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SEETHING HORIZONTAL MAGNETIC FIELDS IN THE QUIET SOLAR PHOTOSPHERE

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ABSTRACT

The photospheric magnetic field outside of active regions and the network has a ubiquitous and dynamic line-of-sight component that strengthens from disk center to limb as expected for a nearly horizontal orientation. This component shows a striking time variation with an average temporal rms near the limb of 1.7 G at ∼3″ resolution. In our moderate-resolution observations the nearly horizontal component has a frequency variation power-law exponent of −1.4 below 1.5 mHz and is spatially patchy on scales up to ∼15″. The field may be a manifestation of changing magnetic connections between eruptions and evolution of small magnetic flux elements in response to convective motions. It shows no detectable latitude or longitude variations.

Subject headings: Sun: magnetic fields — Sun: photosphere

1. INTRODUCTION

It has been known for more than 30 years that the “quiet” photosphere contains magnetic fields (Livingston & Harvey 1971). Most prominent are compact, mixed-polarity flux elements of the order of 10^{16} Mx and arcsecond sizes that vary over tens of minutes (Livingston & Harvey 1975; Smithson 1975). The quiet-Sun magnetic field is known by various names with the term internetwork (IN) field in wide use. Small fluxes and sizes with rapid time changes make the compact IN fields difficult to observe and characterize (e.g., Keller et al. 1994). Lin & Rimmele (1999) detected an additional component consisting of a close association between granulation and a fluctuating ∼1 G vertical component of the quiet-Sun magnetic field that they call a granular magnetic field.

Most previous IN field observations have been made at or near disk center using line-of-sight (LOS) magnetograms that reveal properties of the vertical component of the IN field (e.g., Socas-Navarro et al. 2004). There is scant information about the center-to-limb variation of the IN or its possible horizontal components. Martin (1988) presented IN field observations showing little, if any, center-to-limb variation of the LOS component, implying that the IN fields are more isotropically oriented than the network fields. Lites et al. (1996) used vector magnetograms near disk center to discover sporadic short-lived (5 minute), arcsecond-scale horizontal IN field elements that they named HIFs. They associated HIFs with the eruption of small bipolar elements of magnetic flux from the solar interior. Meunier et al. (1998) made sensitive one-dimensional scans across the disk and concluded that the IN field consisted of relatively strong, mainly vertically oriented features and weaker, mainly horizontal components. De Pontieu (2002), observing at a heliocentric angle of 38°, found several LOS magnetic features, longer lived than HIFs, which were interpreted as being mainly horizontally oriented and closely related to granular flow dynamics.

In this Letter we present results from time sequences of LOS component magnetograms of the quiet Sun made with the SOLIS vector spectromagnetograph (VSM; Keller et al. 2003) and the GONG network instruments (Harvey et al. 1988). Using different methods, the instruments provide the difference between the wavelengths of Zeeman sensitive lines in right and left circularly polarized light. These differences are expressed as the homogeneous LOS field strength in gauss that would produce the measured splitting. Since the field is generally inhomogeneous, we obtain only lower limits of true LOS field strengths. Our observations are unique in combining full-disk coverage and comparatively high time cadence, with good sensitivity and moderate spatial resolution. These properties have revealed that there is a ubiquitous, spatially structured, nearly horizontal field component that varies strikingly over a wide range of time periods.

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2. OBSERVATIONS AND RESULTS

We made time sequences of LOS magnetograms with the VSM (90 s cadence, 3.2 hr duration on 2006 December 15, 1.1″ pixels) and with GONG (10 minute cadence of 10 minute averages coinciding with the VSM data and also a 7 hr duration on 2006 December 6, 2.5″ pixels). Each time sequence was registered to a fixed solar image centering, and then disk features were rotated to a selected time using an assumed representation of solar rotation. These steps led to movies that emphasized real solar changes.

Near disk center the movies show relatively slow variations consisting of evolution of the network fields and the mixed-polarity IN fields. Increasingly obvious away from disk center, another mixed-polarity, more dynamic component is present everywhere in otherwise quiet areas. It is patchy with sizes ranging from our resolution limit of a few arcseconds to ∼15″ that remain visible for a few minutes to more than 15 minutes at our noise levels of ∼1 and ∼0.2 G pixel^{-1} for GONG and VSM data, respectively.

