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Photospheric Magnetic Field: Quiet Sun

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Abstract. The solar photosphere is the layer in which the magnetic field has been most reliably and most often measured. Zeeman- and Hanle-effect based probes have revealed many details of a rich variety of structures and dynamic processes, but the number of open and debated questions has remained large. The magnetic field in the quiet Sun has maintained a particularly large number of secrets and has been a topic of a particularly lively debate as new observations and analysis techniques have revealed new and often unexpected aspects of its organization, physical structure and origin.

1. Introduction

The magnetic field in the photosphere is organized in different types of structures. The most clearly visible and most directly measurable are the magnetic flux tubes or (crinkled) flux sheets, agglomerations of magnetic field lines, most of which are directed roughly vertically. These features are approximately in pressure balance with their surroundings. Due to the decrease in gas pressure with height, the magnetic pressure, i.e. square of the field strength, must also decrease. The conservation of magnetic flux, applied to a unipolar feature with decreasing field strength requires the cross-section of the magnetic feature to expand with height, giving it the exponential funnel-like appearance seen in Fig. 1 (the boundaries or walls of the flux tube are the curved nearly vertical lines). The basic properties of magnetic flux tubes were worked out by Stenflo (1973), Spruit (1976), Parker (1978) and others. See Zwaan (1978, 1987) for early reviews. Maybe the most important contribution to our knowledge of these magnetic flux concentrations came from Stenflo (1973). He showed most clearly and unequivocally what earlier studies (e.g., Sheeley 1967; Beckers & Schröter 1968; Howard & Stenflo 1972; Frazier & Stenflo 1972) had hinted at, namely that the true strength of the magnetic field in these features is 1-2 kG in photospheric layers. This result was found to be valid for both active region plage and for quiet Sun (network) fields, so that the intrinsic field strength was found to be orders of magnitude stronger than the pixel averaged field strength deduced from magnetograms (more on Jan Stenflo and his achievements can be found in the appendix to this paper and in the papers by Stenflo 1993, 2008). In the follow-up, Spruit (1976) discussed the forces confining such a strong field and its consequences for the brightness of a magnetic flux concentration. Later, Parker (1978) provided a mechanism which could explain the formation of such flux tubes (the convective collapse; cf. e.g., Webb & Roberts 1978; Spruit 1979; Grossmann-Doerth, Schüssler, & Steiner 1998).

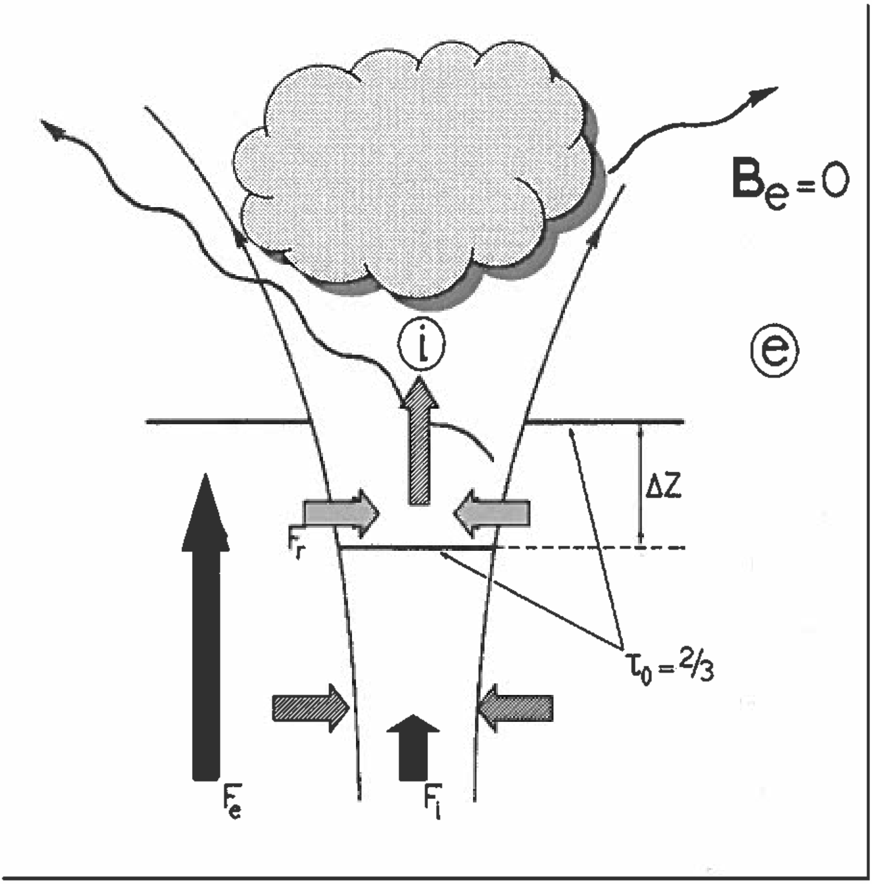

Figure 1. Sketch of a magnetic flux tube and the processes leading to excess radiation emerging from it in the photosphere and the chromosphere. See text for details. Adapted and extended from Zwaan (1978).

3-D MHD simulations have revealed that the classical view of flux tubes (symmetric, with smooth boundary current sheets) is very likely too simplistic. A sketch of the field lines resulting from the MHD simulations of Vögler et al. (2005) are shown in Fig. 2. Above the solar surface (the grey area near the center of the figure) the magnetic field lines do indeed form a structure that is very reminiscent of a flux sheet (something like an elongated flux tube). The field in the observable layers can indeed be well described in the thin-tube approximation extended to second order (Pneuman, Solanki, & Stenflo 1986; Ferriz-Mas & Schüssler 1989), as shown by a recent analysis by L. Yelles. However, even above the solar surface the presence of a number of return-flux field lines seen in Fig. 2 indicates that the magnetic structure is more complex than just a thin tube. Below the surface this complexity becomes far more evident and this particular flux sheet is found to begin to lose coherence already in the shallow interior (less than 500 km below the solar surface).

