: there is no place on the entire sun where physical conditions conform so neatly with the assumptions implicit in the analysis of magnetic spectral data and where we have greater confidence in our ability to accurately predict the magnetic structure. Indeed, if we cannot confirm theoretical expectations in so straightforward a test case, one must seriously question how much progress we can expect to make in divining the small scale structures that are the object of this conference.

The general idea of comparing observations of the magnetic field in spots with model calculations has been around for some time. These attempts have taken two tacks: measurements of the longitudinal field in several lines at different presumed heights to obtain an estimate of the vertical variation of the magnetic field (Beckers and Schroter, 1969; Abdussamatov, 1971; Wittman, 1974; Henze *et al.*, 1982); and, measurements of the vector magnetic field, from which the vertical gradient may be deduced via the divergence-free condition (Denisenko *et al.*, 1982). The most comprehensive of these studies (Hagyard *et al.*, 1983), combining both techniques, indicates that the field probably does not deviate significantly from potential between the photosphere and transition zone.

The problem with these studies, however, is that they are based upon one or a few spots and suffer from uncertainties introduced by the lack of an absolute reference frame for the height of line formation. In addition, all are done at fairly marginal resolution, so that only the vertical gradient near the axis can be estimated with any degree of confidence. The end result is a large scatter in published estimates of the axial vertical gradient and only the most rudimentary data on the evolution of the overall structure with height.

The scaling relation (1) suggests a procedure whereby many of these difficulties could be circumvented. Specifically, because the centers of large, symmetric, isolated spots should have a nearly potential structure, it follows that measurement of the vertical gradient of the axial field $(\partial B_z / \partial z)/B_z$ in a sequence of sunspots of varying horizontal dimension R should show a 1/R trend. There are at least two ways to implement this strategy. The simplest approach parallels earlier studies, in that one would measure B_z in several spectral lines formed at different (and unknown) heights. If the field is really potential, then the 1/R scaling should be evident, *so long* as each spectral line giving rise to the magnetograph signal is formed at the same respective height in the atmospheres of the different spots in the sequence. (For sufficiently large, uniform spots this should be a less risky proposition than deriving the actual heights of line formation from some generic umbral model.) Thus, even without direct knowledge of the line formation heights, one should be able to test convincingly whether the basic geometric properties of the expansion embodied in (1) are indeed valid.

A more complicated experiment, also drawing upon previous efforts, would be to use the observed line-of-sight field in the photosphere to generate a potential model prediction for the overlying magnetic structure and to compare the predicted structure with the observed 2-D distribution in the upper layers. By again assuming that a given line is formed at the same height in all spots of sufficient size, it would be possible to obtain an estimate for that height by seeking consistency of the fit between the model and the observations. A meaningful fit would simultaneously show low variance in the inferred heights of line formation and would exhibit the 1/R scaling in the vertical field gradient.

In either case, the advantage over previous attempts comes from the added constraint afforded by the 1/R scaling of a sequence of spots, as opposed to singular observations of random examples. The scaling may be anticipated to break down systematically in smaller spots and pores, where gas pressure forces become strong enough to affect the entire magnetic structure. It is at this juncture that it becomes possible -- in principle -- to use spectral observations in the upper layers to obtain information on the vertical run of gas pressure below $\tau_c = 1$ in the surrounding photosphere. Provided accurate, high-quality observations can be secured across the entire feature, there is the hope that iteration between the observed spectra and magnetostatic model predictions should converge to a self-consistent structure. Pores may offer the most lucrative return in this regard because they are of sufficiently small scale so as to ensure a strong interaction between the field and the confining gas, yet they are large enough to permit detailed, localized observations if high-resolution instrumentation is employed. Though pores may be construed as unlikely targets for the sort of hardware discussed in this conference, it is to be stressed that the essential information for our purposes resides in the field distribution. If the iterative process envisioned above is to converge uniquely, many data points across the structure -- and therefore quite high resolution -- are required to make the project feasible. For this reason, structures much smaller than pores are inappropriate.

