VECTOR MAGNETIC FIELDS OF SOLAR GRANULATION

CHUNLAN JIN, JINGXIU WANG, AND MENG ZHAO

National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; jinchunlan@ourstar.bao.ac.cn, wangjx@ourstar.bao.ac.cn, zhaomeng@ourstar.bao.ac.cn

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ABSTRACT

Observations of the quiet Sun from the Solar Optical Telescope/Spectro-Polarimeter aboard the Hinode spacecraft reveal the magnetic characteristics of the solar photosphere. By making use of the deep-mode observations of three quiet regions, we have statistically studied the vector magnetic fields of solar granulation. More than 2000 normal granules are manually selected to form a sample. It is recognized that some granules are even darker than the mean photosphere in intensity, and there is a linear correlation between intensity and Doppler velocity in the granules. The distributions of longitudinal and transverse apparent magnetic flux densities, Doppler velocity, and continuum intensity of granules are obtained, and their unsigned magnetic flux measured. Two approaches are used in this study. First, we obtained the magnetic properties of granulation by averaging the measurements for all the sampling granules. Second, we reconstructed an average granular cell based on a subsample, and obtained the detailed distribution of apparent magnetic flux density within the model granular cell. All the results have been compared with those for intergranular lanes and a few typical abnormal granules. Our statistical analysis reveals the following results. (1) The unsigned magnetic flux of individual granules spans the range from $1.1 \times 10^{15}$ Mx to $3.3 \times 10^{16}$ Mx with a peak distribution at $1.6 \times 10^{16}$ Mx. (2) The unsigned longitudinal apparent flux density of granules ranges from almost 0 to 212 Mx cm$^{-2}$ with a mean longitudinal apparent flux density of 12 Mx cm$^{-2}$, while the transverse apparent flux density of granules ranges from 4 to 218 Mx cm$^{-2}$ with a mean transverse apparent flux density of 79 Mx cm$^{-2}$. The longitudinal and transverse apparent magnetic flux densities of granules are positively correlated, and the longitudinal apparent flux density of granules is weaker than the corresponding transverse apparent flux density. (3) The magnetic inclination of granules with respect to the surface that is perpendicular to the line of sight falls in the range of 4.8–76.7 degrees with a peak distribution at 25 degrees. On average, the magnetic vectors in granules are more vertical than those in the intergranular lanes. (4) There is a strong preference that both the vertical and horizontal fields on the quiet Sun reside in the intergranular lanes. (5) The detailed distributions of apparent flux density, Doppler velocity, and continuum intensity within an average granular cell are presented. These distributions can be empirically formulated well.

Key words: Sun: granulation – Sun: magnetic fields – Sun: photosphere – techniques: polarimetric

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1. INTRODUCTION

Under good conditions of atmospheric seeing, observations of the solar surface with a telescope of at least 30 cm aperture can reveal the cellular pattern that covers the entire solar surface, except the sunspots region; this pattern is called granulation. As the smallest convective elements, many properties of granules have been carefully studied. The observed size of granules excluding the surrounding dark lanes ranges from approximately $0.2$ (the limit of ground-based observations) to approximately $3.4$ (Brandt 2001), and the mean granule size amounts to $1.1$ (Namba & Diemel 1969) or $1.35$ (Bray et al. 1984). The mean cell size of the granular elements including one-half of the surrounding dark lanes is $1.94$ according to Bray & Loughhead (1977) and $1.76$ according to Roudier & Muller (1986). The granulation is a nonstationary phenomenon. Frequently the granules expand and split into smaller components that drift apart, and the fragments may in turn grow and fragment, or merge with others, or shrink and decompose. The time for the granular photospheric intensity decay to $1/e$ of an initial value is about 6 minutes according to a number of studies (e.g., Bärg & Schwarzschild 1961; Title et al. 1986). Individual granules may live longer than this, e.g., over 8 minutes as identified by Mehltretter (1978), and a mean lifetime of 12 minutes found by Dialetis et al. (1986). An important feature of granular evolution is the proper motion of granules. From the high-resolution slit spectrograms taken at disk center, one can measure the vertical velocity related to granular motion, and the peak value is in the range $1.5$–$2.0$ km s$^{-1}$, after removing the velocity components due to oscillations. Furthermore, the horizontal velocity components are larger than the vertical components by a factor of 2 (Mattig et al. 1981). The granular motions also seem to have significant influence on the magnetic emergence. The horizontal internetwork fields reported by Lites et al. (1996), with typical sizes of $1''$ and a lifetime of 5 minutes, suggest that small magnetic loops are being advected toward the surface by the upward motion of the plasma inside the granules. If the horizontal internetwork fields are indeed emerging flux, Lites et al. (1996) estimated that the rate of magnetic flux driven to the surface by the upward motion of the plasma inside the granules is greater than the rate of flux emergence in bipolar sunspot regions averaged over the whole solar cycle. The horizontal motions inside the granules carry the vertical magnetic flux toward the intergranular lanes (Harvey et al. 2007; Centeno et al. 2007).

