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MAGNETIC FIELD STRUCTURING

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ABSTRACT

A host of instruments onboard SOHO have cast new light on the generation of the magnetic field in the solar interior, on its evolution at the solar surface and in particular on its manifestations in the solar atmosphere. Thus it is now clear that the magnetic field plays a dominant role in structuring and heating the gas located above the solar photosphere. It also influences photospheric and subphotospheric layers, but to a lesser extent.

On the other hand, the distribution and structure of the magnetic field is itself dictated by processes that take place at or below the solar surface. This includes the influence of convection and the stability and buoyancy of the flux rope that erupts through the solar surface.

Properties of the solar magnetic field, its structure as well as the structuring caused by it are reviewed. Particular emphasis is placed on results obtained by or related to the SOHO mission.

1. INTRODUCTION

The title of this review, magnetic field structuring, may signify two different things, namely the structuring of the magnetic field (caused by processes such as convection) and the structuring of the gas caused by the magnetic field.

Both these aspects of magnetic field structuring are reviewed here, beginning with the structuring of the magnetic field in Sect. 2. In Sect. 3 the structure introduced into the gas (or modified) by the magnetic field is discussed. This structure can introduce a spatial distribution in the brightness or the properties of the emitted radiation and thus becomes (at least partly) detectable. Finally, in Sect. 4 some concluding remarks are made.

2. STRUCTURE OF THE MAGNETIC FIELD

2.1. Subsurface Structure

The structuring of the magnetic field starts already in the overshoot layer below the convection zone, where the main solar dynamo is thought to be located. Data obtained by the Michelson Doppler Interferometer (MDI) onboard the Solar and Heliospheric Observatory (SOHO) support this assumption. According to them the rotation profile of the solar interior exhibits a strong radial shear at both low and high latitudes at this depth (Kosovichev et al. 1997). A shear between the differentially rotating convective envelope and the rigidly rotating radiative interior is required by modern dynamo theories (Schmitt 1993, Schüssler 1993).

Comparison of observed latitudes and other properties of active regions with model predictions has revealed that the strength of the toroidal magnetic field at the base of the convection zone needs to be around 1–$2 \cdot 10^5$ G (D'Silva & Choudhury 1992, Fan et al. 1993, Schüssler et al. 1994, Caligari et al. 1995). This is an order of magnitude larger than expected from equipartition of magnetic with convective energy density. Such an equipartition implies $B_{\mathrm{eq}} = \sqrt{4\pi\rho}\, v$, where ρ is the gas density and v the velocity.)

As a consequence the magnetic field is expected to be concentrated into flux tubes, i.e. bundles of approximately mutually parallel field lines, which become unstable to buoyancy and rise toward the solar surface. As the flux tubes rise through the convection zone their field strength also decreases rapidly. During their passage through the solar convection zone the originally large flux tubes are also shredded, thus breaking into many smaller flux tubes. This breaking up of the tubes could be responsible for much of the complex structure of active regions, which are composed of myriads of flux tubes of different sizes (Zwaan 1978, cf. Moreno Insertis et al. 1995).

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2.2. Photosphere

When the magnetic field finally appears at the solar surface it is highly filamented and is roughly at equipartition with the convective motions (i.e. the magnetic and kinetic energy densities are the same), which corresponds to 200–400 G at the surface (Brants 1985, Lites et al. 1998).

The filamentation and concentration of the field increase further after emergence. The field becomes stronger, reaching values of roughly 1500 G at the solar surface, which is again an order of magnitude larger than the equipartition field strength (Stenflo 1973, Rüedi et al. 1992, Rabin 1992). The concentrated magnetic field covers only approximately 1% of the solar surface.

There are two main physical processes which are responsible for this extreme filamentation of the field and its concentration. The first of these is the expulsion of magnetic flux from within convective cells to their boundaries.

Since the magnetic field is frozen into the solar plasma, field lines are dragged along by a convective flow and collected at the boundaries between convection cells. At the solar surface the strong horizontal flows of the granules drag along the vertical field lines until they land in the intergranular lanes (Parker 1963, Weiss 1966, Hurlburt and Toomre 1988, Stein and Nordlund 1989).

