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Hinode Observations of Horizontal Quiet Sun Magnetic Flux and the "Hidden Turbulent Magnetic Flux"

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Abstract

We present observations of magnetic fields of the very quiet Sun near disk center using the Spectro-Polarimeter of the Solar Optical Telescope aboard the Hinode satellite. These observations reveal for the first time the ubiquitous presence of horizontal magnetic fields in the internetwork regions. The horizontal fields are spatially distinct from the vertical fields, demonstrating that they are not arising mainly from buffeting of vertical flux tubes by the granular convection. The horizontal component has an average "apparent flux density" of $55\,\mathrm{Mx\,cm^{-2}}$ (assuming the horizontal field structures are spatially resolved), in contrast to the average apparent vertical flux density of $11\,\mathrm{Mx\,cm^{-2}}$. The vertical fields reside mainly in the intergranular lanes, whereas the horizontal fields occur mainly over the bright granules, with a preference to be near the outside edge of the bright granules. The large apparent imbalance of vertical and horizontal flux densities is discussed, and several scenarios are presented to explain this imbalance.

Key words: internetwork — quiet Sun — Stokes polarimetry — Sun: magnetic fields

1. Introduction

Magnetic fields in the quiet Sun (QS) are drawing increasingly more attention because of their probable cause of heating of the chromosphere and corona and their possible connections to the solar dynamo (both global and local). On the observational side, there have been many recent attempts to characterize the properties of these fields (distributions of intrinsic field strengths, total unsigned flux, characteristic size scales, and evolutionary history). Here we cite a few recent papers (Lites & Socas-Navarro 2004; Khomenko et al. 2005; Domínguez Cerdeña et al. 2006a, b; Sánchez Almeida 2007; Orozco Suárez et al. 2007) that, taken together, summarize the current observational state of QS magnetism. From a theoretical and modeling standpoint, the observed distribution of magnetic fields is needed to guide MHD simulations of magneto-convection in order to validate our current understanding of convection in the presence of low levels of magnetic flux. Recent simulations include Vögler et al. (2005) and Abbett (2007).

Recognizing that the magnetic fields of the QS occur on very small scales, much of the recent observational emphasis has been to examine its small-scale structure (Domínguez Cerdeña et al. 2003; Lites & Socas-Navarro 2004) using the longitudinal Zeeman effect: circular polarization in spectral lines. This diagnostic technique allows both high sensitivity to weak magnetic flux and high angular resolution to resolve small-scale structures. In contrast, a parallel effort has been to use other magnetic diagnostics that have high sensitivity to the presence and/or average properties of weak fields without the need to distinguish individual structures. One such diagnostic is the Hanle effect in which the scattering polarization is modified by the presence of a magnetic field (e.g., Stenflo et al. 1998). Recent analyses based upon Hanle diagnostics suggest that the photosphere is permeated by fields much stronger (of order 100 gauss) than those seen at the highest resolution studies using Zeeman effect diagnostics (Trujillo Bueno et al. 2004; Manso Sainz et al. 2004). Because fields of this average strength have never been seen with the usual Zeeman diagnostics, presumably because they are unresolved spatially, they have been labeled the "hidden turbulent magnetic fields" of the QS. One of those studies (Trujillo Bueno et al. 2004) suggests that the fields have an average intrinsic strength of

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130 gauss, and that those fields reside dominantly in the inter-granular (IG) lanes. Note that the average field strengths suggested by that study are more than one order of magnitude greater than those observed so far from the ground using precision spectro-polarimetry (Lites & Socas-Navarro 2004).