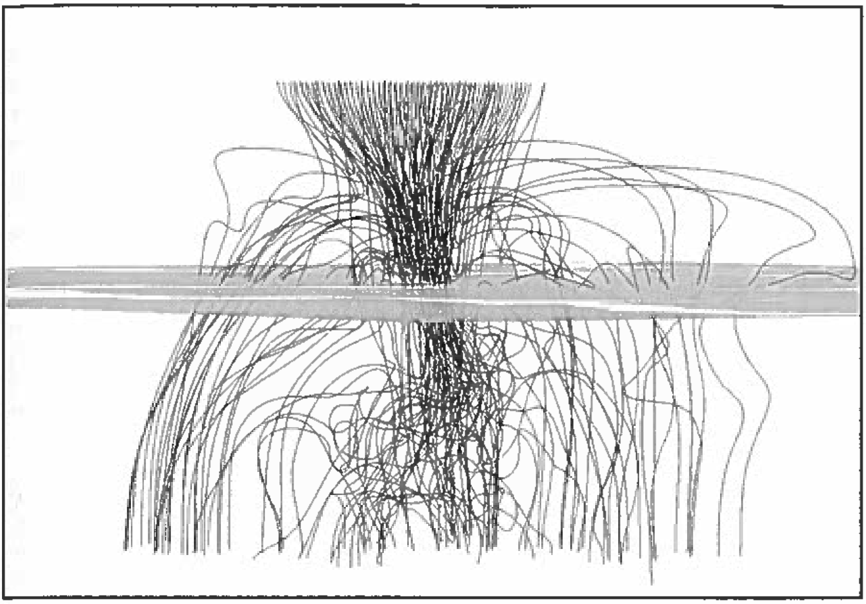

Figure 2. Magnetic field lines forming a magnetic flux concentration in an intergranular lane (seen in the direction parallel to the intergranular lane). Note how the field lines form a structure that looks remarkably like a flux sheet above the solar surface (the grey region near the center of the feature), but how this structure loses its identity below the solar surface.

Flux tubes dominate magnetic structure of active regions. Thus, sunspots are the largest isolated flux tubes at the solar surface (or alternatively they are a large ensemble of slender flux tubes that merge just below the solar surface, as has been proposed by Parker 1979a,b,c). Although sunspots as a whole are well resolved, uncovering their nature by observational means is not without challenge. For example, much of the physics deciding over the energy transport within spots takes place at very small scales, which are just as elusive in sunspots as in the quiet Sun and in some respects more so due to the low intensity and associated sensitivity to scattered light from brighter parts of the solar surface. Their theoretical study is just as demanding since numerical simulations have to cover a large range of spatial and temporal scales.

Magnetic features of different sizes (different amounts of magnetic flux per feature) differ surprisingly little in intrinsic field strength (averaged over the cross-section of the feature; Solanki & Schmidt 1993; Solanki et al. 1998), but their brightness changes very significantly. While large flux tubes, such as sunspots and pores are dark, small flux tubes are bright. Another interesting property is that the contrast of small scale features relative to the "field-free" surroundings increases with height, while that of sunspots decreases, which basically implies that the temperature gradient inside magnetic features (flux tubes) is smaller than in the comparatively field-free gas.

The brightness of magnetic features is determined by the interplay between energy transported by convection and by radiation. The dependence of the brightness or contrast on magnetic flux in the resolution element can be at least qualitatively understood by considering the sketch shown in Fig. 1, which has been adapted from a figure produced by Zwaan (1978). It shows a schematic magnetic flux tube (with the curved boundaries or side walls) passing through the solar surface (the thick horizontal lines; note that the solar surface is offset to deeper layers inside the flux tube due to its evacuation, which in turn is a consequence of the magnetic pressure). In the subphotosphere the magnetic field leads to a reduction in the efficiency of convection (heat blocking), indicated in Fig. 1 by the vertical (solid) arrows (internal vertical energy flux $F_i \ll F_e =$ external vertical energy flux). This is compensated by the lateral inflow of radiation into the flux tube (F_r) through the walls at a level lying above the internal $\tau = 1$ surface, but below the external $\tau = 1$ surface, as indicated by the horizontal (grey) arrows. For a strong field that almost completely blocks the internal convective transport, to first order the amount of heating depends on the ratio of the wall area to the area of the flux tube's cross section (although other factors, such as the properties of the surrounding gas also play a role; cf. Deinzer et al. 1984a,b; Vögler et al. 2005). If the flux tube is small (large wall area compared to the cross-section area), then the inflowing radiation can more than compensate the blocked vertical energy flux, leading to a positive contrast of the magnetic features. This simple model also, at least qualitatively, explains the center-to-limb behavior of the contrast, in particular the brightening seen towards the limb (Spruit 1976), as the hot walls become visible (indicated in Fig. 1 by the long wavy arrow leaving the right wall towards the upper left).

In large features, such as sunspots and pores, the influx of radiation is small compared to the blocked convective energy, since the area of the walls at the side of the magnetic feature is small compared to the cross-sectional area. This leads to a cooling.

In addition to the kG flux tubes dominating active regions and the network, magnetic fields also form other structures. These include canopies around sunspots (and to a lesser extent around smaller magnetic features as well, as revealed, e.g., by Hinode data), weaker flux tubes, small-scale Ω loops, U-loops and turbulent field. The work of Livingston & Harvey (1971, 1975) was instrumental in showing that there are magnetic entities in the photosphere with fluxes well below those found in prototypical flux tubes. Although such features are found everywhere in the photosphere, they are most typical for the quiet Sun, in particular the interiors of supergeranule cells, the internetwork (IN).

After this general introduction to the structure of magnetic features at the solar surface, this publication attempts to review just a single subtopic, which is at the center of a lively debate, namely the magnetic field in the photospheric layers of the quiet Sun. A concentration on a narrower topic was given preference in order to allow a more in-depth treatment. Readers more interested in sunspots are referred to the reviews by Solanki (2003), Thomas & Weiss (2004), Bellot Rubio (2004), and Schlichenmaier (2003).

There have been a number of reviews of the photospheric (non-sunspot) magnetic field. Relatively comprehensive reviews of the state of the field at the time they were written have been given by Zwaan (1987), Stenflo (1989, 1994), Solanki (1993). More focused reviews aimed at quiet Sun magnetism have been given by, e.g., Sánchez Almeida (2003), Khomenko (2006), Trujillo Bueno, Asensio Ramos, & Shchukina (2006), Title (2007). Perforce, this is an incomplete list, just as the references in the remainder of the paper also do not lay claim on completeness.