This process, since it is driven by convective flows, cannot increase the magnetic energy density significantly above the energy density of the flows (i.e. B remains $\approx B_{\mathrm{eq}}$). At this point, however, an instability sets in at the solar surface. The gas enclosed by the magnetic field lines in the downflow lanes is thermally insulated from its surroundings and cools through radiation. In the process it becomes denser and begins to flow down. This lowers the gas pressure near the solar surface within the magnetic patch, leading to a horizontal imbalance of pressure with the gas in the surroundings. Consequently, a horizontal inward-directed flow results which drags the field lines along with it, concentrating them further until the magnetic pressure balances the external gas pressure (e.g., Parker 1978, Spruit 1979, Venkatakrishnan 1986, cf. Schüssler 1990, Thomas 1990).

The resulting entity has a kG field strength in the photosphere and is generally referred to as a flux tube or a magnetic element. The flux expulsion and convective collapse processes have been successfully simulated in 2-D, starting from a homogeneous vertical field (Grossmann-Doerth et al. 1998).

The horizontal flows of the granules do not, however, efficiently expell *horizontal* field into the downflow lanes, so that horizontal fields can survive over granules at (sub-) equipartition field strengths. This combination of weak horizontal fields and strong vertical fields has been observed by Lites et al. (1998) and is also obtained from simulations (Gadun et al. 1999).

The newest simulations also show the constant transformation of the weak horizontal field into kG vertical flux tubes and vice versa (Gadun et al. 1999). A weak horizontal field is concentrated when a granule fragments, thus forming a new downflow lane at a location containing a horizontal field (see Fig. 1). Granule fragmentation is a standard phenomenon characterizing the evolution of larger granules (e.g., Mehltretter 1978, Title et al. 1989, Ploner et al. 1999). The downflowing gas in the newly-formed lane drags the horizontal field lines with it, producing a cusp in the field. The lane now contains concentrated vertical field lines of opposite polarity. A part of this vertical field reconnects below the surface with field that is previously present there. In general the field below the surface is not symmetrically distributed with respect to the field being pushed down from above. The same applies to the convective motions there. Hence one of the polarities of the finger of vertical field is more strongly eroded away after reconnection than the other. The remaining polarity survives as a more or less vertical flux tube. The process is illustrated in Fig. 1 with the help of 6 snapshots taken from the simulations of Gadun et al. (1999). In regions with mixed magnetic polarities this could be the main path to the formation of flux tubes. In contrast to the standard convective collapse mechanism (i.e., starting from a unipolar vertical field) a non-zero magnetic diffusivity and resistivity are important for the success of this process.

According to the simulations the flux tubes survive for between 10 mins and over an hour each before being destroyed, usually through the reconnection of their field lines with weaker fields in their surroundings. The formation and destruction processes take only a few minutes each. Since individual flux tubes are very difficult to resolve spatially with current instruments, we rely on simulations to reveal lifetimes of the flux tubes and the details of their formation and destruction.

Hence, a flux tube survives considerably longer than the granules surrounding it, which live for 5–10 minutes. In the course of their lifetimes granules expand or contract and generally move around. These changes in the granulation push the flux tubes horizontally, squeeze them and twist them (the latter due to the vortical motion of the downflows around flux tubes; see Schüssler 1984).

Each type of motion imposed on the flux tube may excite one or more wave modes. If the excitation happens above the relevant cutoff frequency the wave propagates along the flux tube and dissipates at a greater height through one of a variety of different possible processes. The excitation of waves in flux tubes has been reviewed by Roberts & Ulmschneider (1997). Calculations of the excitation of various waves by footpoint motions of flux tubes and slabs have been carried out by Choudhuri et al. (1992). Similar calculations under conditions of coronal loops have been presented by Murawski & Roberts (1993) and Berghmans & De Bruyne (1995). Propagating shocks (wave pulses) are also naturally excited in the 2-D simulations of flux slabs of Steiner et al. (1996, 1998).