To date, spectro-polarimetric measurements of the quiet solar photosphere have been obtained from the ground at very high sensitivity (Lites 2002; Lites & Socas-Navarro 2004; Domínguez Cerdeña et al. 2003; Socas-Navarro & Lites 2004), but the long integration times required to reach sensitivity levels at the $10^{-3} I_{\rm c}$ level or below have hindered study of weak fields at sub-arcsecond scales. New techniques have made possible wavefront reconstruction of polarimetry at very high angular resolution (Langhans et al. 2007), but so far these reconstructions have had limited polarimetric precision. As a result, they have been applied only to the strong polarization signals in sunspots and active regions. Because of the absence of seeing, the excellent stabilization of the image from the Solar Optical Telescope (SOT: Tsuneta et al. 2007; Suematsu et al. 2007; Ichimoto et al. 2007; Shimizu et al. 2007) aboard Hinode (Kosugi et al. 2007), and the good polarimetric precision of the Spectro-Polarimeter (SP: Tarbell et al. 2007), Hinode offers us access to a new regime of the product of angular resolution and polarimetric precision, thereby permitting the first chance to study in detail the weak magnetic flux both along and transverse to the line-of-sight (LOS) in quiet internetwork (IN) regions.

At the outset, the objective of this work was to characterize the IN fields at the $0.''3$ resolution and polarization sensitivity $\leq 10^{-3} I_{\rm c}$ newly available from the Hinode SP, and thereby search for evidence of the hidden turbulent flux. If that hidden flux exists as small-scale, mixed polarity fields as suggested by Trujillo Bueno, Shchukina, and Asensio Ramos (2004), one might find a rapid increase in the average unsigned LOS component of the fields beyond that of prior measurements. The visibility of such structures with increasing angular resolution, of course, depends upon the probability distribution of the characteristic dimension of those hidden turbulent fields. We report here the net unsigned average flux density (from the LOS component of the field observed at disk center) at the Hinode SP resolution ($0.''3$) is $11.0\,{\rm Mx\,cm^{-2}}$, which represents an average only modestly larger than that found by previous measures of this nature (Lites 2002; Lites & Socas-Navarro 2004). Therefore, the surprising new finding from the Hinode observations reported herein is not the observations of the LOS field, but rather the measurements of the transverse field.

Although prior studies have shown that small-scale horizontal structures do exist in the quiet IN (Lites et al. 1996), there was little indication until early this year that the *horizontal* component of the fields in the quiet Sun could be a significant contributor to the hidden turbulent flux. The study by Lites et al. (1996) revealed only a spatially sparse, transient appearance of measurable horizontal flux at a resolution of the order of $1''$. In order for horizontal fields to be effective in depolarizing line-scattered radiation, the fields must cover much of the solar surface with strengths of order 100 G: much larger than the average flux densities observed with the longitudinal Zeeman effect to date. The recent discovery of "seething" horizontal magnetic fields (Harvey et al. 2007) using the longitudinal Zeeman effect away from the center of the disk demonstrated the presence of a dynamic component of dominantly horizontal flux in the quiet solar photosphere having an rms fluctuation in apparent flux density of $1.7\,{\rm Mx\,cm^{-2}}$ observed with an angular resolution of approximately $2''$. If the horizontal fields responsible for these seething fields are mixed polarity and small scale, it is possible that they could have considerably