2. Quiet Sun Magnetic Fields

2.1. Introduction to Quiet-Sun Fields

The magnetic field found in the quiet Sun has traditionally been categorized into network field and internetwork field (or intranetwork or inner-network field as it has also been called in the literature). Internetwork (IN) fields were discovered by Livingston & Harvey (1971, 1975) on the basis of a weak Stokes V signal they detected throughout the quiet Sun, also in the interiors of supergranule cells, i.e. away from the stronger network field. A separate category, the turbulent field has also been proposed, although it has been argued by Jan Stenflo that IN fields are just the large-scale end of the size distribution of turbulent fields. In addition, further components of the field have also been proposed, such as 'granular fields' (Lin & Rimmele 1999), transient horizontal quiet-Sun fields (Lites et al. 1996) or, 'seething fields' (Harvey et al. 2007). It is not always clear which of these are independent types of magnetic structures, and which are just different names for the same physical entity. The difficulty with identifying one with the other lies in the different techniques used to detect and study them. E.g., IN fields have traditionally been identified and measured using the Zeeman effect, while the turbulent field has been probed mainly using the Hanle effect. Because of the cancellation of the Zeeman signal in the presence of opposite polarity longitudinal fields in the resolution element, a tangled field may escape detection through the Zeeman effect, specially if the field is intrinsically weak.

There have also been suggestions that magnetic fluxes of all magnetic features in the photosphere together form a continuum of values. For e.g., Stenflo & Holzreuter (2002, 2003) argued, based on the fact that magnetograms and Probability Distribution Functions (PDFs) of magnetogram signals observed at different scales look very similar, that there is no difference between magnetic fields at different scales. This work is similar to the determination of fractal dimension of magnetic field on the Sun, (e.g., Lawrence, Cadavid, & Ruzmaikin 1995, Komm 1995, cf. Meunier 1999, Abramenko 2005). Since magnetic features are moved around by the evolving convection cells, possibly such an analysis provides more information on the distribution of convection at different scales, rather than on intrinsic magnetic properties. Convective eddies are expected to be self-similar for a turbulent medium, such as the solar convection zone.

2.2. Magnetic Flux in the Quiet Sun

Methods

Let us begin by discussing the question of the magnetic flux in the quiet Sun. In principle, it is possible to detect magnetic features and partly to estimate their magnetic flux in a variety of ways. However, the different types of measurements give different results.

Widely used, since easy to observe at high resolution even under variable seeing conditions, are proxies of the magnetic field, such as the brightness in the G-band, Ca II H or K line core, or CN-bandhead. These proxies are, however, not ideal for determining the magnetic flux in the quiet Sun, due to their small sensitivity. There is still some uncertainty to what extent internetwork magnetic features produce visible signatures in these proxies (however, see de Wijn et al. 2005) and even some magnetic features with larger fluxes and strong fields (e.g., magnetic elements in the network) do not display significant brightening in such features. For the G-band this has been shown by Berger & Title (2001), Schüssler et al. (2003) and Shelyag et al. (2004). For Ca II H and K core intensity, the relationship is tighter, but still displays a large scatter (e.g., Schrijver et al. 1989; Rezaei et al. 2007).

Far more sensitive is the Zeeman effect, which can, with sufficiently low-noise observations sense extremely small fluxes (on the order of 10^{16} Mx or even less), particularly if the field is aligned along the LOS. It suffers, however, from the fact that Stokes V is also sensitive to the direction in which the flux points (towards or away from the observer), so that if there is a mixture of polarities on a sufficiently small scale, the signal in Stokes V can be canceled. In Stokes Q and U cancellation, although possible, is less likely (it requires two transverse fields at right angles to each other in the resolution element).

Determining the unsigned flux in and the strength of intrinsically weak, possibly turbulent fields is one of the major goals of applying the Hanle effect to solar data and it has been widely used to determine the flux and field strength in the quiet Sun. Basically, the Hanle effect allows the magnetic vector to be determined, if the field strength lies within a fiducial range that depends on the observed spectral line. The Hanle effect is generally sensitive to low intrinsic field strengths (typical values are below a few 100 G, depending on the spectral line). Of importance for the field in the quiet Sun is that the Hanle effect allows a weighted average of the field strength to be obtained even for a field that is isotropically distributed in the resolution element. Such a field would be invisible to the Zeeman effect as long as it doesn't produce any significant broadening of the line profiles (see below).

Magnetic Flux: Results

Unno (1959) was the first to look for an unresolved "turbulent" field (that to first order was expected to be isotropic). He did not find any excess broadening of Zeeman sensitive lines relative to Zeeman insensitive ones, obtaining an upper limit of 300 G. Stenflo & Lindegren (1977) greatly improved the sensitivity of the technique by extending the investigation to hundreds of spectral lines (all the unblended Fe I lines in the visible solar spectrum). The upper limit on the line broadening in the quiet Sun found by them has only been improved by Jan Stenflo's later use of spectra obtained with the Fourier Transform Spectrometer on Kitt Peak (compared with the Jungfraujoch Atlas used by Stenflo & Lindegren 1977). He obtained an upper limit of 100 G for the field outside the network, which includes the contribution of the internetwork and of any turbulent field.

Early work on the determination of unresolved magnetic flux using the Zeeman effect was also carried out by Stenflo (1987), who analyzed Stokes I, Q, V profiles and was able to limit a combination of magnetic field inclination and field strength. A different approach was taken by Tarbell, Title, & Schoolman (1979), who used high spatial resolution observations to circumvent the problem of cancellation of Stokes V by opposite polarity fields. They found that a possible turbulent field cannot exceed 100 G at spatial scales accessible to observations with a spatial resolution of 0.5".