IV. FIELD SPREADING IN THE UPPER LAYERS OF SMALL STRUCTURES

The field expansion in the upper layers of smaller structures, like magnetic elements, is far more complicated than in spots. This is because the energy transport mechanisms are more diverse and that the thermodynamic properties couple into the force balance more directly. Radiation, for example, plays an increasingly important role in establishing the equilibrium thermodynamic structure at and above the photosphere as the scale size of the feature decreases (Spruit, 1976; Kalkofen *et al.*, 1986): radiation from the hot surrounding walls, which penetrate only a short distance horizontally into the umbra of a large spot at photospheric levels, can instead pass entirely across the Wilson depression of a network element. Thus, while the cool lower portions of a spot are effectively insulated from the hotter gases in which they are embedded, the interior of a small flux tube is openly bathed in the external radiation field and should not depart too far from thermal equilibrium with it. Other mechanisms, such as the dissipation of mechanical energy by waves (Spruit, 1982; Ulmschneider and Stein, 1982) and compressive downdrafts (Ribes and Unno, 1976; Hasan and Schussler, 1985), may also contribute to the heating of the upper layers of flux tubes.

The spreading of the magnetic structure is linked to the energy balance via the gas pressure forces. Relation (1) tells us that the smaller the scale size, the greater the effect a given gas pressure differential will have on the magnetic structure. For features at the small end of the horizontal scale spectrum, then, internal-external thermodynamic differences essentially dictate the expansion of the field, at least in the photosphere.

If internal and external temperatures at and above the surface of small structures are roughly equal, then the classic thin flux tube approximation for the field expansion may pertain. For tubes whose horizontal dimension R is less than four times the external atmospheric scale height, it can be shown (Parker, 1955; Roberts and Webb, 1978) that the magnetic field spreads at a very slow rate: the field lines at photospheric levels are nearly straight and vertical, magnetic tension forces are negligible, and the field strength is almost uniform across the tube (see Figure 3). The spreading increases in the upper layers, so that, for typical fill factors, the height at which neighboring tubes begin to merge together is well up into the chromosphere. Twisting the fieldlines in the flux tube has only minor effect upon the merging height (Pneuman, Solanki, and Stenflo, 1986; Steiner, Pneuman, and Stenflo, 1976).

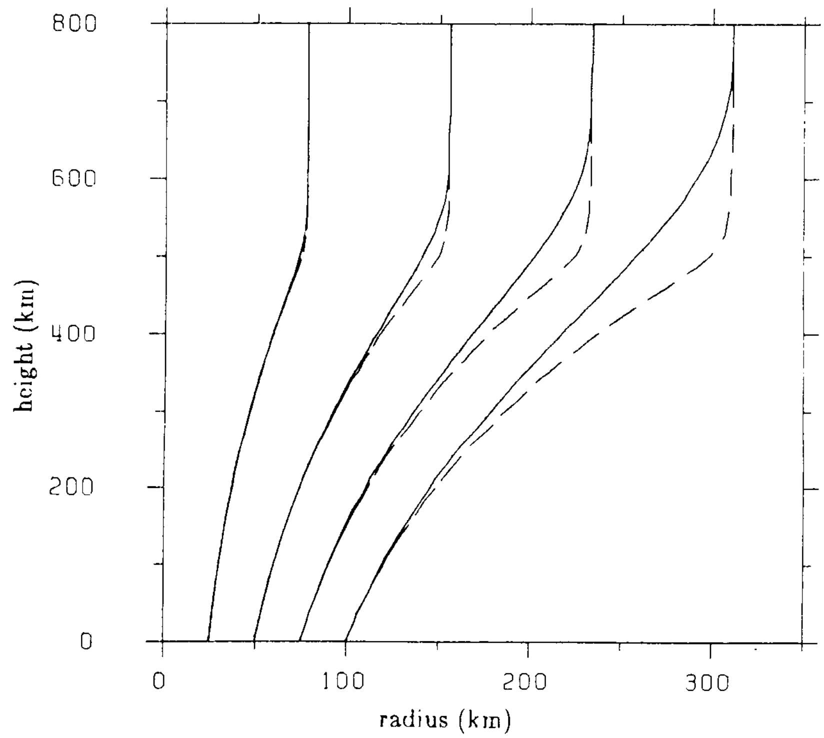

Fig. 3 -- Shape of flux tubes of several different radii as computed from thin flux tube approximation (dashed) and an expansion technique involving second-order corrections in the tube radius (solid). Note that the larger tubes spread out flatter. (From Pneuman, Solanki, and Stenflo, 1986.)