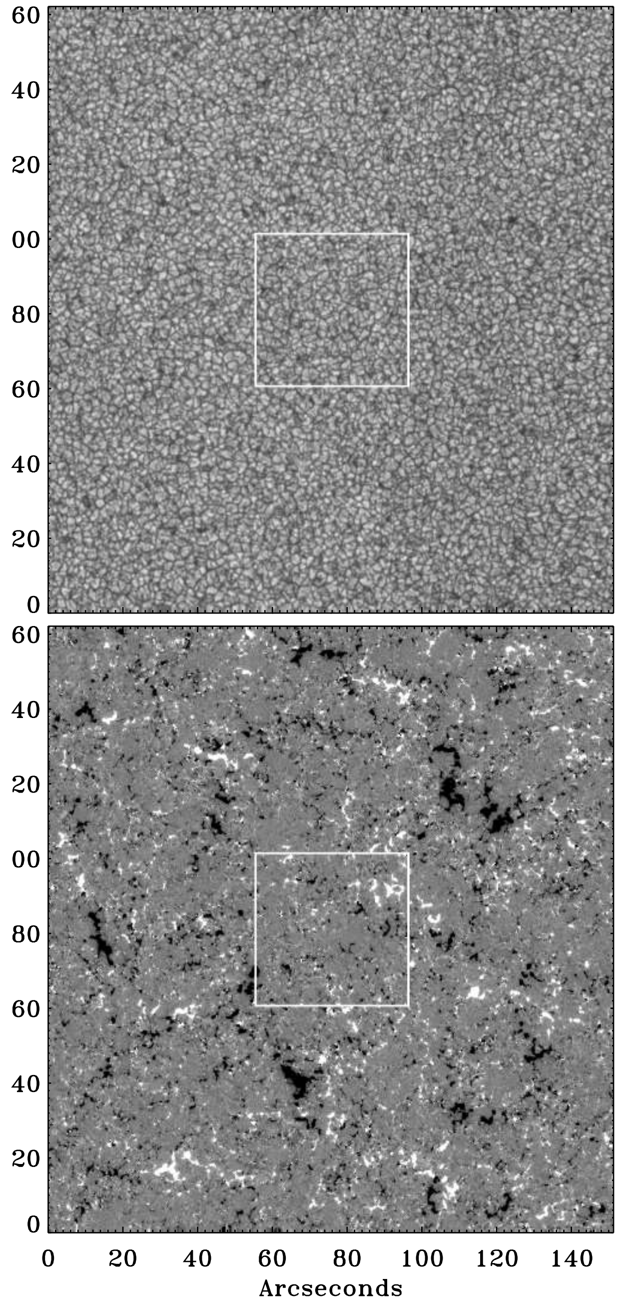

Fig. 1. The continuum intensity of the Hinode SP map taken at quiet disk center on 2006 November 22 between 15:02 and 16:29 UT is shown in the top image, and the corresponding $B^{\rm L}_{\rm app}$ is shown at bottom. The gray scale for the $B^{\rm L}_{\rm app}$ image saturates at $\pm 50\,{\rm Mx\,cm^{-2}}$. This figure is constructed from the $\sim 10^6$ full. Stokes spectra comprising the SP map. The rms intensity fluctuation of this map is 7.53%. The highlighted central area is shown in figures 3 and 4.