The horizontal motion of the flux tubes has different components. One part is driven by the granulation, while on a larger scale mesogranulation and in particular supergranulation are the main drivers (Title et al. 1988). The field thus collects at the boundaries of supergranules and then moves along the boundaries until it reaches the intersection of multiple supergran-

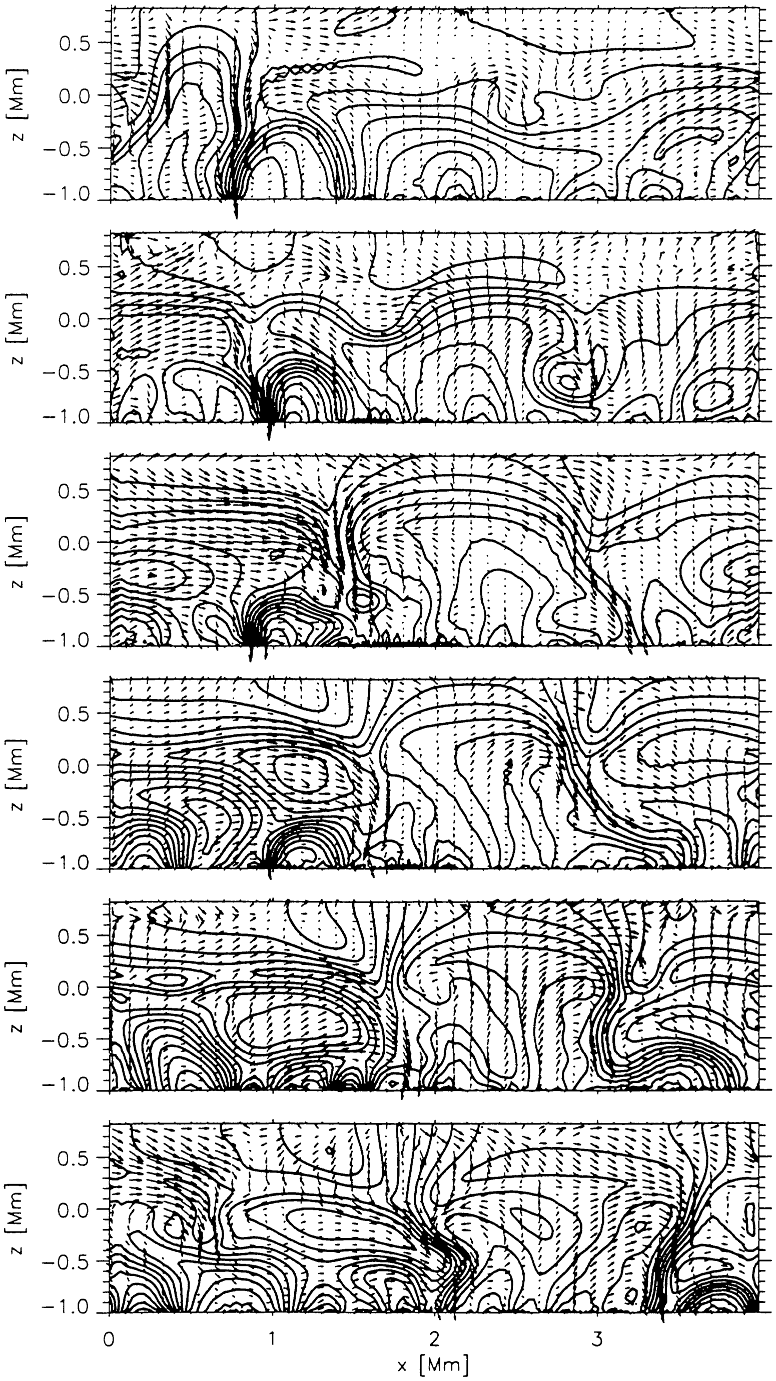

Figure 1. Snapshots of flows (arrows) and magnetic field lines (thick solid curves) at 6 different times picked from the 2-D simulation of Gadun et al. (1999). Height relative to the mean solar surface increases along the vertical axis, while the horizontal axis represents horizontal distance on the sun. Note the destruction of a flux tube at $x \approx 800$ *km in the first two frames and the subsequent formation of two new flux tubes at* $x \approx 1500$*-2000 km and 3000 km. The time step between consequtive frames is 4 mins.*

ules. Hagenaar et al. (1999) argue that this process resembles a random walk and can be described by a diffusion model. The random motion of the flux tubes caused by the convection has important ramifications at coronal heights (see Sect. 2.3).

The driving of magnetic flux to the boundaries of supergranules is so efficient (see Meyer et al. 1979, Schmidt et al. 1985) that at any given time almost all of the flux tubes in the quiet sun are clustered at the supergranule boundaries, forming the so-called magnetic network.

If we neglect spatial scales below 0.5″ the network scale is the dominant one seen. Only at higher resolution can the individual flux tubes and their location in the intergranular lanes be resolved (Keller 1992), although the properties of flux tubes can also be deduced from spectropolarimetric observations through the application of appropriate diagnostics (e.g., Briand & Solanki 1995, Bellot Rubio et al. 1997, Frutiger & Solanki 1998).