In terms of the scaling relation (1), the thin flux tube approximation represents a particular realization of the regime wherein the gas pressure differential is large enough to distort the magnetic structure far from a free, potential expansion. Note, however, that its applicability hinges upon the assumption that the temperature differences are small and that total pressure balance really does apply at the level in the atmosphere at which the flux tube is presumed to be rooted (which depends, in part, upon the scale size R). Under these conditions, the gas pressure differential falls off with height with the same scale as the external atmosphere, and the flux tube experiences significant constriction for a considerable vertical distance. (Recall that as R approaches H, the natural scale of the vertical magnetic field decline shrinks proportionately, enhancing the effects of the gas pressure differential.)

Unfortunately, the available observations provide little insight as to the details of the thermodynamic state of small scale structures. Numerous attempts have been made to infer the temperature and pressure profiles for small flux tubes (e.g. Foukal and Duvall, 1985; Solanki and Stenflo, 1985; Foing, Bonnet, and Bruner, 1986), but the observational difficulties are severe. Not only does the spatial resolution of the instrument impose serious limitations, but so also does the inherent vertical averaging of the magnetograph signal in structures which may well be significantly inhomogeneous over the height of line formation. Perhaps the best that can be stated at present is that there is some evidence for heating within small flux concentrations and that they are probably bright in the continuum, rather than cool and dark like spots (Spruit and Zwaan, 1981). On the other hand, the magnitude and spatial distribution of this heating is not known with any confidence and it is therefore impossible to assess whether the thermodynamic state is generally consistent with the simple radiatively dominated picture outlined above or to identify with any precision where additional heating may become important.

Therefore, until the advent of high resolution instruments of the type advocated in this conference series, progress on understanding the physics of the smaller magnetic concentrations depends heavily on theoretical advances. Two of the most important questions remaining to be answered are:

1. How does heating take place in a spreading magnetic field?
2. How does this heating affect the magnetic topography and its observational properties?

We shall offer some ideas on the second question first, as recent developments allow us to draw a qualitative picture with some confidence. To begin, let us consider a vertically-oriented flux tube in which the internal and external temperatures are equal at any given geometric height in the atmosphere. Let us further stipulate that the tube is of sufficiently small horizontal scale to justify application of the thin flux tube approximation. Thus, the field lines are nearly straight and spread out substantially only at great heights. Suppose the flux tube is now subjected to some heating, which, for the sake of argument, is uniform across the tube and varies only with height along it. The effects of heating upon the force balance may then be summarized as follows:

1. If the temperature enhancement is significant and the structure may be viewed as magnetostatic, then the internal-external pressure differential profile must be affected. For heating, the internal pressure is increased and ΔP must be accordingly reduced.
2. A reduced ΔP causes the tube to spread more than before, since the internal total pressure is increased.
3. If the heating occurs low enough and is of sufficient magnitude, the force balance will be seriously affected and the shape of the flux tube changed. However, if it is confined to the uppermost reaches of the structure, the effects on the spreading will be minimal, as the absolute magnitude of the gas pressure there is so low that the equilibrium state is essentially force-free. Hence even moderate heating at photospheric levels is of greater consequence than vigorous heating in the chromosphere.

Two recent studies directly address the question of flux tube spreading with height in response to an imposed internal temperature enhancement. In one, Pneuman, Solanki, and Stenflo (1986) considered flux tubes wherein the internal temperature was held at some fixed fraction of the local exterior temperature all along the tube. (Such a scenario is physically unrealistic, but it does illustrate the basic principles.) The results for three model tubes are shown in Figure 4, where the merging height serves as a measure of the spreading rate. The tubes with cool interiors ($T_e > T_i$) exhibit little dependence upon the temperature ratio because the lower internal temperatures cause such a rapid fall-off in density with height that the interior is essentially evacuated. As progressively warmer internal temperatures are considered, however, the internal gas pressure becomes significant, forcing the tube to spread more rapidly and thus to reduce the merging height.