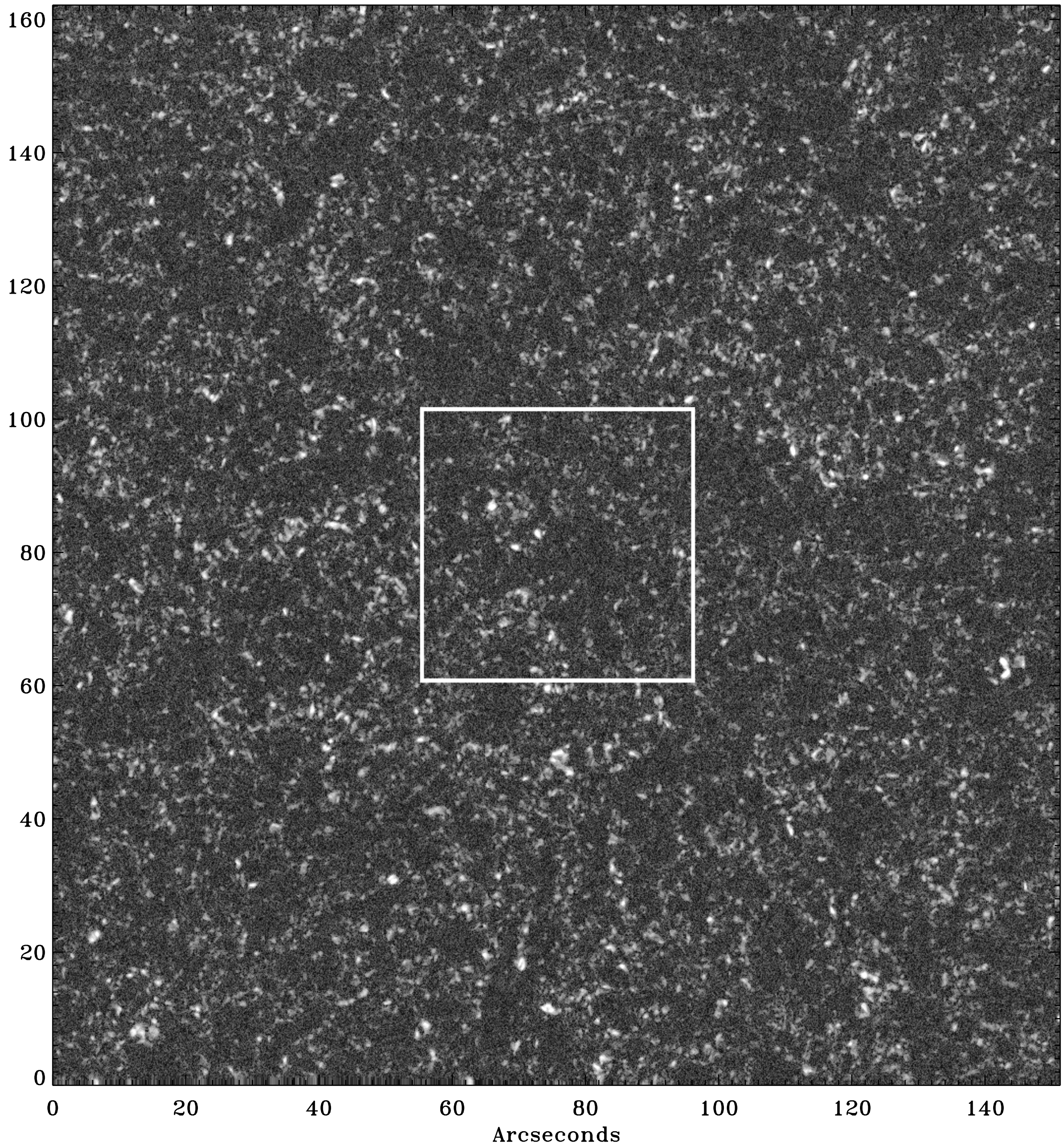

Fig. 2. The magnitude of the transverse apparent flux density, $B^{\rm T}_{\rm app}$, is shown for the 2006 November 22 data. The intensity scale ranges from 0 (black) to 200 Mx cm^{-2} (white). The highlighted central area is shown in figure 3.

larger strength than their observed fluctuation. Furthermore, the fluctuation of those fields could be significantly smaller than their average intrinsic strength. In view of this new discovery, and because there are very few measurements of horizontal fields in the quiet solar photosphere, we set another goal of the present work: to examination of possible sources of this dynamic, horizontal field at much higher resolution.

2. Observations of Apparent Flux Density

Figure 1 shows the continuum intensity $I_{\rm c}$ and the line-of-sight "apparent flux density" $B^{\rm L}_{\rm app}$ for a region of very quiet Sun near the center of the solar disk. The quantity $B^{\rm L}_{\rm app}$ is extracted from the wavelength-integrated Stokes V profiles ($V_{\rm tot}$) as defined in Lites et al. (1999), but here we have modified its computation slightly to allow for the modest nonlinearity of $V_{\rm tot}$ with intrinsic field strength B (see Lites et al. 2007).