Is the magnetic field structured also at scales below that of individual flux tubes? This question can be easily answered in the affirmative for the largest flux tubes, the sunspots. They are primarily divided into an inner, dark umbra and an outer, less dark penumbra with the magnetic field tending to be more homogeneous than the brightness structures. Nevertheless, it decreases from 2500–3000 G at the centre of a sunspot to 700 G at its edge. In addition, both the umbra and the penumbra show structure down to the limit of spatial resolution (0.2–0.3″; Schmidt et al. 1992, Title et al. 1993, Sobotka et al. 1997a, b) and possibly also well below this spatial scale (Sánchez Almeida 1998). The field is most inhomogeneous in the penumbra, with almost horizontal strands of radially outward-directed field (flux tubes) alternating with strands of more inclined field.

For the small flux tubes, the magnetic elements, there is no direct evidence for internal structure, although they may in principle be composed of even smaller entities, as has been argued by Sánchez Almeida (1998).

2.3. Chromosphere and Corona

The intermittancy of the field decreases in the chromosphere, as the individual flux tubes expand with height until they merge with their neighbours. They consequently fill most of the upper chromosphere with field (Harvey & Hall 1971, Rüedi et al. 1995, Penn & Kuhn 1995). The almost horizontal field due to the expanding flux tubes in the chromosphere is often referred to as a magnetic canopy (e.g., Giovanelli 1980, Jones & Giovanelli 1983, Solanki & Steiner 1990).

Above the height at which neighbouring flux tubes merge the field cannot expand unhindered anymore and the field strength becomes nearly independent of height. The gas pressure and density continue to drop exponentially with height, however, so that $B^2/8\pi \gg p$ above the middle chromosphere. [1] Here p is the gas pressure. As a consequence the magnetic field dominates energetically over the gas above this height.

Although the field becomes increasingly homogeneous in strength with height it does become increasingly *in*homogeneous in direction. In the photosphere most of the flux tubes are fairly vertical. Due to the large magnetic pressure and the requirement of pressure balance with the field-free surroundings, the flux tubes are strongly evacuated. This evacuation also makes them buoyant. Since one end is anchored below the solar surface (e.g., in the overshoot layer below the convection zone) the buoyancy forces them to be vertical. The interaction with the granulation described in Sect. 2.2 also ensures that the concentrated fields are vertical. They are perturbed from the rest position by the buffetting through neighbouring granules and the presence of other flux tubes in the vicinity. These effects in general incline the flux tubes by less than 10–20° to the vertical in the photosphere.

In the central chromosphere, at the layer at which the canopy is located, the field is to a large extent horizontal, except within the network elements and in active regions.

If the magnetic field in a sufficiently large region is unipolar then the field becomes largely vertical again in the upper chromosphere and lower corona.

In the upper chromosphere and corona of mixed polarity regions a significant horizontal component of the field is produced by the fact that many field lines return to a neighbouring part of the solar surface having opposite magnetic polarity. At this level magnetic tension (curvature forces) and connectivity play the dominant role in structuring the field, whereas the buoyancy becomes unimportant since the magnetic pressure now dominates over the gas pressure.

As mentioned above, the magnetic field lines point in all possible directions at coronal heights. Then, depending on the location and the history of their footpoints, neighbouring field lines need not be even approximately parallel to each other, forming so-called tangential discontinuities, or current sheets (e.g., Parker 1983a, b, 1987, 1993). Current sheets play a central role in the dissipation of energy and thus in the heating of the corona. For example, they are a necessary prerequisite for reconnection of magnetic field lines.

Field lines crossing each other may be produced either when the axes of emergence of two bipoles are not parallel to each other or through the movements of the footpoints of the loops relative to each other due to the convection (field-line braiding, see Fig. 2). For example, the supergranulation drives elements of intranetwork field, which emerge in the interiors of the supergranule cells, to their boundaries (e.g. Zirin 1987). When these meet the field of the network tangential discontinuities may be formed.

Another way in which tangential discontinuities can be built up is through the twisting of flux tubes and thus of the associated loops. The field lines of two parallel loops, of which one or both are twisted, will in general be tangentially discontinuous if they are bounded by current sheets. Similarly, Alfvénic disturbances (e.g., torsional and kink waves or pulses) can also lead to transient current sheets.

