The magnetism of the very quiet Sun

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Abstract. When the polarimetric sensitivity and the angular resolution exceed a threshold, magnetic fields show up almost everywhere on the solar surface. Here I revise the observational properties of the weakest polarization signals, which appear in the InterNetwork (IN) regions. We already have some information on the magnetic field strengths and inclinations, mass motions, lifetimes, magnetic fluxes, magnetic energies, etc. Since the IN covers a substantial faction of the solar surface, it may account for most of the unsigned magnetic flux and energy existing on the solar surface at any given time. This fact makes IN fields potentially important to understand the global magnetic properties of the Sun (e.g., the structure of the quiet solar corona, an issue briefly addressed here). The spectropolarimeters on board of Solar-B have the resolution and sensitivity to routinely detect these IN fields.

1. Introduction

Most of the solar surface appears non-magnetic when it is observed in routine synoptic magnetograms. However, magnetic fields are detected almost everywhere, also in InterNetwork (IN) regions, when the polarimetric sensitivity and the angular resolution are high enough. These magnetic fields are now accessible to many spectropolarimeters. They cover much of the solar surface and, therefore, they may account for most of the unsigned magnetic flux and energy existing on the solar surface at any given time. The contribution summarizes the main observational properties of the IN fields, as deduced from these recent measurements. In addition, it discusses the origin of the IN magnetism, and why it is a natural target for Solar-B.

2. Operative Definition of Quiet Sun Magnetic Fields

There is no universal consensus on what the term quiet Sun magnetic fields really means. Here it will denote those regions which do not show significant polarization signals in the traditional synoptic magnetograms (e.g., the gray background in Fig. 1). These regions are often called InterNetwork or IntraNetwork (IN). The separation between network and IN is not clear. It depends on the polarimetric sensitivity of the measurement. When the sensitivity is high enough, most of the surface produces polarization and the network and the IN become indistinguishable. Since the observation of the IN requires this high
Eventually, the standard magnetograms will routinely detect IN fields in full. Then the somehow artificial separation between network and IN will be abandoned, and we will talk about quiet Sun magnetic fields with high flux density (network) or low flux density (IN).

It has been adapted from Harvey & Wilson (2000), using the mean Sunspot number plus the scaling between sunspot number and area provided by a typical sunspot group. It has a sunspot number equals to 12, and it covers 200 millionths of solar hemisphere with sunspots and 1800 millionths with plages.

3. Surface Coverage

The quiet Sun IN occupies most of the solar surface, even during solar maximum. Figure 2 shows the area covered by sunspots and plage regions as a function of time. Figure 2 also includes a 10% level to indicate the fraction of surface corresponding to the network (e.g., the contours in Fig. 1 outline some 8% of the area in this Kitt Peak magnetogram). The level is shown as a constant since network signals in conventional magnetograms do not seem to suffer strong variations with the cycle (see, e.g., Harvey-Angle 1993, Chapter 12, Fig. 9). Figure 2 reveals that some 90% of the solar surface is IN quiet Sun, even during the maximum.

4. Complex Topology of the Quiet Sun Magnetic Fields

The spatial resolution of the present or even forthcoming observations is not enough to resolve the structure of the quiet Sun magnetic fields. In other words, the physical properties of the field (e.g., strength or direction) vary within resolution elements which seldom reach 0.75. These variations are so large that often

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Figure 2. Variation of the solar surface covered by sunspots and plage regions along the cycle. Note that even during the solar maximum, most of the traditional full disk magnetograms appear devoid of magnetic structures.

The mean value of a physical quantity bears no information on the actual value of the quantity. Many different observations prove the extreme disorder existing in each resolution element.

The polarization of the spectral lines always shows asymmetries (Sánchez Almeida et al. 1996; Sigwarth et al. 1999; Sánchez Almeida & Lites 2000; Khomenko et al. 2003). In particular, the spectral lines generate net circular polarization, which would be impossible if either the magnetic field or the velocity were uniform. Moreover, the variations of magnetic field and velocity have to occur along the line-of-sight (e.g., Sánchez Almeida 1998). Since the photospheric lines are formed in, say, 100 km or 150 km, large gradients must take place within such small distances.