Determinations of the flux have been carried out for network elements by, e.g., Meunier, Solanki, & Livingston (1998), Hagenaar (2001) (cf. Schrijver et al. 1997). They all find an exponential increase in the number density of elements with decreasing flux, down to the sensitivity limit (lying at 2×10^{18} Mx in the case of the investigation of Hagenaar 2001). In contrast to this result, Wang et al. (1995) obtain a non-exponential, non-power law distribution for the network fluxes and a different (but also non-exponential, non-power law) distribution for the internetwork field. They use a series of criteria to differentiate between the two, including location (at the edges of supergranules or in their interior), proper motion speeds (higher speed of internetwork elements), etc. The weakest fluxes of individual internetwork features that they record are 10^{16} Mx.

An important result was presented by Zirin (1987), namely that the amount of magnetic flux emerging at the solar surface in some interval of time is roughly 100 times larger in IN fields than in ephemeral active regions. In these it is again 100 times bigger than in normal active regions.

Prior to the Hinode mission (Tsuneta et al. 2008) the typical average field strength in the quiet Sun obtained from Zeeman effect measurements were a few G. An exception is the work of Domínguez Cerdeña, Kneer, & Sánchez Almeida (2003a), and Domínguez Cerdeña, Sánchez Almeida, & Kneer (2003b). At a spatial resolution of 0.5" Domínguez Cerdeña et al. (2003a,b) obtain an average field strength of 20 G in the internetwork. Also, Khomenko et al. (2005a) (cf. Khomenko et al. 2005b), compare the distributions of Stokes V amplitudes simultaneously observed in the IR and the visible with the amplitudes of synthetic profiles computed in snapshots of mixed-polarity 3-D MHD simulations harboring different amounts of magnetic flux. The flux is then determined from the simulation, allowing to first order to circumvent the problem that a part of the flux is canceled in the observations. They also obtained 20 G, but this value refers to a spatial resolution corresponding to the grid scale of the MHD simulations, a few 10 km. Therefore, unless there are no magnetic structures below 0.5" in size the value found by Khomenko et al. (2005a) is not consistent with the same value found by Domínguez Cerdeña et al. (2003a,b).

Recently, analysis of Hinode/spectropolarimeter data by Lites et al. (2008) has yielded 11 G for the longitudinal field. The fact that Hinode data (at the significantly higher and homogeneous resolution of 0.32") reveal only half as much flux as the investigation of Domínguez Cerdeña et al. (2003a,b) suggests that seeing may have affected the data of Domínguez Cerdeña et al. (2003a,b) in a way that it increased the strength of the V signal (this is easily possible if brightness and velocity changed somewhat between the different images needed to complete the observation - Hinode, in particular its spectropolarimeter, of course suffers from this problem far less severely).

From the Hanle depolarization of the resonant polarization of lines formed in the quiet Sun's photosphere (mainly from the Sr I line at 4607 Å, but also from molecular lines), a turbulent B field in the range of roughly 10–60 G has been inferred (Stenflo 1982; Faurobert-Scholl et al. 1995; Faurobert et al. 2001; Stenflo, Keller, & Gandorfer 1998; Berdyugina & Fluri 2004; Trujillo Bueno, Shchukina, & Asensio Ramos 2004; Bommier et al. 2005, 2006; Derouich et al. 2006). With time investigations have increased in sophistication, now including multi-dimensional polarized radiative transfer (pioneered by Stenholm & Stenflo 1978) and atmospheres produced by 3-D radiation-hydrodynamic simulations. In general, a field of this average strength covering the whole quiet Sun harbors less magnetic energy than the field in the network. However, see Sánchez Almeida (2005), for arguments why the measurements made in the Sr I line actually imply that more than half of the Sun's surface is covered by fields stronger than 60 G, even if the measurements give average field-strength below 60 G.

Trujillo Bueno et al. (2004) also favor a higher energy density in the internetwork than in the network field (deduced from observations obtained at IRSOL by Stenflo et al. 1997). They adopt an exponential PDF for the field strength, as propagated by MHD simulations. For a single PDF of the magnetic field, they find an e-folding width of 130 G (deduced from the same observations give a 60 G average field). Finally, they introduced different PDFs of the field in granules and intergranular lanes, with $B_0 = 15$ G in the former structures and with $B_0 = 450$ G in the latter, in order to simultaneously satisfy Sr I (atomic) and C_2 (molecular) lines. The energy density in the turbulent field in this scenario is larger than in the network.

2.3. Magnetic Field Strength of Quiet Sun Fields

One question that has led to considerable debate over the last decade has been whether the magnetic fields in the quiet Sun are intrinsically weak or strong. Here, however, we have to distinguish clearly between network and internetwork fields. For the network, ever since the pioneering work of Howard & Stenflo (1972), Frazier & Stenflo (1972) and in particular Stenflo (1973), with the line-ratio technique, it is certain that the magnetic field in the network has kG field strengths. This has been widely confirmed, e.g., by Wiehr (1978), Solanki & Stenflo (1984), Stenflo & Harvey (1985), Stenflo, Solanki, & Harvey (1987), Solanki, Keller, & Stenflo (1987), Rabin (1992a,b), Rüedi et al. (1992), Grossmann-Doerth, Keller, & Schüssler (1996), etc.

There were also a few advocates of weak fields, even in plage and the network, foremost among them Hal Zirin, and a memorable debate on this topic took place at the 1992 IAU colloquium in Beijing between him and Jan Stenflo. Looking back, it is clear that Jan Stenflo (Stenflo 1993) argued for strong network fields and was not thinking of internetwork (he had been propagating the presence of weak turbulent fields for a long time before that meeting), while Hal Zirin extrapolated from his experience of internetwork fields (and the belief that they were intrinsically weak) to the network. Thus, Zirin & Popp (1989) had argued that highly Zeeman sensitive Mg I lines at 12.3 μm only show weak fields, so that there are no strong fields in the network or in plages (except in occasional micro-pores). However, detailed radiative transfer modeling of these lines by Bruls & Solanki (1995) has shown that they are formed sufficiently high in the atmosphere (just below the temperature minimum), so that they only sense fields of a few hundred G, even if lower in the atmosphere the field is relatively strong (in good agreement with the simple model of slender flux tubes).