The heretofore unrecognized patchy field is visible in single observations such as Figure 1 as an increasingly mottled background structure as one looks from disk center to the limb. In contrast, the visibility of network fields decreases toward the limb. Figure 2 better emphasizes these dynamic background structures by subtracting a long time average from a single magnetogram. In addition, we prepared Figure 3 from 7 hr of magnetograms to study the center-to-limb behavior of the changing fields. It shows the temporal rms of the time-varying fields over the solar disk. To emphasize the patchy field variations, we excluded any measurements with absolute field strengths >5.5 G and set such areas to white in the figure. Remaining is the temporal rms variation of the dynamic back-

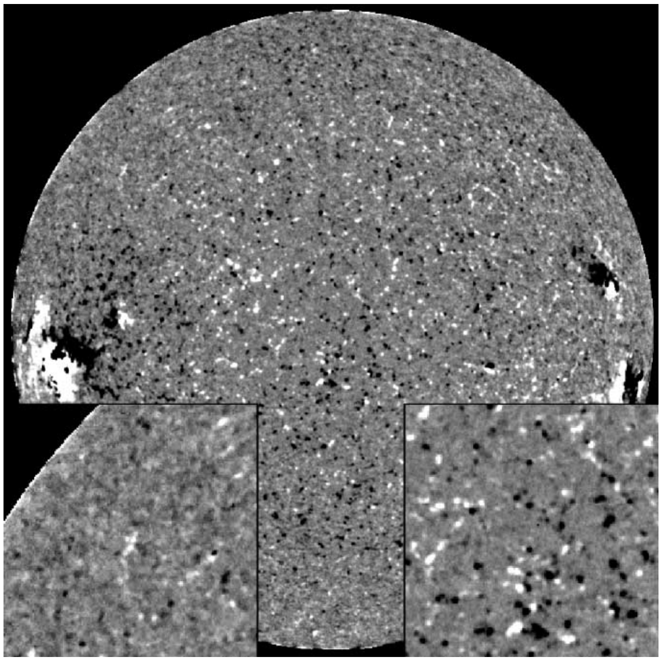

FIG. 1.—LOS component of the photospheric magnetic field averaged from 18:42–18:49 UT on 2006 December 6 observed with the GONG instrument at Big Bear Solar Observatory. Insets are twice-magnified pieces from the upper left (*left*) and disk center (*right*). Note increased background mottling toward the limb compared to near disk center. The display saturates at ± 15 G.

ground field and other sources of changes. These other sources include seeing and registration variations, proper motion of magnetic features, appearance, disappearance, and shape changes of magnetic features, barely resolved IN fields, and instrumental noise. The latter is a combination of camera and photon noise—being relatively low near the bright disk center and greater near the darker limb. We modeled this noise and find it to vary with radius only slowly except close to the limb.

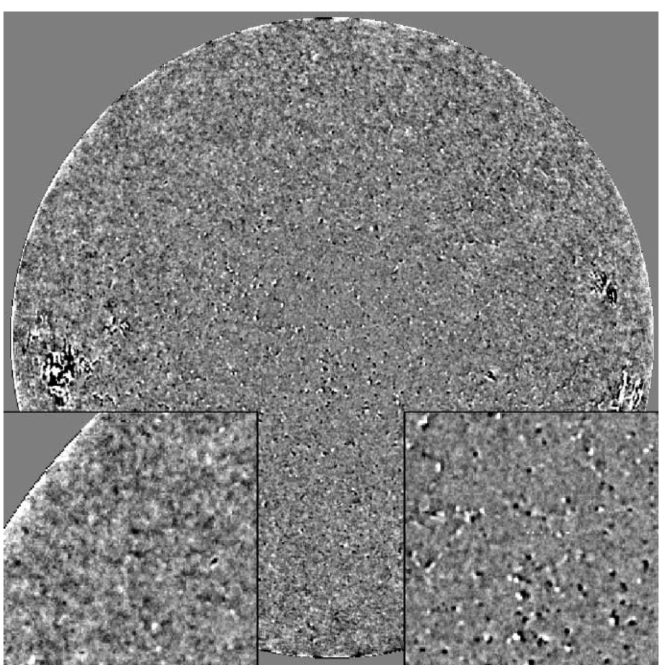

FIG. 2.—Difference between the data of Fig. 1 and a 16:42–23:34 UT averaged magnetogram to emphasize the increased background structure near the limb compared to near disk center. Same format as Fig. 1. Display saturates at ± 7.5 G.