Furthermore, the magnetic emergence also has an important influence on the shape of the underlying granulation pattern. The magnetic emergence of flux tubes with a flux of more than $10^{19}$ Mx of longitudinal flux disturbs the granulation and leads
to the transient appearance of a dark lane (Cheung et al. 2007), that is, the so-called abnormal granulation. The abnormal granulation is also a term sometimes used for granulation in plage regions. Small-scale flux tubes with less than $10^{18} \text{ Mx}$ are not sufficiently buoyant to rise coherently against the granulation and produce no visible disturbance in the granules (Cheung et al. 2007). Therefore, one of the crucial points to understand the structure of the granulation is how the convective elements are modified by the presence of surface magnetic fields.

In the photospheric layer, the plasma $\beta$ is close to 1, and thus the magnetic fields and the convection of plasma in the photosphere are vigorously interacting all the time. To quantify the magnetic properties of solar granulation will provide clues to understanding the interaction, and test the theories and numerical simulations of this magnetic convection.

Unfortunately, for the very fundamental convection cells, limited by the spatial resolution and sensitivity of polarization measurements, their magnetic properties, i.e., the magnitude and distribution of magnetic fields in granules, are poorly known. With infrared polarimetry Lin & Kimme (1999) identified magnetic elements with flux less than $5 \times 10^{16} \text{ Mx}$ and a field strength of 200–1000 G, which they called granular magnetic fields. The spatial distribution and time evolution of these magnetic features are closely associated with the solar granulation. These magnetic elements seem to occupy 68% of the quiet Sun area. From wavelength-integrated measurements from the Hinode Spectro-Polarimeter (SP), Lites et al. (2008) uncovered the horizontal magnetic flux on the quiet Sun. They obtained average horizontal and vertical flux densities in quiet internetwork regions, which were 55 Mx cm$^{-2}$ and 11 Mx cm$^{-2}$, respectively. These authors found evidence that magnetic fields are organized on mesogranular scales, with both horizontal and vertical fields showing voids of reduced flux density of spatial extent a few granules. Moreover, the vertical fields are concentrated in the intergranular lanes, whereas the stronger horizontal fields occur most commonly at the edges of the bright granules.

The unprecedented spatial resolution and sensitivity of the Stokes SP onboard Hinode seem to provide a new opportunity to advance our knowledge of the interaction between the magnetic field and granulation. A very key question is whether or not the magnetic field in internetwork regions can be modified and organized by granulation, the smallest convection elements on the quiet Sun. Getting the average properties of magnetic characteristics in granules, and their overall correlation with convection flow and intensity, becomes the first step of the relevant studies and serves as the aim of this current work. With this goal we analyze the Hinode SP data inverted by the full Stokes profiles based on the assumption of the Milne-Eddington (ME) atmosphere model, and take two simple approaches: we obtain longitudinal and transverse magnetic flux densities, convection flows, and intensities of all the 2100 sampling granules and we obtain the detailed distributions of magnetic flux densities within a model granular cell.

In Section 2, we describe the observations used for this study and the strategy of the Stokes profile inversion. In Section 3, we obtain the statistical properties of granular vector magnetic fields and other relevant parameters. In Section 4, we put forward a model of average solar granular cell and get detailed distributions of magnetic flux densities, convection flow, and continuum intensity in the model granular cell. In Section 4, we discuss the uncertainties resulted from the effect of projection. The last section is devoted to the conclusion.
we assume that we may use such a map to characterize the granules as if it were a snapshot.

From the three quiet regions observed on 2007 June 1, 2, and 4, a total of 2100 granules are selected manually according to the image of continuum intensity, and there are distinct intergranular lanes surrounding each selected granule. Here, we define the granular pattern, including the surrounding intergranular lanes, as a granular cell, while we define the granular pattern excluding the surrounding intergranular lanes as a granule. The granular apparent flux densities, i.e., the mean unsigned longitudinal and the mean transverse apparent flux densities inside the granular pattern excluding the intergranular lanes, are measured. Furthermore, the granular unsigned magnetic flux is also calculated according to the granular area and the corresponding unsigned longitudinal apparent flux density. In addition, the granular intensity, Doppler velocity and magnetic inclination, i.e., the mean intensity, the mean Doppler velocity and the mean inclination within the granular pattern excluding the intergranular lanes, are also measured.