More recently, the debate on the intrinsic strength of quiet Sun fields has been rekindled, but now concentrating on the IN fields. The intrinsic field strength is much more subtle to measure than the magnetic flux per feature, since the Zeeman splitting often gives an equivocal result, except for kG fields that fill a sufficiently large part of the aperture. Here, measurements in the infrared have a certain advantage, since the ratio of Zeeman splitting to Doppler width scales roughly linearly with the wavelength. It is therefore possibly not so surprising that the first clear measurement of weak fields anywhere on the Sun was made in the IR at 1.56 μm (reported by Rüedi et al. 1992). Furthermore, the studies of the strength of IN fields that employ infrared data (all have used the Zeeman sensitive line pair at 1.56 μm) give consistent results: the field strength of most IN features lies below roughly 600 G (Lin 1995; Solanki et al. 1996; Khomenko et al. 2003, 2005b; see also Lin & Rimmele 1999, Martínez González et al. 2007). These field strengths are consistent with equipartition between magnetic energy density and convective energy density.

Observations of spectral lines in the visible have given very different intrinsic strengths of internetwork fields. Partly the results depend on the employed spectral lines, but they can also differ between different studies using the same set of lines. An initial investigation by Keller et al. (1994) employing Stokes V measurements of Fe I 5250.2 Å and Fe I 5247.1 Å (the line pair introduced by Stenflo for measuring intrinsic magnetic field strengths of network and plage fields in his seminal 1973 paper) could not determine the true field strength, but provided evidence that the fields were weak, with the field strength B lying below a kG. Interest in these lines has been dormant until very recently when Khomenko & Collados (2007) and Socas-Navarro et al. (2008) have studied them in comparison with the more widely used 6302 and 6301 line pair as well as the 1.56μm lines.

Most widely used have been the Fe I line pair at 6302.5 Å and 6301.5 Å which have been observed by, e.g., the Advanced Stokes Polarimeter (ASP; Elmore et al. 1992) and now the Hinode Spectropolarimeter. Magnetograms in these lines have been investigated by Domínguez Cerdeña et al. (2003a,b) recorded with the Göttingen Fabry-Perot at the VTT. They found magnetic flux throughout the quiet Sun (covering 45% of the surface area, typically located in the intergranular lanes). In addition, this flux was found to be in the form of intrinsically strong fields, so that according to these investigations most of the magnetic flux in the internetwork is in the form of kG fields. Spectroscopic investigations employing ASP data by Lites & Socas-Navarro (2004) did not reproduce the preponderance of strong fields, while the analysis of Socas-Navarro & Lites (2004) indicated a mixture of strong and weak fields (cf. Socas-Navarro, Martínez Pillet, & Lites 2004). Sánchez Almeida, Domínguez Cerdeña, & Kneer (2003), from a comparison of visible and IR lines, also found a mixture of field strengths, although in their case the visible lines gave strong fields, while the IR lines indicated weak ones (see further below for a more detailed discussion of this result).

Most recently, these lines, as recorded by Hinode/SP have been analyzed by Orozco Suárez et al. (2007a,b). In contrast to earlier authors, they obtained weak fields with strengths in the range of equipartition with the convection.

A final Zeeman-effect based diagnostic has been developed by López Ariste, Tomczyk, & Casini (2002, 2006). It makes use of the change in line profile shape introduced by hyperfine structure in Mn I lines in the visible part of the spectrum as the field strength increases. Applying this diagnostic to measurements of Stokes I and V in the internetwork they obtain mainly hecto-Gauss fields (which cover the majority of the area and contain the majority of the flux), although they do not give precise numbers regarding the field strength. This result is confirmed by Asensio Ramos et al. (2007) employing a Mn I line in the infrared. Sánchez Almeida et al. (2008), however, argue that in a MISMA-like atmosphere (Micro-Structured Magnetic Atmosphere, an approximation to describe the influence on the Stokes profiles of an atmosphere with, e.g., the magnetic field structured at a very small, optically thin, scale; Sánchez Almeida et al. 1996) the Mn I line will indicate weak fields even if more than 50% of the magnetic flux is in the form of kG fields.

The difference between the results obtained with the IR 1.56 μm and those from the visible 6302 Å lines has fueled the debate on the true field strengths of IN fields. It has also led the groups using either one of these diagnostics to comment on the shortcomings of the other. For example, it has been argued that the visible lines miss much of the weak fields, since for incomplete Zeeman splitting (which is the case for these lines for sub-kG fields) the signal in a given pixel is proportional to the magnetic flux in that pixel. Since the internetwork fields are associated with very small fluxes per pixel, these lines could miss a considerable portion of it. Also, because the intrinsic field strength as found in the IN changes the I and V profiles only in subtle ways, the deduced values are susceptible to noise or systematic errors. Conversely, it has been argued by Socas-Navarro & Sánchez Almeida (2003) that the IR lines, by dint of their large Zeeman sensitivity, give too much weight to the weak fields. For these lines, the amplitude of the Stokes V signal is proportional to the fractional area covered by the field (the magnetic filling factor) rather than to the amount of magnetic flux in the pixel. Therefore, fields with small field strength give proportionately larger signals. Socas-Navarro & Sánchez Almeida (2003) argue that the rapid drop of the field strength with height (due to pressure balance; see § 1) compounds this effect: since a spectral line is formed over a range of heights, this gradient of the field spreads the signal from the strong fields (which are associated with the largest vertical field-strength gradients) too much in the wavelength direction, making the Stokes amplitudes small, and possibly hidden in the noise. Consequently, they argue, the IR lines are missing much of the flux in the strong fields.

A comparison of the results obtained from the infrared and the visible lines of a simultaneously observed patch of quiet Sun might be a way of deciding between the different diagnostics and associated points of view. Such a comparison was first carried out by Sánchez Almeida et al. (2003), who found that the Stokes maps in the two wavelength ranges looked quite different. In particular, they noted that the visible and IR lines displayed opposite polarities in 25% of the pixels, which was a remarkably high proportion. If correct, this would indeed support the view that the IR and visible lines were sampling rather different components of the IN field. The main drawback with this investigation was that data from different telescopes had been used that suffered from rather different amounts of seeing, which could affect the two wavelength bands in different ways, making their comparison less straightforward. In a following analysis, Khomenko et al. (2005a) compared visible and IR lines observed with the same telescope under identical seeing conditions and obtained a more similar distribution of polarities and fluxes from both wavelength ranges. The magnetograms obtained in both wavelength ranges are shown in Fig. 3. Remaining differences between the two images are due to the larger sensitivity of the IR line to weak fields and to the remaining unavoidable differences in seeing (which possess a dependence on λ).