The magnetometry of the quiet Sun based on visible lines is seemingly incompatible with the InfraRed (IR) magnetometry. For example, Fig. 3 shows two co-spatial (1′′5) and simultaneous (1 min) magnetograms obtained with Fe i 6302.5 Å and Fe i 15648 Å (Sánchez Almeida, Domínguez Cerdeña, & Kneer 2003). Often the polarity of the visible and IR signals is opposite (see, e.g., the circle) indicating that the direction of the magnetic field is not defined. The true field has many different orientations in the resolution element. The existence of unresolved opposite polarities is well documented in the literature. They are needed to explain the asymmetries mentioned above (Sánchez Almeida & Lites 2000), and the bias of magnetic field inclinations observed away from the solar disk center (Lites 2002). They also emerge naturally in the numerical simulations of magneto-convection (e.g., Cattaneo 1999; Stein & Nordlund 2002).

The amount of magnetic flux in quiet Sun features increases exponentially with increasing spatial resolution. It goes from 1 G for 2–3′′ to some 20 G at 0′′5 (e.g., Sánchez Almeida, Emonet, & Cattaneo 2003a, Fig. 3; Domínguez Cerdeña, Sánchez Almeida, & Kneer 2003, Fig. 12). These systematic changes would not happen unless much IN structure remains unresolved.

The Hanle depolarization signals of photospheric lines are consistent with a turbulent magnetic field occupying most of the volume. Although the field
strength is a model dependent quantity, the estimates require fields certainly different from zero and smaller than some 130 G (cf., Faurobert-Scholl et al. 1995; Bianda, Stenflo, & Solanki 1999; Shchukina & Trujillo Bueno 2003; Trujillo Bueno, Shchukina, & Asensio Ramos 2004).

Two main consequences arise from the combination of complex magnetic field topology and limited spatial resolution. First, the measurements are bound to underestimate the magnetic flux and energy existing in the quiet Sun. The polarization signals tend to cancel when the structure is not resolved\(^3\). Second, the measurement of the magnetic field properties turns out to be non-trivial. Extracting physical information from the observed polarization involves modeling and assumptions on the underlying atmosphere. The measurements become model dependent and non-unique. This is an unavoidable tribute that must be paid.

5. Magnetic Field Strength

The traditional solar magnetic structures have magnetic field strengths larger than 1 kG. It varies from 2.5 kG to 1 kG when going from the sunspot umbra to the penumbra (e.g., Bray & Loughhead 1964). Magnetic concentrations of plage and network regions have a field strength between 1 kG and 2 kG (e.g., Solanki 1993). The situation is very different in the quiet Sun, where magnetic field strengths spanning more than three orders of magnitude have been detected. Observations show field strengths going all the way from zero to 2 kG. Those measurements based on visible lines tend to show kG (e.g., Sigwarth et al. 1999; Sánchez Almeida & Lites 2000; Socas-Navarro & Sánchez Almeida 2002). Infrared line based measurements prefer hundreds of G (e.g., Lin & Rimmele 1999;

\(^3\)Not true for the Hanle signals; see, e.g., Stenflo (1994).
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Finally, the observed Hanle depolarization signals demand even weaker fields, of the order of tens of G (e.g., see the references in § 4.). All these different values are probably consistent with a single distribution having all field strengths between 0 G and 2 kG. Different observations, using different spectral ranges and physical principles, are only sensitive to part of the true distribution. Physical mechanisms responsible of the selectivity of the measurements have been put forward. Hanle signals cannot sense Zeeman splittings larger than the natural width of the atomic levels, which corresponds to some 100 G for the transitions employed in photospheric measurements (e.g., Faurobert-Scholl et al. 1995). On the other hand, the large Zeeman splitting of the IR lines smears the polarization signals arising from kG fields which, however, can be observed with lines of smaller splitting, i.e., with visible lines (Sánchez Almeida & Lites 2000; Socas-Navarro & Sánchez Almeida 2003).

