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Origin of quiet-Sun magnetic fields revealed with Hinode

Ryohko Ishikawa

National Astronomical Observatory of Japan,
2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
email: ryoko.ishikawa@nao.ac.jp

Abstract. Quiet-Sun magnetic fields are enigmatic in terms of their properties, and their origin is not well understood. One likely possibility is that they are a consequence of interactions with turbulent convective motions of various temporal and spatial scales. Here we investigate the relationship between small-scale magnetic fields and various convection flows. We demonstrate that in addition to granulation and supergranulation, mesogranulation also plays an important role in structuring quiet-Sun magnetic fields. We also study the vector magnetic fields in the quiet Sun, and propose that emerging granular-scale bipolar loops are major sources of the quiet-Sun magnetic fields.

Keywords. Sun: magnetic fields, Sun: granulation, convection, polarization

1. Introduction

Supergranulation is a convection pattern with a typical scale of $\sim$ 30 Mm ($\sim$ 40″) and a lifetime of $\sim$ 24 h (Leighton *et al.* 1962) on the quiet solar surface. The horizontal flow velocity directed radially from the center to the boundary is measured to be in the range $300 - 500$ m s^{-1} (Shine *et al.* 2000). The strong kG vertical fields concentrated around the boundaries of supergranulation (e.g., Simon & Leighton 1964) are referred to as network fields. The network fields, whose magnetic field vector is vertical with respect to the solar surface, have an intrinsic magnetic field strength that is determined to be $1 - 2$ kG.

The region inside the network, which is referred to as the internetwork region, contains weak magnetic fluxes of smaller size and mixed polarity. Although the nature and origin of the quiet-Sun magnetic fields has not been well understood, these properties are likely related to turbulent convections of various spatial and temporal scales. Since the discovery of internetwork fields by Livingston & Harvey (1971), several observations have been carried out to explore the properties of internetwork magnetic fields using the Zeeman effect. However, given the difficulty of observing small magnetic fluxes with mixed polarity, no consensus has been reached regarding their magnetic properties such as intrinsic field strengths and inclinations.

The Solar Optical Telescope spectropolarimeter (SOT/SP; Tsuneta *et al.* 2008a) on board the Hinode satellite (Kosugi *et al.* 2007) has allowed us to measure the full Stokes spectra at the Fe I 630.2 nm lines with high polarization sensitivity at an unprecedented high spatial resolution of 0.32″. The SOT/SP has revealed ubiquitous horizontally inclined magnetic fields with intrinsic field strengths of a few hundred G in internetwork regions (Orozco Suárez *et al.* 2007, Lites *et al.* 2008). The presence of such horizontal internetwork magnetic fields was originally reported by Lites *et al.* (1996). Since the launch of Hinode, these magnetic fields have been studied in detail by many authors and their properties have been revealed. These horizontal fields appear inside bright granules (Ishikawa *et al.* 2008), which correspond to upwards-moving parcels of hot gas, and their size and lifetime are always smaller than those of the granules (Ishikawa & Tsuneta 2009b). The lifetime ranges from 1 to 10 min; hence the fields are called transient horizontal magnetic fields (Ishikawa *et al.* 2008). They are emerging Ω-shaped loops, which could provide a total magnetic flux whose magnitude is orders larger than that of sunspot regions during an entire solar cycle (e.g., Jin *et al.* 2009, Martínez González & Bellot Rubio 2009, Ishikawa *et al.* 2010).

Transient horizontal magnetic fields are ubiquitous all throughout the solar surface, as they observed in the quiet, plage, and polar regions (Harvey *et al.* 2007, Ishikawa *et al.* 2008, Tsuneta *et al.* 2008). Their occurrence rates and field strength distributions do not differ among these regions, and their intrinsic field strengths are smaller than the equipartition field strengths that correspond to granular convection (Ishikawa & Tsuneta 2009a, Ito etal 2010). Furthermore, their magnetic flux in the polar region has been stable between 2008 and 2011, while the vertical magnetic fields with kG field strength have changed considerably in association with the evolution of the solar cycle (Shiota *et al.* 2012). These observations indicate that a local dynamo process (i.e., amplification of seed magnetic fields due to surface turbulent convection) generates these small-scale magnetic fields.