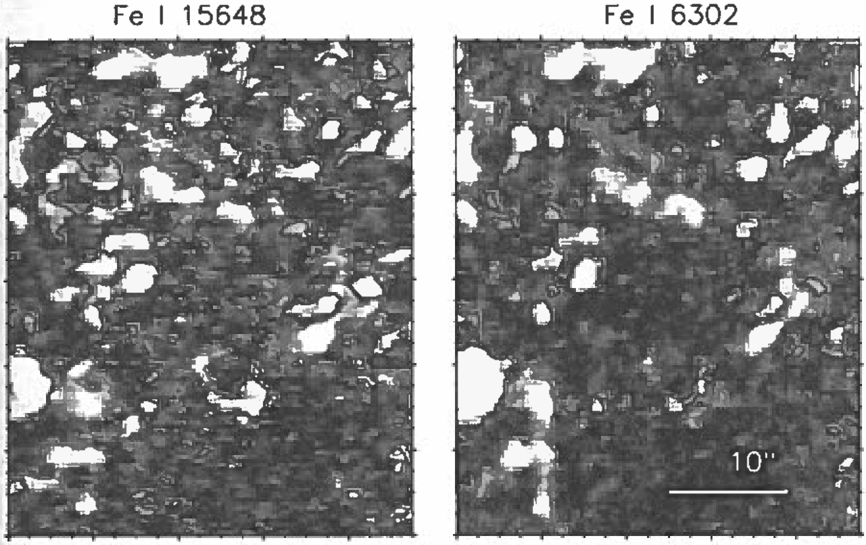

Figure 3. Magnetograms in the infrared at 1.56 μm (left panel) and in the visible at 6302 Å (right panel) obtained simultaneously and cospatially with the VTT on Tenerife. Greater brightness indicates larger amounts of magnetic flux per pixel. Opposite magnetic polarities are bounded by red (grey) and by blue (black) lines, respectively. Adapted from Khomenko et al. (2005a)

Finally, Domínguez Cerdeña, Sánchez Almeida, & Kneer (2006) inverted a set of combined IR and visible spectra using a 3-component model, which allowed a field-free component to co-exist with two different magnetic components. They obtained a mixture of strong and weak fields, with a clear relationship between magnetic field strength and magnetic flux in the sense that the larger the magnetic flux in a pixel, the stronger the field (left panel of Fig. 4). This result is similar to that found by Solanki et al. (1996), shown in the right panel of Fig. 4. An increase of field strength with magnetic flux of the feature is in agreement with predictions of the efficiency of the convective collapse mechanism that leads to the formation of the intense flux tube (Venkatakrishnan 1986). As in their earlier papers Domínguez Cerdeña et al. (2006) argue that most of the flux and of the magnetic energy is in the kG fields.

Many of the investigations discussed so far have been based on Stokes I and V profiles only. This can be explained partly by instrumental constraints, partly by the fact that the Q and U profiles scale as B^2, while Stokes V scales

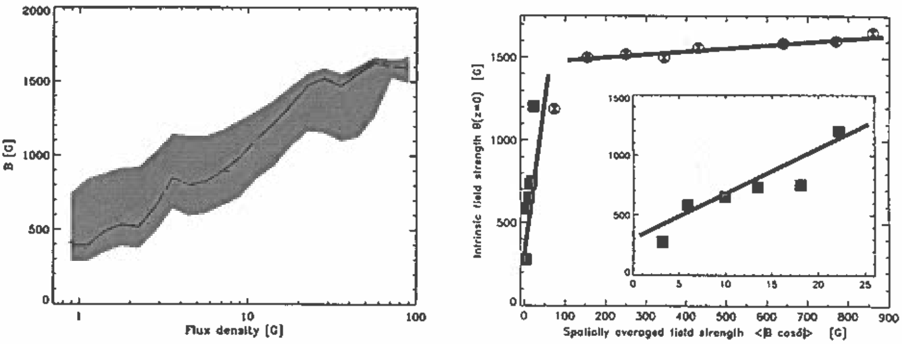

Figure 4. Left panel: Field strengths retrieved from a combination of 1.56 μm and 6302 Å cospatial observations obtained nearly simultaneously. Adapted from Domínguez Cerdeña et al. (2006). Right panel: Same, but from an investigation of the 1.56 μm lines alone. The results of observations covering both the quiet Sun and active regions are displayed in the larger frame. In the inset only the results for the quiet Sun are shown (each point is a value binned over numerous individual data values (adapted from Solanki et al. 1996).

proportionally to B. For a relatively weak Zeeman splitting (typical of visible lines in the quiet Sun) this implies that Q and U are much weaker than V.

The difficulty to measure B reliably from just I and V of a visible line pair, in particular from Fe I 6302 and 6301 Å, has been demonstrated by Martínez González, Collados, & Ruiz Cobo (2006). They fit a set of these lines profiles two times, once starting from a strong B initial guess, once from a weak B initial guess. Depending on the initial guess the final result was also very disparate, although the fits to the profiles were equally good. The differences in the Stokes profiles produced by the different field strengths were completely compensated by slightly different temperatures and turbulence velocity values returned by the inversion code. Another approach was taken by Khomenko & Collados (2007). They used the output atmospheres from the 3D radiation-MHD simulations of Vögler et al. (2005) to test different diagnostics of the field strength. According to their analysis the most reliable of the tested diagnostics is the 1.56 μm line pair, the least reliable the 6302/6301 Å line pair. These exercises have demonstrated just how difficult it is to obtain reliable B values from this line pair, in particular if only Stokes I and V are available.

The great advantage of also having a linear polarization profile available is that the shape of the Q and U profiles changes with the field strength, with the ratio of the strength of the π-component to the σ-components depending on this quantity, providing further (although not in itself unique) constraints on the field strength, as demonstrated by, e.g., Solanki et al. (1987).