The $B^{\rm L}_{\rm app}$ image in figure 1 is scaled so as to reveal weak flux, and on this linear scale we notice a "bloom" of polarization signature surrounding network elements that makes them appear much larger than the sizes of the associated

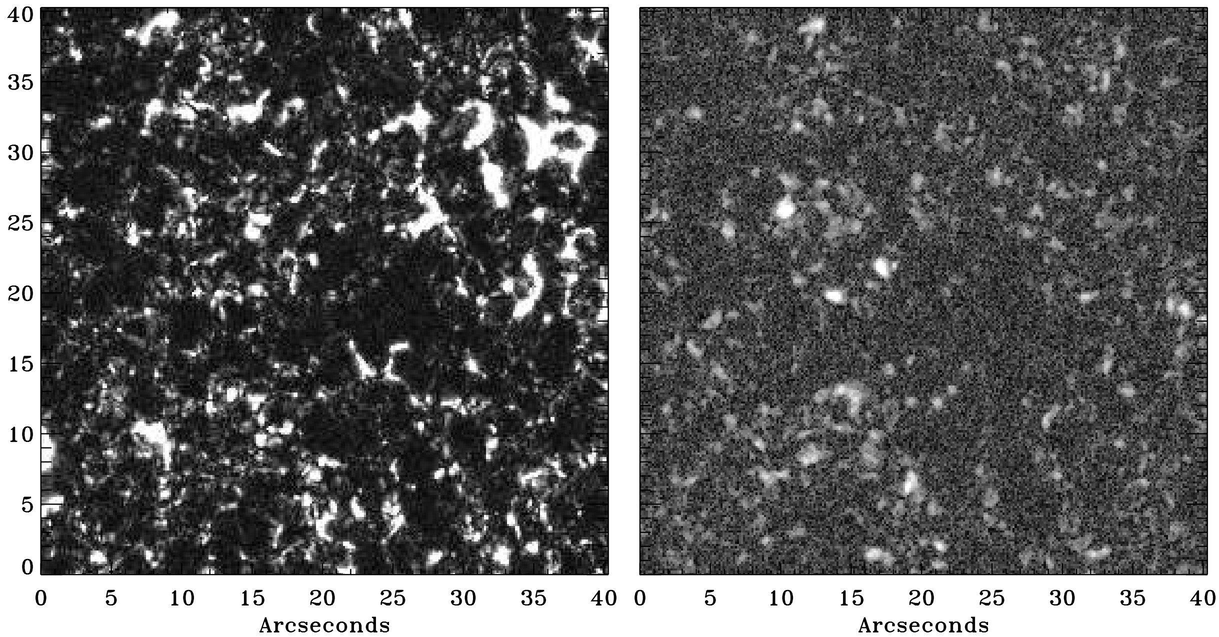

Fig. 3. The central 40″ square highlighted in figures 1 and 2 is shown in expanded view. The gray scale for the $|B^{\rm L}_{\rm app}|$ image at left saturates at 30 Mx cm^{-2}, whereas the $B^{\rm T}_{\rm app}$ image at right saturates at 200 Mx cm^{-2}. Note the meso-granular size areas in both images having small $|B^{\rm L}_{\rm app}|$ and $B^{\rm T}_{\rm app}$. The measurement noise is clearly apparent in $B^{\rm T}_{\rm app}$.

intense kilo gauss network flux elements. This bloom may be attributed in part to instrumental scattering. The network will also form a canopy (Jones & Giovanelli 1983) that, like sunspot fields (Lites et al. 1993; Adams et al. 1993; Solanki et al. 1994), may contribute to the bloom. However, the network fields will not spread horizontally within the photosphere as rapidly as those of sunspots due to the vertical orientation of network fields (Martínez Pillet 1997) relative to those of a sunspot penumbra.