The relationship between granules and horizontal magnetic fields has been clarified thus far. Here we concentrate on the spatial distributions of these small-scale magnetic fields and clarify their relationship to the flow fields on larger temporal and spatial scales, i.e., mesogranulation and supergranulation. To discuss the origin of quiet-Sun magnetic fields, we also investigate the relationship between the vertical magnetic fields, which have been extensively studied before, and the horizontal magnetic fields.

2. Relation of horizontal magnetic fields to mesogranulation

Figure 1 shows a small portion ($19.2'' \times 19.2''$) of internetwork region at disk center obtained with narrowband filter imager (NFI) of the SOT. 123 maps of the linear polarization (LP= $\sqrt{Q^2+U^2}/I$) signals taken at the Fe I 525.0 nm line for 2 h were summed (Figure 1(a)). The summed LP map clearly shows cellular structures on a scale

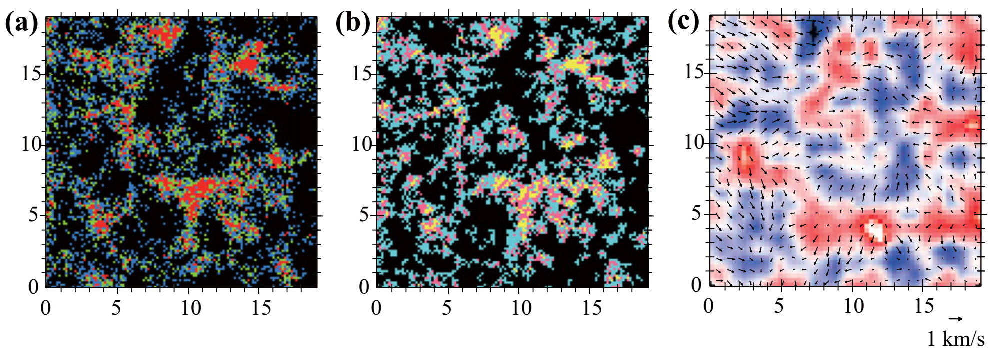

Figure 1. All panels represent a small area of $19.2'' \times 19.2''$ in the internetwork region. (a) A 2-h summed linear polarization (LP) map. Blue, green and red regions indicate statistical significance levels of 1σ, 2σ, and 3σ of the summed LP signals, respectively. (b) Number of appearances of horizontal magnetic fields during a 2-h period. Light blue, pink, and yellow regions show regions where horizontal magnetic fields appear once, twice, and at least three times, respectively. (c) Horizontal flow map plotted over the divergence map (negative is blue, positive is red). Adapted from Ishikawa & Tsuneta (2010).

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of $5'' - 10''$ with voids (Ishikawa & Tsuneta 2010). These cellular structures, which are larger than granules, are also seen in the snapshot (Pevtsov 1989, Lites *et al.* 2008). Figure 1(b) represents the number of occurrences of horizontal magnetic fields in the small area. The black area corresponds to the region where no horizontal fields appear during a 2-h period. A cellular structure on a scale of $5'' - 10''$ similar to that seen in the summer LP map is identified. The summed LP map (Figure 1(a)) is expected to potentially show a spatial distribution of much weaker horizontal magnetic fields not detected in an individual LP map. However, the similarity between the summed LP map and the occurrence map (Figure 1(b)) suggests that isolated horizontal magnetic fields fill the signal in the deep magnetogram, and that the voids correspond to field-free regions where horizontal magnetic fields do not emerge (Ishikawa & Tsuneta 2010). This has been confirmed by Martínez González *et al.* (2012) using the Sunrise/IMaX instrument.