Note that in the corona the field strength is not completely homogeneous, inspite of the negligible gas pressure relative to the magnetic pressure. Consider

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[1] This is true except near the outermost part of the flux tube; i.e. over the centres of supergranule cells; cf. Solanki & Steiner 1990.

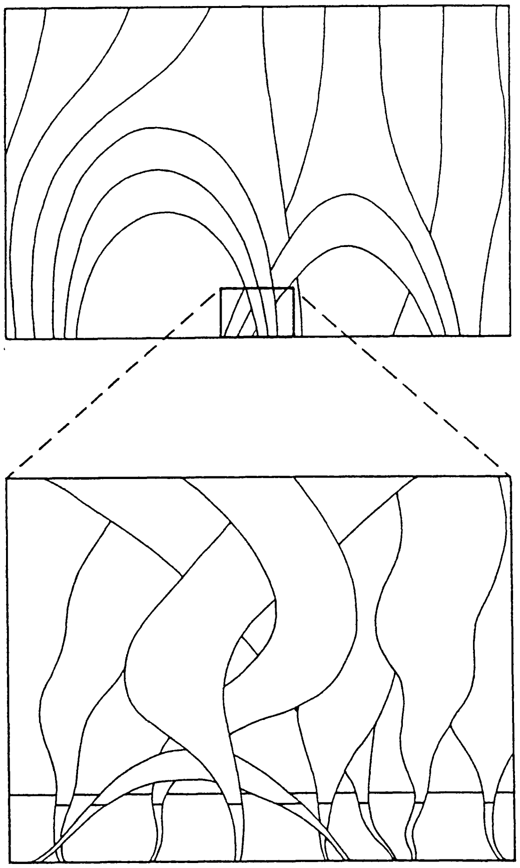

Figure 2. A simple sketch of the magnetic structure in the solar atmosphere. The solid curves are sample field lines. The upper frame shows the structure at a scale of, e.g., an active region. The lower frame is a blow-up of the little box at the centre of the upper frame. The plotted field lines outline individual flux tubes. Note how these are braided around each other. The horizontal line indicates the solar surface.

the field lines forming a loop. To first order the trajectory of such a field line is circular, so that the total height reached by the loop is approximately half the foot-point separation (see Peres 1999). Hence the larger the loop the higher into the atmosphere it reaches. In general, loops of many different lengths are present in a given part of the solar atmosphere. As we go up in height only the increasingly larger loops, connecting regions lying further apart survive. The magnetic field thus becomes increasingly homogeneous in strength with height. The small scale inhomogeneities disappear already at relatively small heights, and as we move up this becomes true also for larger and larger scales.

2.4. Solar wind and the heliosphere

As the height increases further an additional player, the solar wind, enters the scene. The kinetic energy density, $\rho v^2/2$, of the wind increases with distance from the solar surface and eventually overtakes the magnetic energy density, $B^2/8\pi$. Beyond this Alfvén radius the magnetic field is structured by the solar wind. On at least a large scale the properties of the solar wind themselves depend on the magnetic topology in the chromosphere and corona, however (see Sect. 3.3).

At different phases of the solar cycle the magnetic field in the heliosphere emanates from different parts of the solar surface. At solar minimum the magnetic field is of mixed polarity at the supergranulation scale over most of the solar surface. It thus forms a very high order multipole (of order 100) and falls off extremely rapidly with radial distance. Only over the poles does one magnetic polarity dominate over the other (Babcock & Babcock 1955, Babcock 1959). The large-scale unipolar field from these regions expands superradially (DeForest et al. 1997, Koutchmy & Bocchialini 1998) and thus fills a dominant part of the heliosphere, also at lower latitudes. At a distance of around 1 AU the radial component of the field has become almost independent of latitude (Balogh et al. 1995).

In addition to this large-scale structure of the magnetic field in the heliosphere there are also small-scale fluctuations, detectable using in-situ measurements. These fluctuations differ in the fast and slow solar winds. In the fast wind they are mainly Alfvénic (i.e. incompressible and associated with a change in direction of the magnetic field) and are stronger than in the slow solar wind. The frequency spectrum of the fluctuations is very broad, reaching from the solar rotation rate to the gyrofrequency (approximately 1 Hz). The shape of the spectrum corresponds to a piecewise power law and is reminiscent of turbulence.