Figure 2 shows the corresponding magnitude of the transverse apparent flux density $B^{\rm T}_{\rm app}$ as determined from the magnitude of the wavelength-integrated linear polarization. It is evident from this figure that an abundance of small-scale features are seen for the first time in the transverse Zeeman effect diagnostic of the horizontal magnetic field in the quiet Sun. This horizontal flux appears to be present over a significant fraction of the surface. In closer view, figure 3 compares $|B^{\rm L}_{\rm app}|$ and $B^{\rm T}_{\rm app}$ for the highlighted areas in figures 1 and 2. The measurement noise in the linear polarization is clearly visible in the $B^{\rm T}_{\rm app}$ image, but it is possible to distinguish the solar features from the noise by their spatial extent.

Figure 4 presents a continuum image with contours of $|B^{\rm L}_{\rm app}|$ and $B^{\rm T}_{\rm app}$ superimposed. The contours indicate the 10σ and 3σ signal levels above the noise: 24 and 124 Mx cm^{-2}, respectively for $|B^{\rm L}_{\rm app}|$ and $B^{\rm T}_{\rm app}$. This figure allows one to visualize the relationship of the vertical and horizontal flux to one another and to the granulation. Several aspects of IN fields are immediately apparent from inspection of figures 3 and 4:

- Both the horizontal and vertical flux appear to be ordered on a *mesogranular* scale, with the apparent lack of flux over the size scales of a few granules. We term these reduced-flux areas "voids".
- The typical fine-scale structure of the field is smaller than a granule, and many structures appear to be at or below the 0.″3 resolution of these observations.
- The horizontal flux is spatially distinct from the vertical flux. Note that the stronger network elements of $B^{\rm L}_{\rm app}$

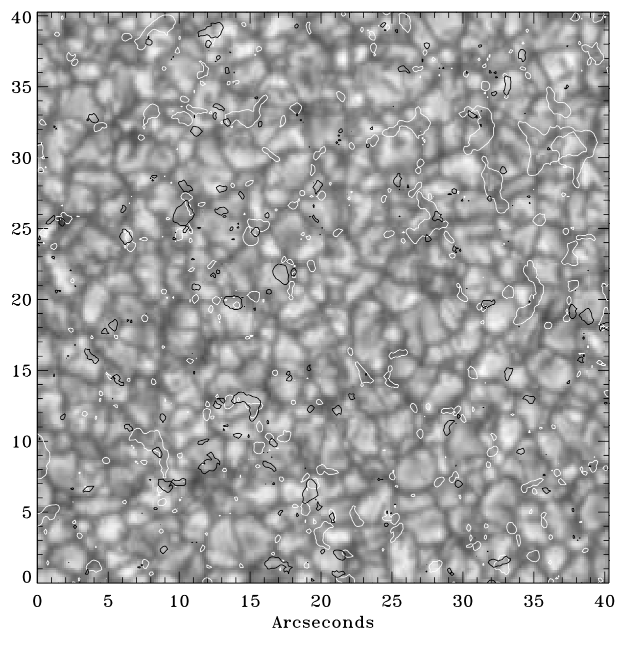

Fig. 4. The continuum intensity of the subarea highlighted in figure 1 is shown with overlain contours of $|B^{\rm L}_{\rm app}|$ (white) and $B^{\rm T}_{\rm app}$ (black). The 10σ and 3σ contours correspond to 25 and 124 Mx cm^{-2} for $|B^{\rm L}_{\rm app}|$ and $B^{\rm T}_{\rm app}$, respectively.

are not distinguished in $B_{\rm app}^{\rm T}$, and vice-versa.

- The vertical flux favors strongly the IG lanes.
- The horizontal flux tends to occur over the edges of the bright granules, usually near vertical flux, but not spatially coincident with it.

The void structures have been noted previously in sensitive ground-based measurements of $B_{\rm app}^{\rm L}$ (Lites 2002; Domínguez Cerdeña 2003), but this is the first time that such structures have been seen in the horizontal flux.