Figure 1(c) represents the horizontal flow field over the divergence map derived from the local correlation technique (e.g., Shine *et al.* 2000). Areas of positive divergence are distributed on a scale of $5'' - 10''$; these flow fields are referred to as mesogranules. The summed LP (or emergence of horizontal magnetic fields) evidently avoids the region with areas of positive divergence (e.g., (X,Y)= $(2'', 9'')$). In other words, the LP signals are concentrated on areas of negative divergence, which corresponds to the mesogranular boundaries (see Ishikawa & Tsuneta 2010 for further detail). A similar correspondence between mesogranules and internetwork vertical fields has been reported by Yelles Chaouche *et al.* (2011). The nature of mesogranulation and whether mesogranulation represents a distinct scale of convection remain a matter of debate. Nevertheless, mesogranulation evidently plays an important role in structuring quiet-Sun magnetic fields.

3. Relation of horizontal magnetic fields to supergranulation

A natural question here is whether horizontal magnetic fields are concentrated in the supergranular boundaries. To address this issue, we examined the areal densities of linear

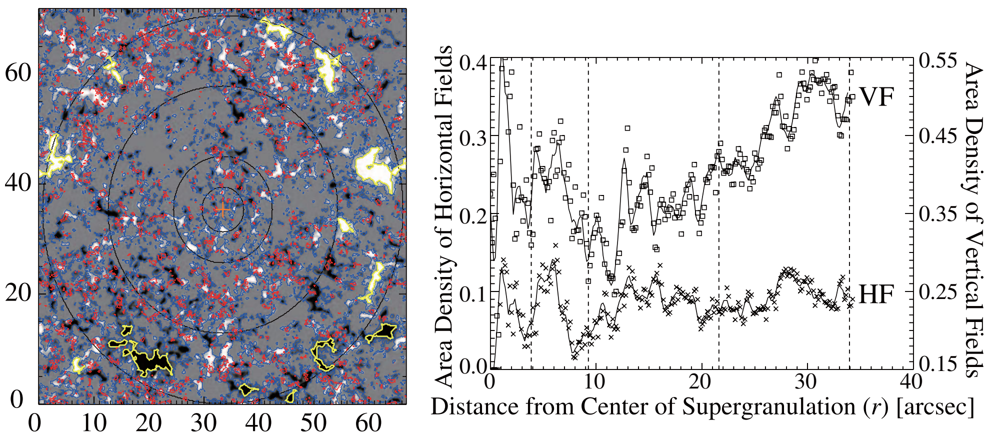

Figure 2. Left panel shows circular polarization (CP) map. Red contours indicate regions with significant linear polarization (LP) signals. Yellow contours indicate the network magnetic fields, whereas blue contours enclose regions with significant CP signals. Right panel indicates the areal density of vertical field (VF) patches defined as pixels with significant CP signals, and that of horizontal field (HF) patches defined as pixels with significant LP signals, as a function of the distance from the center of the supergranule. The four dashed lines correspond to the four circles in the left panel. For the VF areal density plot, pixels defined as network fields and enclosed by yellow contours are excluded. Adapted from Ishikawa & Tsuneta (2011).

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polarization (LP) and circular polarization (CP) signals inside the network by investigating a quiet-Sun region covering a single supergranular cell observed with SOT/SP (Ishikawa & Tsuneta 2011). Pixels with significant LP signals, shown with red contours in the left panel of Figure 2, correspond to granular-scale transient horizontal magnetic fields. As shown in the right panel of Figure 2, the areal density of horizontal magnetic fields is constant whereas that of vertical magnetic fields increases toward the boundary. This indicates that purely vertical magnetic fields tend to be concentrated around supergranular boundaries, whereas horizontal magnetic fields are not.

4. Relation between vertical and horizontal magnetic fields

A clear positional association of CP and LP signals exists in the internetwork region (Ishikawa & Tsuneta 2011). As seen in the left panel of Figure 2, LP signals overlap with CP signals. This association between horizontal and vertical magnetic fields in the internetwork region is also confirmed by the right panel of Figure 2; within a distance of 20″ from the center of the supergranulation, (i.e., in the internetwork region), both areal fractions are flat. These observations indicate that internetwork regions are overflowing with granular-scale closed loops, and that these footpoints are observed as vertical magnetic fields (Ishikawa & Tsuneta 2011).