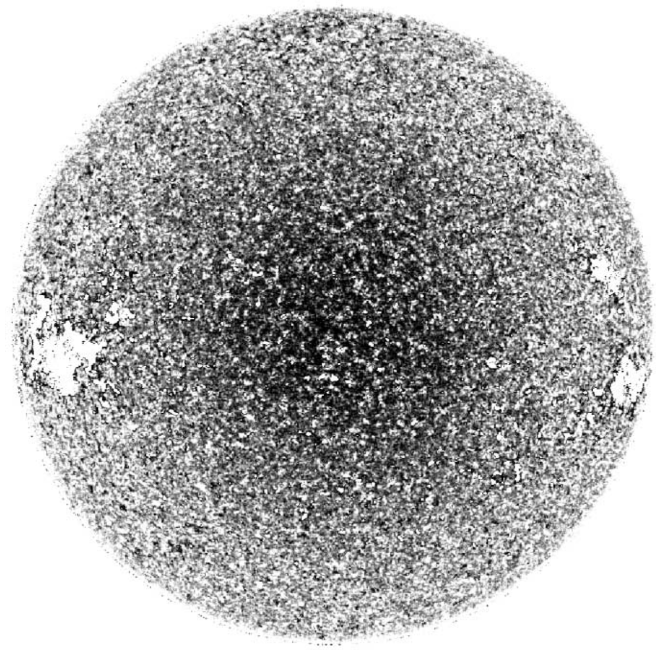

FIG. 3.—Temporal rms variation of the LOS magnetic field from 16:42–23:34 UT. Black corresponds to 1.3 G and white to 2.3 G. Regions with measured absolute LOS field strengths >5.5 G were not included in the calculation of the temporal rms and are set to white. Note the increase of the rms toward the limb and the absence of any large-scale departure from radial symmetry.

The majority of the signal variation in Figure 3 is caused by the dynamic background field.

The obvious increase of the magnetic field fluctuations toward the limb suggests that the dynamic features are mainly horizontally oriented. Figure 4 (*upper solid curve*) is a radial average of the LOS data in Figure 3 (excluding strong fields) and supports this idea. Horizontally oriented structures should strengthen with the sine of heliocentric angle, i.e., a linear increase with distance from disk center. The upper curve nicely shows a linear trend but also contains instrumental noise (and a seeing-noise spike at the limb). The dashed curve is a model of camera and photon noise. The lower curve is the quadratic difference of the observed rms minus the instrumental noise model. The corrected rms is not linear, suggesting that the

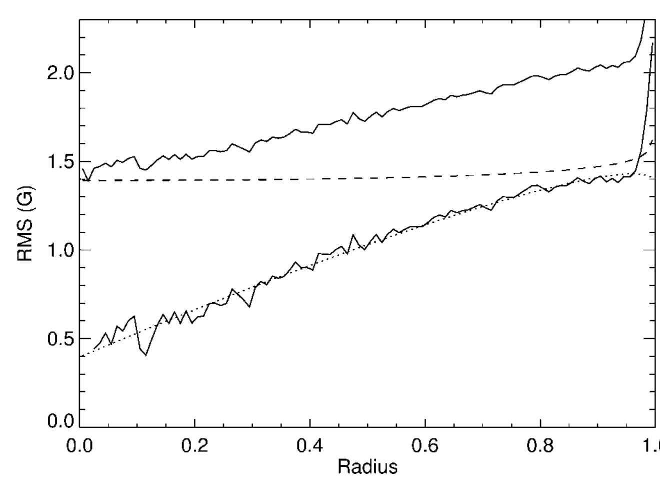

FIG. 4.—*Upper solid curve*: Radial average of the data in Fig. 3 excluding regions with measured absolute fields >5.5 G. *Dashed curve*: Model of noise due to the camera and photon statistics. *Lower solid curve*: Observed rms corrected for the noise model. *Dotted curve*: Model of the corrected rms.