3. High Sensitivity IN Stokes Spectra

The striking image of figure 2 reveals for the first time the ubiquity of horizontal flux in the quiet solar photosphere, but it is apparent that this SP Normal Mode observation does not have the sensitivity to needed to quantify this newly-discovered component to the solar magnetic field. Owing to the excellent image stabilization of the Hinode SOT, the SP has the capability for integrating as long as is allowed by the evolution of the solar scene (i.e., granular evolution). Figure 5 shows a randomly chosen spectrum from a time series of observations at a fixed slit position at quiet Sun center. This image is a result of a continuous integration for 67.2 s; an integration time short enough that it causes minimal degradation at the image plane of the SP (the rms continuum contrast of the original sequence decreases from 7.50% to 7.35%). The noise level in the polarization continuum at each spectral/spatial position is 0.029% in these observations. Here it is possible to identify fine structure in Stokes V at every position along the slit, and the symmetric linear polarization signals in Stokes Q,U are visible along more than half of the points sampled. With these high sensitivity measurements we are able to reduce the rms noise levels in $B_{\rm app}^{\rm L}$ and $B_{\rm app}^{\rm T}$ to 0.64 and 21.1 Mx cm^{-2}, respectively. The average values of $|B_{\rm app}^{\rm L}|$ and $B_{\rm app}^{\rm T}$ over the 2 hour time series are 11.0 and 55.3 Mx cm^{-2} respectively. Unlike the Normal Mode observations, the average time series $B_{\rm app}^{\rm T}$ is above the noise floor, so we have increased confidence in the measured average horizontal apparent flux density.

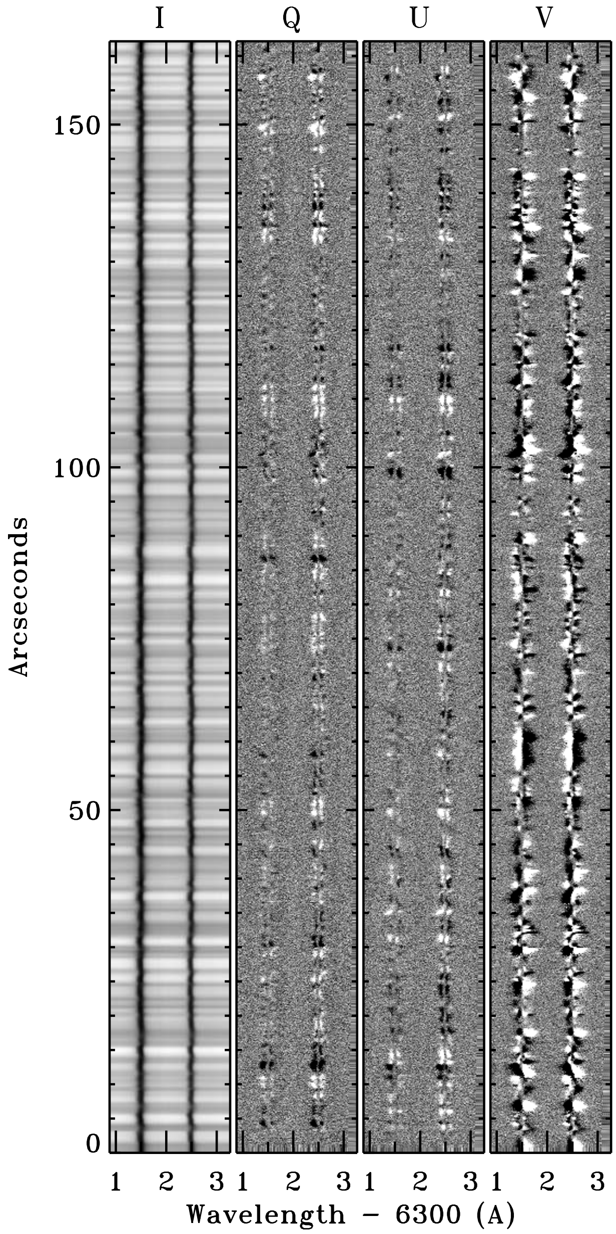

Fig. 5. A time series of Hinode Stokes spectra of a single slit position at quiet disk center was obtained on 2007 February 27. This program had a 9.6 second "deep mode" exposure. The time sequence was subjected to a running mean of 7 exposures, resulting in a net exposure time of 67.2 s for the spectra shown. Note the presence of solar Stokes V signals at nearly every point along the slit, and recognizable symmetric Stokes Q or U at most positions.