To retrieve the intrinsic field strength within a resolution element, Stenflo (1973) introduced the Stokes V line ratio method. Applying this method to the Fe I 630.2 nm line system of SOT/SP, Stenflo (2010) found two distinct populations of strong (kG) fields in the intergranular lanes and weak fields within the bright granules, and speculate that this can be understood in terms of a convective collapse mechanism; hence, they refer to these two populations as collapsed and uncollapsed fields. The convective collapse scenario was proposed by Parker (1978) as a process of kG field formation, and observationally confirmed by Nagata *et al.* (2008) using SOT/SP.

We applied the same Stokes V line ratio method to the inside and outside of horizontal magnetic fields (Figure 3, Ishikawa & Tsuneta 2011). The data points inside the horizontal magnetic fields are clearly concentrated along the dashed line, which indicates the weak field regime (left panel of Figure 3). Note that the LP and CP signals overlap in this region. Outside the horizontal fields, most data points remain around the dashed line, although some with larger Stokes V amplitudes start to diverge. This could indicate the transition from uncollapsed to collapsed fields outside the horizontal fields. We conjecture

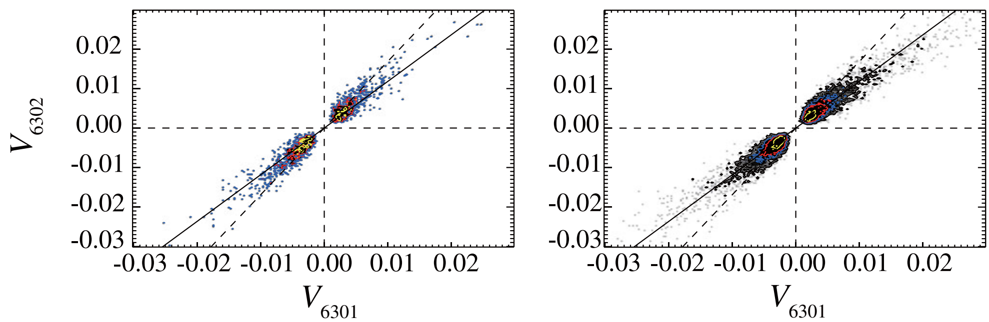

Figure 3. Scatterplot of Stokes V amplitudes derived for the 630.15 nm line vs. the corresponding amplitudes for the 630.25 nm line. The dashed line represents the regression line expected for weak fields. The solid line represents the regression line for strong (kG) fields. Left and right panels show plots for the inside and outside of horizontal fields, respectively. Adapted from Ishikawa & Tsuneta (2011).

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that the weak magnetic fields are provided by the emergence of granular-scale horizontal fields, and that the footpoints of some horizontal fields are intensified beyond the kG level owing to convective collapse (Ishikawa & Tsuneta 2011).

5. Conclusion

The properties of small-scale magnetic fields in the quiet Sun are presented, with a special focus on their spatial distributions. In the internetwork region, both horizontal and vertical magnetic fields are concentrated on the mesogranular boundaries. These horizontal and vertical magnetic components have a clear positional association, suggesting the presence of abundant granular-scale loops whose footpoints are observed as vertical magnetic fields. These small-scale magnetic fields could be provided by a local dynamo process (Section 1). If so, seed fields could conceivably be transported by the mesogranular flow and accumulate at mesogranular boundaries. On the other hand, only vertical magnetic fields are concentrated at supergranular boundaries. The footpoints of these small-scale horizontal magnetic fields may be a source of collapsed fields (kG) in the quiet Sun (Section 4). Vertical magnetic fields anchored in the intergranular lane are more stable than horizontal fields and can be transported by the supergranular flow toward the boundary to eventually form network fields. de Wijn *et al.* (2008) have found that the apparent flow velocities of magnetic elements (vertical magnetic fields) in the internetwork region are slightly biased by 0.2 km s^{-1} in the radial direction toward the network boundary. More directly, Orozco Suárez *et al.* (2012) have provided evidence to show that magnetic elements that appear within supergranules tend to drift toward the supergranular boundaries.

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