In the slow solar wind the disturbances are compressible, with characteristics closer to those of acoustic waves or pulses. The source of the turbulence is not understood, although the short frequency, mesoscale fluctuations are often identified with the network flux tubes (due to solar rotation a spacecraft samples plasma from different locations on the sun as time goes by), while the longer frequencies (respectively larger scales) are possibly built up in the wind itself (e.g., through velocity shear). The small-scale structure of the field in the heliosphere has been reviewed by, e.g., Marsch (1991), Tu & Marsch (1995) and Goldstein et al. (1996, 1997).

3. STRUCTURING OF THE GAS BY THE MAGNETIC FIELD

The magnetic field is the dominant structuring agent in the solar atmosphere. It is responsible for such diverse phenomena as sunspots, faculae, chromospheric and transition region network and plage, filaments and prominences, spicules and macrospicules, explosive events, blinkers and flares (including the nano and micro variety), coronal loops and streamers, coronal holes, coronal mass ejections, corotating interaction regions, the first-ionization-potential effect and much more. In general, the importance of the magnetic field as a structuring agent of the gas increases with height as the plasma β decreases.

3.1. Photosphere

The most striking features seen in white light are dark sunspots and bright faculae, both of which are magnetic in origin, being composed of large and small flux tubes, respectively.

The influence of the magnetic field on the brightness at visible wavelengths has a combination of causes. A sufficiently strong magnetic field suppresses convection, thus allowing less energy to emerge from below, which leads to a cooling. Due to this process the energy flux is diverted away from the magnetic feature and is distributed throughout the convection zone (Spruit 1982, cf. Spruit 1999).

Conversely, the strong magnetic field evacuates a flux tube and allows energy to enter it from the sides, thus providing excess heating. The evacuation also locally increases the surface area over which radiation can escape (e.g., Spruit 1976, Deinzer et al. 1984, Grossmann-Doerth et al. 1989).

Thus the main thermal structuring in the photospheric layers due to the magnetic field is a result of the diversion of the energy flux it causes. The thermal influence of the field is strongest in the interior of the magnetic flux tubes, although to some extent the surrounding convection is also affected. In areas with large concentrations of flux tubes the granulation clearly appears abnormal (e.g., Dunn & Zirker 1973, Muller et al. 1989, Brandt & Solanki 1990, Title et al. 1992).

By suppressing convection the magnetic field automatically also introduces structure into the photospheric velocity field. At the same time it locally and globally suppresses and in some cases absorbs solar p-modes (Braun et al. 1987, 1988, Title et al. 1992, Bogdan et al. 1993). On the other hand, the flux tubes are themselves observed to support a variety of oscillations and waves (Giovanelli et al. 1978, Lites 1992, Volkmer et al. 1995, Ulrich 1996, Rüedi et al. 1998).

3.2. Chromosphere

The network in the quiet sun and plages in active regions dominate the radiation sensitive to the temperature in the chromosphere. This includes the continuum below 1700 Å, the Ca II H_2 and K_2 peaks, EUV emission lines of neutral and singly ionized species, etc.

The relative brightness of the network implies that the chromosphere is hotter within a magnetic flux tube than outside it. It has even been argued that the chromospheric temperature rise is present inside the flux tubes only (e.g., Ayres et al. 1986, Solanki et al. 1994, Carlsson & Stein 1995). It is generally thought it is the wave modes supported by the magnetic field that are responsible for the enhanced brightness of the magnetic features in the chromosphere (e.g., Herbold et al. 1985, Fawzy et al. 1998). In general, chromospheric brightness (e.g. in Ca II K) increases with increasing magnetic flux in a given solar surface area (e.g., Schrijver et al. 1989). Nevertheless, the chromospheric heating is not simply proportional to the strength of the field and the amount of magnetic flux. For example, sunspot umbrae, which have the strongest magnetic field in the chromosphere exhibit little chromospheric emission compared to plages, i.e., more loosely packed ensembles of small flux tubes (Lites & Skumanich 1982, Gurman 1993). The temperature above umbrae begins to rise at greater heights than in small flux tubes (or even the "average quiet sun", Avrett 1981, Maltby et al. 1986). The likely explanation is that small isolated flux tubes, which are unshielded against the granular buffetting are likely to harbour larger amplitude waves than the well-shielded inner part of a sunspot.