4. Discussion

At first glance, the observations presented in sections 2 and 3 suggest that the horizontal flux is much stronger, by a factor of about 5, than the vertical flux. If this initial interpretation is correct, then the horizontal fields in the quiet photosphere are a likely candidate for the hidden turbulent flux suggested by Hanle effect studies. This explanation is attractive because we find that the horizontal fields cover much of the quiet solar photosphere, and are also likely to be present in and around active regions. However, it is unwise to glibly adopt this explanation without further consideration. It turns out that the assumptions underlying our analysis for $B_{\rm app}^{\rm T}$ in particular have significant implications for the interpretation of the results. But if the photosphere is indeed dominated by horizontal fields, we must then ask how such a situation might arise. In the following we comment on some further investigations that will be pursued in following papers.

First, it is important to recognize that our analysis for $B_{\rm app}^{\rm T}$ assumes that the features are spatially resolved. All studies of weak IN flux to date have used Stokes V, for which the net flux in the observing element is independent of the fill fraction f because $V_{\rm tot} \propto fB$. Thus, for determining the net average vertical flux density, $|B_{\rm app}^{\rm L}|$, one may ignore the fill fraction. In contrast, the linear polarization signals Q,U vary quadratically with field strength B in the weak field limit. If, for example, we are under-resolving the area covered by horizontal fields by a factor of four, then the field strength need only be a factor of two larger to yield the same average

$B^{\rm T}_{\rm app}$. But in that case, the product of surface area and intrinsic horizontal field strength is half that resulting from an analysis assuming $f = 1$. Small fill fractions would make the average scattering much less sensitive to depolarization from the Hanle effect, and depending on the amount of under-resolution of our observations, we may not be able to explain the hidden turbulent flux by the observed horizontal fields.

Next, we need to consider the variation of the observed IN polarization from disk center toward the solar limb. If the photosphere is dominated by horizontal fields, we should find a rapid increase in $V_{\rm tot}$ away from disk center. In a following paper (Lites et al. 2007) we will present an analysis of such observations, and will demonstrate that $V_{\rm tot}$ actually *decreases* toward the limb.

We note that there are magnetic field configurations that could explain the relative difference of $B^{\rm L}_{\rm app}$ and $B^{\rm T}_{\rm app}$ without resorting to small fill fractions. The transverse Zeeman effect is subject to an ambiguity of 180° in the field azimuth (the angle of the field in the plane perpendicular to the LOS). Mixed polarity, oppositely-directed, nearly balanced flux tubes would show Stokes Q, U profiles as if all the fields were aligned the same direction. But seen end-on, such flux elements would present much smaller Stokes V signals. This scenario might explain both our measured inequality of $|B^{\rm L}_{\rm app}|$ and $B^{\rm T}_{\rm app}$ and its behavior away from disk center. Further study is needed to understand if the Sun could generate and maintain the mixed-polarity flux bundles.

Finally, we comment that the mean value of $|B^{\rm L}_{\rm app}|$ measured with the high angular resolution of Hinode is only about 20–30% larger than that from prior measurements of much lower angular resolution (Lites 2002; Lites & Socas-Navarro 2004). If the hidden turbulent flux exists at very small scales, then the distribution of the mixed polarity flux must peak very sharply at size scales considerably smaller than the 0.″3 resolution of these Hinode SP measurements. Otherwise, we would have expected a dramatic increase in $|B^{\rm L}_{\rm app}|$ seen in the measurements presented herein.

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