論文内容の要旨

論文題目：Properties of transient horizontal magnetic fields as revealed with Hinode and their implication to the origin of quiet Sun magnetism

（「ひので」によって発見された短寿命水平磁場の性質と太陽静穏領域磁場の起源について）

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The origin and evolution of the quiet Sun magnetic fields are not well understood. Most of the studies on the quiet-Sun magnetism have taken measurements of the line-of-sight magnetic fields with moderate spatial and temporal resolution. In the quiet Sun, vertical strong (kG) magnetic flux tubes concentrate around the boundaries of supergranulations, and are called network fields. Meanwhile, the magnetic fields in the internetwork regions (regions within the network) appear to have quite different magnetic properties, namely, relatively small magnetic fluxes with mixed polarities, and smaller magnetic patches.

This thesis is concerned with the properties of magnetic fields in the quiet-Sun photosphere, as revealed by the *Hinode* satellite. The spectropolarimeter of the Solar Optical Telescope (SOT) on board *Hinode* measures magnetic field vectors with unprecedented high spatial resolution of $0\farcs32$, obtaining full Stokes spectra at Fe I 630.2 nm lines. Throughout this thesis, we considered the effect of photon noise, and performed statistically valid analysis. Following the introduction in Chapter 1, the thesis begins with the discovery by *Hinode* of ubiquitous transient horizontal magnetic fields (THMFs) in the solar photosphere. The THMFs are smaller than 1 arcsec^2 and have lifetimes ranging 1–10 minutes. The occurrence rate is quite high, and THMFs are embedded in $\sim 10\%$ of granules.

We report the temporal evolution of a spatially isolated, transient horizontal magnetic field (THMF) in a weak plage region in Chapter 2. The evolution starts with the appearance of small-scale horizontal magnetic fields inside a granular cell, which is followed by the appearance of bipolar vertical fields. These THMFs seem to be tossed about by upflows and downflows of the granular convection. The emergence of THMFs is quite different from prototypical emerging phenomena leading to the formation of active regions in terms of their small size, short lifetime, and ubiquity.

We present the statistical properties of THMFs in Chapter 3. The THMFs statistically appear within the granules but near the edges. Apparently the upward granular convective motion drives and/or assists the emergence. When they disappear, some have reached the intergranular lane where downflow dominates, and some are still located inside the granular region. Both the lifetime and size of the THMFs are less than those of granules. As with granules, THMFs do not have a typical spatial scale, while the horizontal magnetic fields have a characteristic lifetime of 4 minutes. Combining the typical lifetime with their behaviors with regard to disappearance, we speculate that some THMFs pass through the line-forming layer and reach higher atmospheric layers.

In Chapter 4, we present the three-dimensional magnetic structure of a THMF during its evolution through the photosphere using SIRGAUS inversion code. SIRGAUS code is a modified version of SIR (Stokes Inversion based on Response function), and allows for retrieval of information on the magnetic and thermodynamic parameters of the flux tube embedded in the atmosphere from the observed Stokes profiles. Rigorous error estimation with a χ^2 map allows us to point to the existence of a Ω-shaped flux tube with magnetic field strength of ~ 400 G rising through the line-forming layer of the analyzed lines. The flux tube is located at around $\log \tau_{500} \sim 0$ (z =0 km) at Δt=0 s and around $\log \tau_{500} \sim -1.7$ (z =240 km) at Δt=130 s. At Δt=260 s, the horizontal part is already above the line-forming layer. The observed Doppler velocity is maximally 3 km s^{-1}, which is consistent with the ascending motion of the structure as retrieved from the SIRGAUS code. The magnetic flux carried by this THMF is estimated to be 3.1×10^{17} Mx. The total magnetic flux of THMFs for the entire Sun (7×10^{28} Mx) in one solar cycle is greater than those of ephemeral regions (3×10^{26} Mx) and sunspot regions (10^{25} Mx). The three-dimensional structure also suggests that THMFs would be part of a larger flux tube embedded below the photosphere.