The high contrast between network and intranetwork at transition-region temperatures below 5×10^5 K was first explained by Gabriel (1976). A central feature in his model is the expansion of the field with height. As energy from the hot corona is conducted down it gets concentrated, along with the field lines, to the location of the magentic network. This "standard model" has come under pressure from two sides.

The first is that the field is now known to fill most of the available space already in the middle chromosphere (Jones & Giovanelli 1983, Solanki & Steiner 1990) instead of gradually expanding outwards over a larger height range, encompassing the transition region. This is probably not a serious problem for Gabriel's model, since the field is by far not horizontally homogeneous at these heights. Each element of the network is thought to be composed of a number of flux tubes. The outer ones expand more rapidly than the inner ones, since the former are unhampered by neighbouring fields, at least on one side, whereas the latter are caged in by their neighbouring flux tubes. Only at much greater heights have all expanded by equal amounts, so that the field is relatively homogeneous.

This structure of the field also helps explain the localized network in the lower chromosphere, where conduction from the corona is unimportant. Fawzy et al. (1998) have shown that for a given wave energy flux within a magnetic tube the chromospheric temperature depends very sensitively on the expansion rate of the flux tube: a tube that expands less rapidly is more strongly heated. These calculations have, so far, not taken radiative damping into account, however.

Another, more serious challenge has come from Dowdy et al. (1986), who point out that Gabriel's model is restricted to monopolar fields, while most of the solar surface has a "salt and pepper" distribution of the two polarities. They argue that the magnetic field in the quiet sun must dominantly form short loops connecting nearby opposite polarities. The cooler transition region is found in these loops, while the hotter transition region is present in open funnels, just as in Gabriel's original model.

One problem with their interpretation is that the magnetogram they use to illustrate their model is very sensitive and also appears to show the intranetwork field. This magnetic component indeed exhibits both polarities at a small scale and is certainly composed of many small loops. It is, however, not concentrated in the network, but throughout the supergranule cell. In addition, even loops connecting two opposite polarity elements of the network are just as likely to cross a supergranule as to follow its boundary. The question as to why these loops do not leed to a more or less homogeneous brightness over the whole supergranule then arises. One answer could be projection effects. A given vertical ray passes through more gas of a particular loop above a footpoint, due to the long line-of-sight, than across the loop top. Since there is a stronger concentration of magnetic flux at the supergranule boundaries, more loop footpoints are concentrated there, leading to a brightening. Unfortunately, so far many of the consequences of the idea of Dowdy et al. (1986) have not been studied quantitatively.

The presence of transition region material along field lines that do not connect with the corona implies that this material needs to be actively heated.

One possibility is that the heating is due to energy release via magnetic reconnection. This can happen either through the appearance of fresh flux, due to flux (e.g., intranetwork field) being dragged towards the network by the supergranular flow, or due to the twisting of individual magnetic elements. In the first two cases reconnection is expected to take place at the edges of each network element (containing multiple flux tubes). According to Schrijver et al. (1998) these are important for sources of reconnection. This is indeed the location where most explosive events are seen (Dere et al. 1991, Zhang et al. 1997) which are thought to be the signatures of magnetic reconnection (Innes et al. 1997).

If, however, the reconnection is between field lines belonging to different flux tubes of the same network element (due, e.g., to *strong* twisting of the field of each flux tube) the reconnection and thus the heating is expected to be concentrated inside a network element. Note that both flux-tube braiding due to footpoint motions and the build-up of high twists work best in closed-field regions. In open field regions the twist can unravel by giving rise to a torstional Alfvén wave.

The similarity of the chromospheric and transition-region brightness in open-field regions (e.g., coronal holes, see Sect. 3.3) as in closed-field regions raises some questions regarding the structure of the transition region, in particular the role of the loops proposed by Dowdy et al. (1986). However, there is a need to investigate if the network structure is really the same in coronal holes as in the normal quiet sun in order to settle this point.

3.3. Corona and solar wind

The magnetic field is obviously important for producing the large-scale structure of the corona, such as loops, helmet streamers and coronal holes (Altschuler et al. 1977, Levine et al. 1977).

If the magnetic flux in both polarities is approximately equal in an area corresponding to the size of a few supergranules then the field will mainly be closed, i.e. dominated by loops of various lengths and orientations, which harbour gas at different temperatures.