The field strength of the quiet Sun needs to be characterized with a Probability Density Function (PDF). This function, \( P(B) \), gives the probability of finding a field strength \( B \). Although we still lack of a reliable PDF, tentative PDFs based on either Zeeman or Hanle signals have been suggested. As explained above, Hanle and Zeeman signals only provide partial information on the true PDF. For illustrative purposes, I have constructed a PDF that tries to accommodate both the Zeeman and the Hanle signals. It is shown in Fig. 4a (the solid line). This \( P(B) \) has been set up using the PDF from visible and IR Zeeman signals in Sánchez Almeida, Domínguez Cerdeña, & Kneer (2003), \( f_Z(B) \), plus an exponential\(^4\) component to account for the Hanle signals,

\[
P(B) = wB_0^{-1} \exp(-B/B_0) + (1 - w)f_Z(B),
\]

with \( f_Z \) normalized to unity. The two unknowns of \( P(B) \), \( w \) and \( B_0 \), can be set from the two first moments of the distribution,

\[
< B > = \int_0^\infty B \cdot P(B) dB = wB_0 + (1 - w) \int_0^\infty B \cdot f_Z(B) dB,
\]

\[
< B^2 > = \int_0^\infty B^2 \cdot P(B) dB = 2wB_0^2 + (1 - w) \int_0^\infty B^2 \cdot f_Z(B) dB.
\]

\( < B > \) and \( < B^2 > \) have a clear physical interpretation and can estimated from observations. The mean, \( < B > \), is related to the unsigned flux density of the quiet Sun as measured with magnetograms\(^5\). On the other hand, \( < B^2 > \) is proportional to the mean magnetic energy density in the quiet Sun. Figure 4a has been produced using

\[
< B >= 60 \text{ G}, \quad < B^2 >^{1/2} = 170 \text{ G}.
\]

The value for \( < B > \) represents an educated guess based on the average fields deduced from Hanle signals (e.g., Shchukina & Trujillo Bueno 2003), as well as on the true unsigned flux in numerical simulations whose synthetic polarization

\[^4\]The exponential shape of the Hanle PDF is suggested by the weak fields in numerical simulations of magneto-convection (e.g. Cattaneo 1999), and it has been used to model Hanle signals (Shchukina & Trujillo Bueno 2003; Trujillo Bueno, Shchukina, & Asensio Ramos 2004).

\[^5\]For example, assuming that the three components of the magnetic field are identical, then \( < B > \) is \( \sqrt{3} \) times the unsigned flux density measured with longitudinal magnetograms.
Figure 4. (a) Probability density function \( (P) \) of finding a magnetic field strength \( B \) in the quiet Sun (the solid line). This probability includes a contribution from measurements based on the Zeeman effect (the dotted line), and another arising from Hanle signals (the dashed line). (b) \( B \times P(B) \), or the unsigned flux density per unit of field strength. The contributions from Zeeman and Hanle signals are coded as in (a). (c) \( B^2 \times P(B) \), or the magnetic energy density per unit of field strength. The contribution from Zeeman and Hanle signals are coded as in (a). (d) \( P(B) \) in (a), together with some other PDFs existing in the literature. (SN&SA ≡ Socas-Navarro & Sánchez Almeida 2003.)