More recently, the advent of Hinode has opened up new possibilities, by providing I, Q, U, V spectra of Fe I 6302 Å and 6301 Å at a constant high spatial resolution corresponding to approximately 0.3". Recent inversions by Orozco Suárez et al. (2007a,b) indicate that the Hinode data give mainly weak fields (hG), possibly because of the presence of the linear polarization signals (only pixels with profiles lying above a given threshold in Stokes Q, U and V are inverted).

2.4. Horizontal Fields in the IN

Evidence for horizontal fields in the IN can be noted in data published by Martin (1988) in the fact that IN fields are visible from the center of the solar disk right to the limb, suggesting the presence of both vertical and horizontal fields. With considerable foresight, Martin already interpreted these measurements as possibly due to the presence of low-lying loops in the internetwork.

Lites et al. (1996) found arc-sec scale, short-lived horizontal fields (lifetimes of minutes) in the internetwork. The size scale was determined by their spatial resolution. Another approach was taken by Meunier et al. (1998). They considered the center-to-limb variation of the Stokes V amplitude of the $g = 3$ line at 1.56 microns and found that the quiet Sun field is composed mainly of intrinsically weak, nearly isotropically distributed fields, in addition to strong, nearly vertical fields. Martínez Gonzalez et al. (2008) also find evidence for a more or less isotropic distribution of the internetwork field (and little change in the field strength PDF) from the center to limb variation of the polarization signal in the quiet Sun, in agreement with Martin (1988) and Meunier et al. (1998). With the very sensitive SOLIS instrument on Kitt Peak, Harvey et al. (2007) found a "seething" horizontal field throughout the internetwork. This field of typically 1-2 G at the spatial resolution of SOLIS of 2.5-5" changed within minutes. Further evidence for horizontal fields has been provided by Hinode: Orozco Suárez et al. (2007a,b) inverted Stokes spectra to obtain that internetwork fields display a peak in the distribution of inclination angles at 90°, which corresponds to horizontal fields. This interesting result may partly be an artifact of the higher sensitivity to noise of Stokes Q and U due to their weakness unless fields are intrinsically strong. Finally, Lites et al. (2008) obtained 5 times more flux in horizontal fields than in the vertical fields in the internetwork (to be more precise they found that the average field strength in the horizontal field is 5 times larger than of the vertical field; a precise determination of the flux for horizontal fields is rather difficult from Stokes parameters). With a strength of 50-60 G, it is comparable to the values obtained by the Hanle effect.

What is the structure of these internetwork fields? Martínez Gonzalez et al. (2007) found evidence in observations at 1.56 μm that at least some of the internetwork elements are (parts of) low-lying loop-like structures. The loops were reconstructed in a way similar to the technique applied by Solanki et al. (2003), although the 180° ambiguity inherent in the Zeeman-effect did not allow Martínez Gonzalez et al. (2007) to distinguish between small Ω loops and U-loops at a granular scale. An example of a loop reconstructed by Martínez Gonzales et al. (2007) is shown in Fig. 5. These loops may correspond to the small-scale emerging loops observed by Centeno et al. (2007) in the quiet Sun and by Ishikawa et al. (2008) in active region plage. These small loops have approximately 10^{17} Mx each and are found to emerge in granule centers.

2.5. Source of IN Fields

How could such a magnetic structure be explained? There are different possibilities.

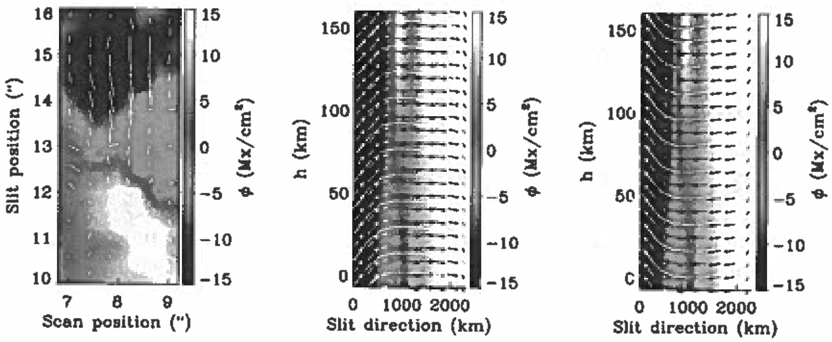

Figure 5. Reconstructed loop in the internetwork. Left panel: vertical magnetic flux density in a small region of the total scan (flux density is indicated by the color) at height zero (average solar surface). The azimuthal direction of the field is overplotted. Central panel: the vertical dependence of the magnetic vector along a cut going from the upper part of the left frame to its lower part at the scan position marked 8". The colors mark the magnetic flux density, while the direction of the magnetic vector is indicated by the arrows. The white lines are smoothed curves joining the arrows and outlining the loops. The right panel is the same, but now for the other solution allowed by the 180° ambiguity.

1. Emergence of fields generated in deeper layers (e.g. by a deep convection-zone or an overshoot-layer dynamo). This could be the extension of ephemeral active-region fields (studied by Harvey & Martin 1973; Harvey et al. 1975; Harvey 1993; Hagenaar 2001) to still smaller scales. Note that there is a power-law distribution of flux in bipolar regions (following an inverse square law) from large active regions down to small ephemeral regions. The cut-off at the small scales is consistent with a lack of resolution and/or sensitivity. Whereas the large active regions have a strong tendency towards an E-W orientation following Hale's polarity law, increasingly smaller bipoles have increasingly weaker preferred orientations. Any lack of orientation of the smallest emerging bipoles does not automatically rule out this scenario, since there is a very gradual decrease of the level of orientation with decreasing area or magnetic flux, and no abrupt transition.

2. Flux recycling after decay of active-regions and ephemeral active regions. The magnetic flux from a decaying region very likely partly gets dragged down by convection and can emerge again at another point on the solar surface. Such an effect has been identified in MHD simulations carried out by Ploner et al. (2001), suggesting that such recycling does take place. The work of de Wijn et al. (2005), see below, also provides evidence that either mechanism 1 or 2 is acting as the source of also some of the flux in the internetwork (or some combination of both).