If, however, there is a sufficient relative amount of excess flux in one polarity over a sufficiently large area then a coronal hole results (e.g., Harvey & Sheeley 1979, Harvey et al. 1985). Except near the boundary of the unipolar region (Bohlin & Sheeley 1978) this excess flux can only connect to fields on distant parts of the sun over extremely large loops, which can be pulled open, e.g., by the solar wind relatively easily, leading to open field lines.

The density of flux (or magnetic filling factor) does not appear to be of particular relevance for the formation of a coronal hole (as long as it is below that of an active region). The spatially averaged field strength in a coronal hole does not differ from that in the average quiet sun by more than a factor of 2 (Zhang et al. 1997). Of greater importance is the ratio between the amount of flux in the two polarities. But even this is unclear and may vary considerably from hole to hole or within a hole (Harvey & Sheeley 1979). According to Giovanelli (1982) at least 10% of the total flux is always of opposite polarity in any unipolar region (cf. Zhang et al. 1997). This minimum fraction of opposite polarity flux is expected to depend on the polarimetric sensitivity, steadily increasing as the polarimetric sensitivity increases, since the mixed polarity, but weak intranetwork field becomes increasingly prominent.

Wilhelm et al. (1998) have shown that coronal holes become readily visible at temperatures above 5×10^5 K. Thus at cooler transition-region temperatures the state of a coronal hole and of the normal quiet sun, as revealed through the radiances, are *almost* identical. If, as suggested by Dowdy et al. (1985), the transition region emission were to come from short loops this would require the dominance of mixed polarity field at small scales, so that there is an equal density of short loops as in the normal quiet sun.

How this can be achieved in a region in which only 10% of the total flux is in the minor polarity is at present unclear. There are basically four possibilities. 1. The model of Dowdy et al. (1985) is wrong and small loops harbour only a small fraction of the transition region gas. 2. The transition region is structured quite differently in coronal holes and the normal quiet sun (in which case it is unclear why the properties of the transition region are so similar in these two types of regions; note, however, that Huber et al. 1974 find that relative to the normal quiet sun the network in holes is reduced more strongly than the intranetwork). 3. There is far more flux in the minor polarity than has so far been detected, e.g., associated with intranetwork elements of the magnetic field. 4. The observations showing equal transition-region brightness in coronal holes and in the normal quiet sun may refer to holes with considerable opposite polarity flux. An investigation into transition region radiance as a function of "unipolarity" of the field would be useful.

The detailed fine-scale structure of the magnetic field also has an influence on the solar wind, or at least the fast solar wind. SUMER observations have shown that an outflow is best visible at the supergranule boundary, in particular at the vertices of such boundaries (Hassler et al. 1999). Note that Marsch & Tu (1997) had already earlier predicted a relationship between the solar wind and the network. The gas is obviously accelerated near the axes of the flux tubes, but little or not at all over the canopy. Whether this has got to do with the fact that only the field lines above the network are open, as Hassler et al. (1999) state, or with the specific mechanism accelerating the solar wind is not clear. For example, below coronal holes the argument of Hassler et al. (1999) needs to be considered with care, particularly if there really is a significant excess of one magnetic polarity. A difference between coronal holes and the quiet sun is shown clearly when more spectral lines are considered than just Ne VIII 770 Å analyzed by Hassler et al. (1999). At temperatures below roughly $2 \cdot 10^5$ K the dependence of the line shift on the brightness shows opposite signs in coronal holes and in the normal quiet sun (Stucki et al. 1999).

4. CONCLUSIONS

The aim of this review was to provide a flavour of the structure of the solar magnetic field and the structure that it produces in the gas, as revealed by the radiation arising at different heights and temperatures. For reasons of brevity and to avoid a simple listing up of phenomena I have concentrated on a restricted sample, thus neglecting many phenomena that are rlevant for the current subject.

Among the discussed topics there are many where we reach the limits of our knowledge and understanding rather quickly. Partly this is caused by a lack of physical understanding due to the complexity of the material, but partly the limitation is observational. A higher spatial resolution and improved spectroscopy would be of great use at all observed wavelengths. In the transition region and corona the limitations of the available magnetic field diagnostics are probably the main stumbling block to a better understanding. In this sense the approach taken by Raouafi et al. (1999), who used the instrumental peculiarities of SUMER to observe the scattering polarisation and possibly the Hanle effect, is interesting. The importance of incorporating robust polarimetric capabilities into future EUV spectrographs cannot be stressed sufficiently.

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