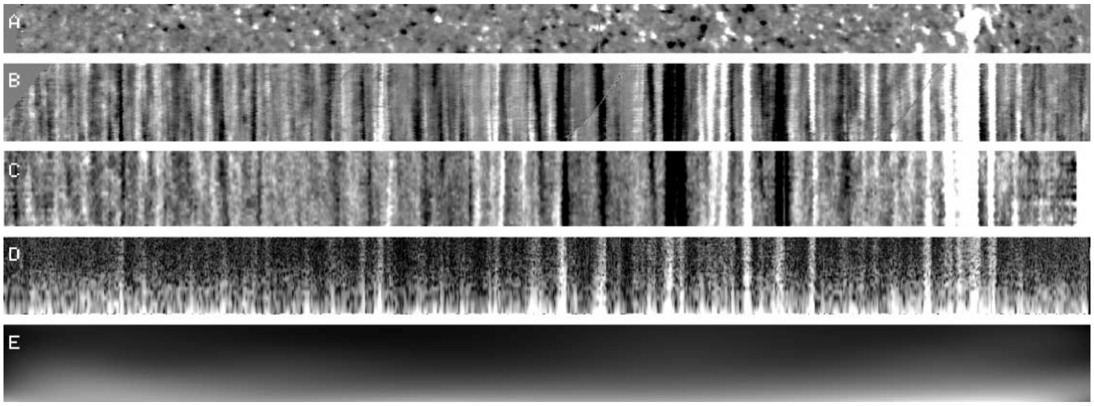

FIG. 5.—Limb-to-limb cuts across the solar disk on 2006 December 15. (*a*) A VSM LOS magnetogram displayed with saturation at ± 22 G. (*b*) VSM data time variation for 3.2 hr along a trace through the area shown in (*a*). The display saturates at ± 11 G and the spatial glitch in the middle is a data reduction artifact. (*c*) Same as (*b*), except using GONG data. Registration with (*b*) is best near the limbs. Coarser spatial and time GONG samples were interpolated to match the VSM data. Note higher noise level compared to VSM data. (*d*) Log of 3 decades of power spectra of the columns in (*b*) displayed on a log frequency scale from 0.09 at the bottom to 5.2 mHz at the top. Note absence of any obvious periodic signal. (*e*) Spline-smoothed fit of the background of (*d*). Note the larger background power levels toward the limbs.

fluctuating field is not strictly horizontal. The dotted curve is a model for which the field is inclined to the vertical by 74° and fits the data. The rms near the limb could also be reduced by loss of resolution due to foreshortening and a possible height variation of the dynamic field, factors that would make the inferred field direction more nearly horizontal.

VSM data confirm the GONG results with lower noise and higher spatial resolution and cadence. Figure 5*a* is a 1880″ × 83″ cut from one frame of a VSM time series of LOS magnetograms (offset ∼2′ from disk center). The time variation over 3.2 hr along a trace through this area is shown in Figure 5*b*. The varying horizontal magnetic field is seen near the edges as mottling. In comparison, the mottling is nearly absent in quiet areas near disk center. The temporal rms of network-free regions near disk center measures 0.8 G, while near the limb it is 1.9 G. Quadratically subtracting these values gives 1.7 G as the temporal rms of the horizontal field near the limb. This can be compared with the lower resolution GONG value of ∼1.4 G near the limb (Fig. 4, *bottom curve*). Higher spatial resolution data would no doubt give a larger value for the temporal rms of the horizontal field. Figure 5*c* shows data from the GONG instrument located at Cerro Tololo processed to try to match the VSM data. The GONG data are noisier, and the registration is imperfect, especially just left of center, but similarity of the background solar signals is evident here and in movies. Figure 5*d* is a series of power spectra of the data in Figure 5*b* covering the frequency range from 0.09 to 5.2 mHz. Figure 5*e* is a spline-smoothed fit to the lower envelope of the power spectra to show the enhanced background power toward the limbs.

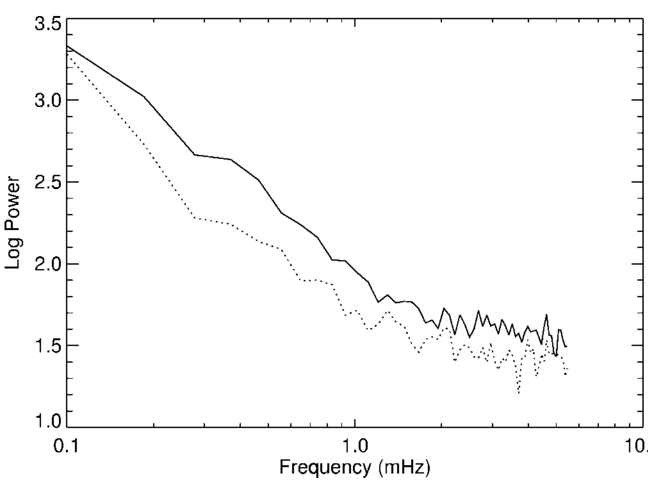

FIG. 6.—Typical power spectrum averages for a region near the limb (*solid line*) and near the disk center (*dotted line*). See text for discussion.