3. Flux produced at or very close to the solar surface by a truly local dynamo. Simulations that sustained a local dynamo in a convective medium similar to the solar interior, were carried out by Cattaneo (1999) The most realistic simulation of the local dynamo, however, has been performed by Vögler & Schüssler (2007), who considered also a proper 3D radiative transfer etc. to simulate the conditions in the layers close to the solar surface. Starting from a very low value, the magnetic energy within the simulation box increases exponentially with time, before it saturates. The saturation value depends on the magnetic Reynold's number R_m of the simulation, being higher for larger R_m. For $R_\mathrm{m} = 2600$ the simulations give an average, unsigned vertical field of approximately 35 G, which lies within the range of values found from the Hanle effect.

The field produced by such a simulation is structured on very small (subgranular) scales with strongly mixed opposite polarities. It is also largely horizontal. It is basically composed of short, flat loops that are concentrated in intergranular lanes and generally have both their footpoints within a single intergranular lane. Note that the simulations carried out so far do not allow any flux to be advected into the box. Note also that changes in R_m should have an influence on the magnitude of the produced magnetic field and energy, but not on its distribution, so that the shape of the PDF of the field strength and of the magnetic orientation should remain independent of R_m.

Any difference between the observed and simulated distribution of the flux may be telling us something about other effects besides a purely local dynamo acting to produce the observed field. Therefore, it is heartening that Schüssler & Vögler (2008) obtain a ratio between horizontal and vertical field that is close to the value found by Lites et al. (2008) from Hinode spectropolarimeter data. One difference between the two is that Lites et al. (2008) found most of their horizontal flux regions at the edge of granules, while simulations place the flux clearly into the intergranular lanes.

Quite generally, there is an observed relationship between the weak quiet-Sun fields and convective features. Best known is that the strong fields found in the network are located at the boundaries of supergranules. On a smaller scale Lin & Rimmele (1999) find a weak field distributed following the granulation. The field also changes over a granular life-time (consequently they called this component of the field a granular field). Khomenko et al. (2003) find a preponderance of the weak field in the intergranular lanes. Socas-Navarro et al. (2004) find that the field strength depends on the location of the field relative to the granule in a non-trivial manner. Arguments against the origin of at least the stronger IN flux from a local dynamo have been given by de Wijn et al. (2005) on the basis of the fact that this part of the flux is seen to be distributed on a mesogranular scale and displays a lifetime well in excess of that of granulation.

Such dependences may (or may not) provide an indication of the origin of the magnetic flux. However, they do tell us that the flux must survive without complete cancellation for a sufficiently long time to be dragged to the edge of the particular convective feature it is found to be lying at the boundary of. In the case of the network this implies a survival time of at least 10 hours, for the mesogranulation roughly an hour or two.

3. Conclusions

The magnetic field in the solar photosphere remains a lively and interesting field of research. In particular this is the case for the quiet Sun field. The progress already achieved with Hinode and by MHD simulations promises considerable further insights in the coming few years, which will hopefully lead to a more definitive understanding of this, the possibly simplest part of the solar surface. It is a tribute to the richness of the Sun and its fine structure that even its simplest and, at first sight, most unremarkable portion, the quiet Sun, has produced so many surprises and still hides so many secrets.

Appendix: A Brief Tribute to Jan Stenflo in Pictures (and Words)

As already mentioned at different places in this paper, the contributions of Jan Stenflo to solar magnetic field research are immense and go well beyond the few (but ground-breaking) results mentioned in this paper (others are of greater relevance for topics that lie outside the scope of this review). Instead of listing all the major contributions that Jan Stenflo made to solar physics, I restrict myself to showing and annotating a selection of photographs taken at different times in his career (and even before his career per se started).

The first photograph is typical for Jan Olof Stenflo's character. It shows him successfully completing a high jump (see Fig. 6). He has been doing this, i.e., jumping over hurdles standing in his path and in the path of scientific progress, all through his life. The capability of coming up with original ideas to overcome seemingly unsurmountable barriers and the tenacity with which he has followed them have led to many important results. An excellent example of his tenacity in sticking to a topic he felt was important although widely neglected is the Hanle effect and its applications to the search of weak fields (here he was in the company of a few other pioneers, such as E. Landi Degl'Innocenti). An early culmination of this interest was his book on "Solar Magnetic Fields" (Stenflo 1994), which is getting increasing exposure as the field matures and expands. With his 1982 paper on turbulent fields in the quiet Sun Jan Stenflo was ahead of his time by over a decade. His early breakthroughs were honored by the Edlund prize of the Swedish Academy of Sciences (see Fig. 7).

The width of his contributions have spanned from theory, over modeling and observations to instrumentation (see Jan Stenflo together with another great observer in Fig. 8). Besides being an active and original observer himself, who hought of unusual ways of using existing instruments, he also initiated the highly successful ZIMPOL (Zürich Imaging POLarimeter) project, brought to ruition by one of the unsung heroes of solar physics, Peter Povel. In addition, an Stenflo was one of the main proponents of a major solar facility, the LEST Large European Solar Telescope, or Large Earth-based Solar Telescope), e.g., n his capacity as president of the LEST foundation. The Gregor telescope now nder construction on Tenerife builds largely on the work done in preparation or LEST. His enthusiasm and influence have been so large that the abbreviation f the Joint Organization for Solar Observations, JOSO, has, only half-jokingly, een referred to as the organization for the Jan Olof Stenflo Observatory.

In addition to his many scientific results Jan Stenflo has given to solar esearch a significant number of new scientists by introducing PhD students to he joys of doing solar physics (16 in all, of which more than half are still working n the field). One of the things that struck me as one of his early students was his nthusiasm which has remained undiminished, not just for science, as exemplified y Fig. 9.

Figure 6. The 11-year old Jan Olof Stenflo (at the left) successfully negotiating a barrier, a quality that he has retained all through his life.

Figure 7. Jan Olof Stenflo (left, in the foreground) receiving the Edlund prize from the King of Sweden.

Figure 8. Jan Olof Stenflo together with the statue of another great swedish astronomer, Tycho Brahe. Stenflo is at the left.

Figure 9. Jan and Joyce Stenflo at the Santorini meeting in 2002 - during the conference dinner, not a scientific session. Jan is the one on the left, again.

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