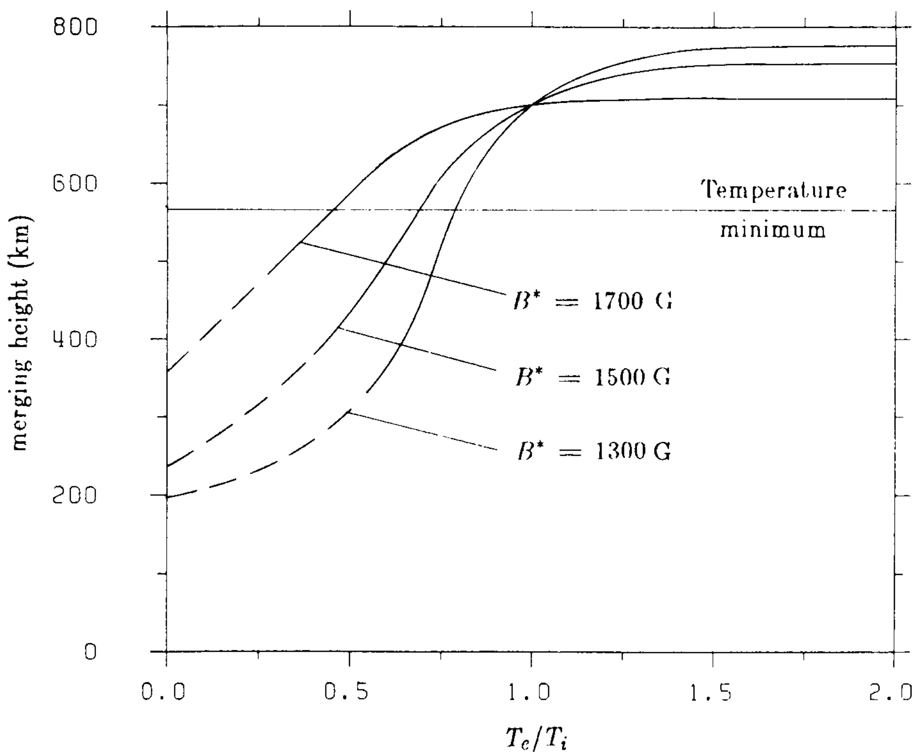

Fig. 4 -- Dependence of merging height upon ratio of external (T_e) to internal (T_i) temperature for different base magnetic field strengths. At $T_e/T_i = 1$, the merging height is independent of the field strength. For $T_e/T_i > 1$ the height decreases with increasing field strength and for $T_e/T_i < 1$ the reverse is true. (From Pneuman, Solanki, and Stenflo, 1986.)

Figure 4 also points up a subtlety of parametric modeling. Note that the tube with the greatest field strength shows the least spreading, in apparent contravention of relation (1). The resolution of the problem lies in recognizing what is held constant in the parametric series. Since it is desired to enforce horizontal total pressure balance at the base across the entire parameter range, it becomes necessary to reduce the base density (a free parameter of the calculation) to compensate for the higher field strengths and for the increase in the internal temperature due to the applied heating. The density profile at all higher levels is therefore affected, and the net internal gas pressure enhancement is accordingly diminished. In short, increasing the temperature in a sequence of models need not increase the internal pressure to the degree one might first suppose, depending upon what else is held constant.

A second parametric study aimed at elucidating heating effects utilizes a numerical technique (Steiner, Pneuman, and Stenflo, 1986) to obtain full magnetostatic solutions for flux tubes bounded by a current sheet (Steiner and Pizzo, in progress). A horizontally uniform temperature increase of arbitrary magnitude and vertical scale is introduced above some $z = z_c$ in the model tubes to simulate the effects of heating in the upper layers. Preliminary results indicate that temperature enhancements of several thousand degrees occurring within several hundred kilometers of the $\tau_c = 1$ level in the undisturbed photosphere are needed to produce a major change in the spreading rate. It is not at all clear that heating of this magnitude can be supported by the observations. The models suggest, however, that the optical and magnetic signatures may still be seriously affected even if heating does not change the overall shape of the tube very much. What happens is that the increase in opacity stemming from the elevated temperatures and densities shifts the surfaces of constant τ higher up in the tube, where the magnetic field begins to fan out. Hence, the observed properties may be altered perceptibly, leading to erroneous interpretations.

Parametric studies such as these are illuminating and instructive, but their many simplifications restrict their utility. Most onerous are those associated with the neglect of energy balance. It is to be expected that radiation, conduction, and wave transport effects should impose limits on the amount and location of heating, and they must therefore be included in any realistic physical model. Further progress in this area thus awaits the application of more sophisticated treatments that take the energy transport and force balance into account self-consistently (e.g., Deinzer *et al.*, 1984a,b).