We obtain and compare the properties of THMFs in both a plage and the quiet Sun, and examine the possibility of a local dynamo process in Chapter 5. The occurrence rate in the plage region is the same as that in the quiet Sun, although the vertical magnetic flux in the plage region is $\sim$8 times that in the quiet Sun. Probability density functions of intrinsic field strengths inferred from the inversion using a Milne-Eddington atmosphere do not show any difference between the quiet Sun and the plage region. Most (93%) of the horizontal fields are weaker than 700 G, which is the equipartition field strength corresponding to granular convective motion. The sub-equipartition field strengths of THMFs and the exact coincidence of the probability density functions and the occurrence rates between plage and quiet regions suggest that a local dynamo process caused by granular motion generates THMFs all over the Sun. THMFs in the plage region with higher linear polarization signals have a preferred azimuth direction consistent with that of the plage-region's large-scale vertical field pattern. This non-uniform distribution of the horizontal magnetic vectors indicates that THMFs may be somewhat influenced by the larger-scale magnetic field pattern as represented by the plage region. We also find that the total magnetic energy carried by THMFs ($\sim 2 \times 10^6$ erg cm^{-2} sec^{-1}) is comparable to the total chromospheric and coronal energy loss.

In Chapter 6, we present results obtained with a long exposure vector magnetogram taken by the Narrowband Filter Imager (Fe I 525.0 nm) of SOT. We sum the linear polarization maps of the quiet-Sun photosphere at the disk center with a wide field of view of $51'' \times 82''$, and the polarization sensitivity would be more than 4.6 (21.2 in exposure time) times the standard observation (4.8 sec exposure) with the SOT spectropolarimeter. The linear polarization map shows a cellular structure with a typical scale of $5'' - 10''$. We find that the enhanced linear polarization signals essentially consist of isolated sporadic THMFs, and are not contributed by long-duration weak horizontal magnetic fields. The cellular structure coincides in position with the negative divergence of the horizontal flow field; i.e., mesogranular boundaries with downflows. The azimuth distribution appears to be random for the scale of mesogranules. Some pixels have two separate appearances of THMFs, and the measured time intervals are consistent with random appearance. THMFs tend to appear at mesogranular boundaries, but appear randomly in time. We propose that the seed fields of THMFs are advected by the mesogranular flows, and the granular convective motion amplifies the field strength and drives the emergence of the horizontal fields around the mesogranular boundaries.

So far we have concentrated on the properties of THMFs. In Chapter 7, we broaden our scope to clarify the origin and properties of internetwork magnetic fields, both vertical and horizontal, in a unified way. We find clear positional association between vertical and horizontal magnetic fields in the internetwork region. Essentially all of the horizontal magnetic patches (THMFs) are associated with vertical magnetic patches. Alternatively, half of the vertical magnetic patches accommodate horizontal magnetic patches. These horizontal patches are located around the borders of vertical patches. The intrinsic magnetic field strength within the horizontal patches as obtained with the Stokes V line ratio is weak, and is in sub-equipartition field regime ($B < 700$ G), while the field strength outside the horizontal patches ranges from weak to strong (kG) fields. Vertical magnetic patches are known to be concentrated at mesogranular and supergranular boundaries, while horizontal magnetic patches are found only at mesogranular boundaries. We quantitatively present properties of both vertical and horizontal magnetic patches, such as the size, mutual location, magnetic flux density and total magnetic flux, in this chapter.

With our combined knowledge of the newly investigated THMFs and the vertical magnetic fields known for decades to exist, we conjecture that magnetic fields in the internetwork regions are provided by the emergence of small-scale flux tubes with bipolar footpoints, and the vertical magnetic fields of the footpoints intensify to kG fields owing to convective collapse. Resultant strong vertical fields are advected by the supergranular flow, and eventually form network fields.