Table 1. Filling factor, and fraction of magnetic flux and energy in the PDF of Fig. 4a, the solid line.

| threshold  | filling factor | Magnetic Flux | Magnetic Energy |
|------------|---------------|---------------|-----------------|
| \( B > 150 \) G | 5              | 50            | 94              |
| \( B > 500 \) G | 2              | 36            | 86              |
| \( B > 1000 \) G | 1              | 25            | 69              |
is compatible with observations (Sánchez Almeida, Emonet, & Cattaneo 2003a). The value for the second moment corresponds to a magnetic energy equals to a sizeable fraction of the solar granulation kinetic energy, explicitly,

\[ \frac{\langle B^2 \rangle}{(8\pi)} = \alpha \frac{\langle \rho U^2 \rangle}{2}, \]

with the fraction \( \alpha = 20\% \), the density \( \rho = 3 \times 10^{-7} \text{ g cm}^{-3} \), and the velocity \( U = 2 \text{ km s}^{-1} \). According to the PDF in Fig. 4a, most of the plasma has very weak magnetic fields. Some 98% of the quiet Sun has a field weaker than 0.5 kG (see Table 1). However, the 2% tail of kG field is quantitatively important since it carries a significant part of the magnetic flux and energy. See § 6.

So far no distinction has been made between the magnetic field strength in granules and intergranules. The possible differences have to be confirmed in the future, however, kG fields seem to prefer intergranules whereas the weak fields are associated with granules (see, Socas-Navarro, Martínez Pillet, & Lites 2004; Domínguez Cerdeña, Kneer, & Sánchez Almeida 2003). This behavior is actually predicted by the numerical simulations of magneto-convection.

6. Magnetic Flux Density and Magnetic Energy Density

As the previous section points out, the two first moments of the PDF are closely related to the unsigned flux density measured with longitudinal magnetographs (1st moment), and with the magnetic energy density (2nd moment). Due to the qualitative character of the forthcoming discussions, \( \langle B \rangle \) is identified with the unsigned flux density, and \( \frac{\langle B^2 \rangle}{(8\pi)} \) with the energy density. Figures 4b and 4c contain the PDF multiplied by \( B \) and \( B^2 \), respectively. They represent the unsigned magnetic flux and the magnetic flux density corresponding to each field strength. The multiplication by \( B \) or \( B^2 \) suppresses the peak at \( B = 0 \) and, consequently, despite the fact that most of the quiet Sun has \( B \sim 0 \text{ G} \), these weak fields do not contribute to the flux and energy. In other words, the feeble tail of strong fields is not negligible but, rather, it determines the magnetic properties of the quiet Sun. To be more quantitative, only 5% of the surface has field strengths larger than 150 G. However, this 5% carries 50% of the flux and holds 94% of the magnetic energy (Table 1). Obviously, these values will be modified upon improvement of the observational PDF. Nevertheless, significant amounts of strong fields are already inferred from the Zeeman magnetometry (e.g., Domínguez Cerdeña, Kneer, & Sánchez Almeida 2003), implying that the tail of strong fields is bound to play a major role.

The total magnetic flux density and energy of the PDF in Fig. 4a have been imposed artificially. However, the chosen values are realistic since they are based on reasonable extrapolations of observed quantities. If they were real, the quiet Sun magnetism would be really important. A quiet Sun having as much as \( \langle B \rangle = 60 \text{ G} \) carries 5 times more flux than all active regions at solar maximum, mainly because it covers most of the solar surface (§ 3.). Refer to Sánchez Almeida (2003) for details on this issue.

\[^6\text{It would be difficult to exceed this 20\%, which is the level of magnetic energy generated by the highly efficient turbulent dynamo of Cattaneo (1999).}\]
7. Motions and Lifetimes

The strong kG fields are associated with intergranules (§ 5.) and, consequently, with downflows. However, the downflows primarily occur outside the magnetic concentrations (see Sánchez Almeida & Lites 2000). The motions of the weaker fields are more uncertain, but they are probably related to granules and upflows (see Socas-Navarro, Martínez Pillet, & Lites 2004). The strong IN fields are dragged by horizontal plasma motions (e.g., Zhang et al. 1998a; Domínguez Cerdeña, Sánchez Almeida, & Kneer 2003). This is the reason why the network (i.e., the supergranulation) shows in the magnetograms. Actually all spatial scales of organized photospheric motions appear in the quiet Sun magnetograms, including the granulation and the mesogranulation (Domínguez Cerdeña, Sánchez Almeida, & Kneer 2003; Domínguez Cerdeña 2003). In particular, the mesogranulation is fairly easy to detect, whereas it remains elusive when using conventional techniques.