Going beyond a simple rms analysis, Figure 6 shows average power spectra for data near the limb (*solid line*) and near disk center (*dotted line*). The near-limb spectrum is dominated by a $\nu^{-1.4}$ slope at low frequency up to about 1.5 mHz. At higher frequencies, after a short transition, the spectrum is essentially flat due to instrumental and registration noise. There is no obvious indication of excess power around 3 mHz. Near the disk center, where the horizontal field component is small, the average power spectrum is weaker and more complicated. At low frequencies it becomes steeper than -1.4. From 0.3 to ∼2.0 mHz the power varies as ν^{-1}. At higher frequencies the spectrum is flattened by noise with no sign of extra power at 3 mHz.

3. SUMMARY AND DISCUSSION

We discovered a ubiquitous, nearly horizontal component of the solar magnetic field in quiet regions of the photosphere. Its reality is confirmed using observations with different instruments, spectrum lines, and measurement techniques. This component exhibits wide ranges of spatial and temporal scales: from our resolution limit of a few arcseconds up to ∼15″ and from times of several minutes to hours. In movies of the LOS field, this component looks like a seething pattern of mottling. At a spatial resolution of 5″ the average temporal rms of the horizontal field variation near the limb is 1.4 G. Doubling the spatial resolution to 2.5″ increases the temporal rms value to 1.7 G.

On the basis of its temporal and spatial scales, we speculate that the seething horizontal field is driven by granular and supergranular convection, and by field line reconfigurations in response to evolving flux distributions in the nearby network and IN. De Pontieu (2002) observed eruption and subsequent shredding of a few IN magnetic flux elements consistent with this notion. If connections with existing network flux elements are important, we might expect a dependence of the strength of the horizontal component on the amount of neighboring large-scale magnetic flux. The lower right part of Figure 3 contains such a location, and there is no evidence to support this expectation. This finding, and the absence of any evidence of latitudinal or longitudinal dependence, favors the idea that the horizontal field is mainly created and driven by local processes. Recent numerical simulations by Georgobiani et al. (2007) show that it is impossible to separate temporal and spatial components of a solar convective turbulence spectrum. So we cannot make a simple interpretation of the observed $\nu^{-1.4}$ power variation over more than a decade of frequency. The absence of any but feeble hints of excess power at 3 mHz suggests that *p*-mode oscillations play little, if any, role in the dynamics of the horizontal field.

The sporadic HIFs observed by Lites et al. (1996) are probably small bipolar flux elements erupting from the interior. They are too infrequent to explain the ubiquitous, nearly horizontal field fluctuations that we found. Numerical magnetoconvection simulations can provide insight into the physics of the horizontal field. For example, Gadun et al. (2001) find a weak, predominantly horizontal field in the photospheric layers of granules associated with strong horizontal flows. It would be interesting to see what more advanced models, such as those of Khomenko et al. (2005) would predict on a scale larger than granulation. More extensive and detailed observations are certainly required to clarify the physical nature of the nearly horizontal field. Many questions remain unanswered: Is a similar field observed higher in the solar atmosphere? (Our preliminary observations of the LOS field in the chromosphere do not show the seething field.) Is the field a miniature version of canopy fields found around strong flux concentrations? What is the detailed relationship with the photospheric convective and oscillatory velocity fields? What is the association with the granular magnetic field of Lin & Rimmele (1999)? How does the field fit with Hanle-effect observations of a microturbulent magnetic field (e.g., Stenflo et al. 1998)?

Although most attention has been directed to the vertical component of the quiet-Sun magnetic field, the ubiquitous presence of a nearly horizontal component suggests that additional studies may prove it to be at least as significant in improving our understanding of solar magnetism. A practical consequence of the field involves extrapolations of photospheric field measurements to the corona. It is usually assumed that the observed LOS fields are radially oriented in order to estimate the surface distribution of magnetic flux. This assumption is acknowledged as wrong in active regions. Now we know that it is also incorrect for quiet regions observed near the limb. However, time and spatial averaging of observations may mitigate this effect. Finally, we note that it is overly simplistic to consider the IN field as being composed of independent vertical and horizontal components. It is most likely that these are just observational manifestations of a dynamically interacting field of wonderful complexity.

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Facilities: GONG, SOLIS

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