In this context, we return to the question concerning wave heating in a spreading magnetic field. Owing to formidable computational problems, theoretical efforts to date (see the review by Thomas, 1985, and the references therein) have included the influence of the magnetic field upon the propagation and dissipation of waves in only the simplest ways. Allowance is made for the variation of field strength along the tube, but the curvature in the field lines is neglected. This is perhaps justifiable in the deep photosphere but clearly breaks down in the upper layers. Neglect of the field spreading eliminates an important mode-coupling mechanism and may result in serious underestimation of the role played by fast-mode waves.

In a similar vein, we note that spreading is an inherently differential effect and that wave heating effects might be quite inhomogeneous. Typically, the field intensity along the axis exceeds that at the edges in the upper layers of the flux tube models, the difference increasing with the spreading. If the density is relatively stratified, lower field intensity at the edge implies a lower alfven speed there. This raises the possibility of differential heating, as waves may be refracted into regions of low relative alfven speed under certain conditions (e.g. Habbal, Leer, and Holzer, 1979). Furthermore, the low field strengths at the edges of flaring structures make them locally more susceptible to the effects of gas pressure forces due to any such heating. Therefore, it is conceivable that a highly inhomogeneous structure could exist in the upper layers -- a cool, concentrated, nearly vertical core surrounded by a warm, diffuse, predominantly horizontal fringe. Such a structure would only be revealed by high resolution observations, and, even then, proper analysis of the spectroscopic data might be complicated by the line-of-sight inhomogeneities.

Thus, the feedback between heating, field spreading, and observational properties virtually guarantees that improved understanding of the wave processes occurring in rapidly flaring flux tubes will lead to interesting new perspectives on the state of small scale erupted flux on the solar surface.

V. THREE-DIMENSIONAL MAGNETIC STRUCTURE

Thus far, we have been treating emerged magnetic flux concentrations as isolated phenomena, i.e. with little regard for their interaction with the surrounding magnetic medium. For many solar features, particularly sunspot groups, this conceptualization is overly simplistic and obviously inadequate. While some 3-D aspects of the network structure, for example, may be approximated with a 2-D arcade configuration (e.g. Gabriel, 1976; Deinzer *et al.*, 1984a,b; Jones, 1985), it is to be expected that tension forces should play an important role in the equilibrium force balance of 3-D structures down into the photosphere and that this modified state should be reflected in the thermodynamic properties. Unfortunately, computational difficulties have long stood in the way of quantitative magnetostatic models of collections of flux tubes in realistic 3-D geometries, and only purely potential models have been available to study more complex and therefore more interesting structures (e.g. Anzer and Galloway, 1983). While such models may, in some instances, provide a reasonable approximation to the magnetic structure of the nearly force-free upper layers, on a practical basis they incorporate into their boundary conditions information taken from deeper layers, where thermodynamic effects are non-negligible. Furthermore, even in the upper layers, potential models neglect tension forces associated with field-aligned currents stemming from footprint displacements, for example.

Recently, a methodology has been worked out making it feasible to obtain 3-D magnetostatic solutions with surprising ease (Low, 1985). The power of the technique lies in its mathematical proximity to standard boundary value problems and in the computational tractability accruing from longstanding practical experience with these methods. It is able to include simultaneously the effects of both field-aligned and drift currents in a realistic, though not completely general way. The weakness in the approach is that it hinges upon an assumption that is of dubious validity in the real solar atmosphere and that the parameterization used to construct the individual examples is convolved and obscure. (Explication of the technique is beyond the scope of this review, and the reader is referred to the original work for full details.) What is important for our purposes, however, is that the formulation -- despite its shortcomings -- provides an avenue for tackling for the first time some intriguing questions concerning the influence of bipolarity on flux tube structure. Is, for example, the spreading of flux tubes with height changed in any substantial way when they are in the form of loops tightly connected to the solar surface? What is the nature of the magnetic field topology in the upper layers of a complex spot group? What are the properties of the associated magnetograph signal, especially for structures at and below the resolution limit? All these questions and more could be addressed if the requisite modeling were pursued vigorously; it is virgin territory waiting to be explored.

SUMMARY

We have considered how the interplay between magnetic and gas pressure forces regulates the spreading of simple magnetic flux concentrations with height above the solar surface. We have suggested that the magnetic structure in the center of large sunspots provides a simple observational test of the basic physical concepts and have discussed some theoretical and observational intricacies associated with small magnetic features. In addition, we have identified theoretical questions concerning wave heating in flux tubes and 3-D effects in erupted active region groups that need to be addressed if proper advantage is to be taken of the high resolution observations hopefully to be obtained in the future.

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