The quiet Sun magnetograms are observed to evolve on a timescale similar to that of the granulation (say, 10 min; see, e.g., Lin & Rimmele 1999). The mesogranular pattern lasts at least half an hour (Domínguez Cerdeña, Sánchez Almeida, & Kneer 2003). Moreover, the lifetimes of the large IN patches is of the order of a few hours (Zhang et al. 1998b). Two comments are in order. In spite of the uncertainties of the lifetimes, it is very clear that the IN timescales are much shorter than those characterizing the evolution of active regions (several days; see, e.g., Harvey-Angle 1993). Second, the persistence of a signal in a magnetogram does not necessarily imply the survival of a single magnetic structure during this period. It may well be that the flow pattern dragging magnetic features persists this long (e.g., Rast 2003).

8. Variations with the Solar Cycle

Due to the potential importance of the quiet Sun magnetism (§ 6.), its variations along the cycle are of particular interest. Little is known about this issue, though. Faurobert et al. (2001) find a factor 2 variation of the mean field. Sánchez Almeida (2003) claims no variation within his error bars (40%). Shchukina & Trujillo Bueno (2003) also find no variation. Based on this limited information, we can conjecture that the quiet Sun magnetic flux does not seem to suffer large variations along the cycle. If it changes, the variations are far smaller than those observed in active regions, whose total flux varies by more than one order of magnitude (e.g., Harvey-Angle 1993, Chapter 12, Fig. 4).

9. Origin of the Quiet Sun Magnetism

Several possibilities have been put forward. The IN may result from the decay of active regions. This possibility has problems due to the large amount of magnetic flux and the short decay time of the IN fields as compared to the active regions (see Sánchez Almeida, Emonet, & Cattaneo 2003b for a quantitative argumentation). The quiet Sun may be generated by a surface turbulent dynamo which transforms part of the convective kinetic energy into magnetic energy (Petrovay & Szakaly 1993; Cattaneo 1999). This local dynamo has been
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criticized by Stein & Nordlund (2002), arguing that the mass flows of the granulation are not restricted to a narrow layer close to the solar surface but involve the whole solar convection zone. These authors propose that the IN fields are produced by the turbulent component of the global solar dynamo. The numerical simulations inspired in the turbulent dynamo scenario (no matter whether it is local or global) produce a complex magnetic field resembling the observed IN fields (see, e.g., Sánchez Almeida, Emonet, & Cattaneo 2003a).

10. Conclusions and Final Comments

The quiet Sun is the component of the solar surface magnetism that seems to account for most of the magnetic flux and magnetic energy (§ 6.). This fact makes it potentially important to understand the global magnetic properties of the Sun (solar dynamo, coronal heating, origin of the solar wind, and so on). However, its influence has been neglected so far. It produces very weak polarization signals which hardly show up in conventional magnetograms. The situation is slowly turning around, and it will dramatically change with the advent of spaceborne polarimeters like those of Solar-B. For example, Fe i 6302 Å is expected to produce a circular polarization of the order of $5 \times 10^{-3}$ when the angular resolution reaches 0″5 (Domínguez Cerdeña, Sánchez Almeida, & Kneer 2003). These signals are well above the noise level in the normal mapping model of the SOT spectropolarimeter (Shimizu 2004). In other words, Solar-B is expected to routinely detect the quiet Sun magnetic fields (at least that fraction having kG field strengths, see § 5.).

The true role of the quiet Sun magnetism is still unknown. Only preliminary steps to figure it out have been given. Let me point out a recent work by Schrijver & Title (2003) where they study the influence of the quiet Sun magnetic fields on the extrapolation of the photospheric field to the corona. They conclude that an important modification of the network-rooted field lines is induced by the presence of the IN, implying that a significant part of this disorganized IN photospheric field does indeed reaches the quiet corona.

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