3. THE STATISTICS OF GRANULAR MAGNETIC PROPERTIES

Figure 1 shows the map of continuum intensity overlapped by the longitudinal apparent flux density \( B_{\text{app}}^L \) and the transverse apparent flux density \( B_{\text{app}}^T \) for a small portion of the observed region on 2007 June 1. In these small quiet regions, about 14% of the area represents the pixels which have not been inverted because of their small polarization signals.

The mean unsigned longitudinal apparent flux density in the FOV of the integrated regions observed on 2007 June 1, 2, and 4 is 28 Mx cm\(^{-2}\), with the corresponding mean transverse apparent flux density of 98 Mx cm\(^{-2}\). The mean magnetic inclination to the surface that is vertical to the LOS calculated over these inverted pixels is only 24.8 degrees. The larger occurrence of transverse fields confirms the discovery of strong linear polarization signals by Lites et al. (2007a, 2007b, 2008).

The current observations confirm the findings by Lites et al. (2008) that the magnetic fields on the quiet Sun are not uniformly distributed. Magnetic fields appear to be organized on mesogranulation scales. Moreover, there are “voids” in either longitudinal or transverse fields where the flux density is much lower than other locations, even close to zero. In this study, we focus on the statistical properties of granular vector magnetic fields and their overall correlation with convection flow and intensity. Because the granular transverse and unsigned longitudinal apparent flux densities are computed over the whole granule, assigning zero fields to those pixels which are not inverted, they represent the lower limits. However, the granular magnetic inclinations are calculated over only those pixels which are inverted. Considering the spatial resolution 0′′.32 of the SOT/SP aboard the Hinode, and the 1σ sensitivity of 2.0 Mx cm\(^{-2}\) of longitudinal apparent flux density, the minimum observable magnetic flux should be 1.1 \times 10^{15} \text{ Mx}. Therefore, when the granular flux is less than 1.1 \times 10^{15} \text{ Mx}, we think that it cannot be detectable.

The transverse apparent flux density, unsigned longitudinal apparent flux density, Doppler velocity, and continuum intensity of granules are measured. These physical parameters of 2100 granules form a good sample. We refer to these parameters as basic magnetohydrodynamic (MHD) parameters of granules. The statistical MHD properties of the granules are listed in Table 1.

Figure 1. Continuum intensity with the contours of the transverse and longitudinal apparent flux densities. The yellow and red contours show, respectively, the negative and positive 50 Mx cm\(^{-2}\) longitudinal apparent flux density levels. The blue contour is the 180 Mx cm\(^{-2}\) level for the transverse apparent flux density.

Here we define the granular relative intensity with respect to the mean intensity of the quiet photosphere. We find that some granules are darker than the mean photosphere in intensity. The relative intensity of granules spans the range from 0.97 to 1.14 with the peak distribution at 1.07, just as shown in Figure 2. Therefore, the granule is, of course, brighter than its surrounding dark lanes, but not necessarily brighter than the mean photosphere.

For studying the convection of granulation, the effects of solar oscillations have to be separated from the velocity variations of the granular pattern. In order to reduce the influence of the oscillations, the method of “boxcar” smoothing function is adopted (Krieg et al. 2000; Lites et al. 2008), i.e., applying a smoothing function to the \( V_{\text{Los}} \) image, then subtracting that image from the \( V_{\text{Los}} \) to obtain a “flattened” image \( V'_{\text{Los}} \) of the local velocity variation which is mostly due to granulation. Here, we smooth the \( V_{\text{Los}} \) image in a width of 3′′2, and remove the oscillation by subtracting that image from the \( V_{\text{Los}} \) to obtain the Doppler velocity related to the granular motion. The distribution of the granular Doppler velocity is shown in Figure 2. The statistical analysis shows that the range of the granular motion is from −3.3 km s\(^{-1}\) (blueshift) to 2.0 km s\(^{-1}\) (redshift) with a peak at −1.0 km s\(^{-1}\).

3.1. The Distributions of Magnetic Flux and Apparent Flux Densities

The magnetic flux distribution of the granules is presented in Figure 3. Their flux spans the range of 1.1 \times 10^{15} \text{ Mx} (the minimum observable limit) to 3.3 \times 10^{18} \text{ Mx} with a peak distribution at 2.0 \times 10^{16} \text{ Mx}, which is less than the peak distribution at 6 \times 10^{16} \text{ Mx} of internetwork magnetic elements from ground-based observations at poor spatial resolution (Wang et al. 1995). This suggests that the magnetic fields of granulation are likely to belong to the internetwork magnetic fields. The mean granular flux is 1.4 \times 10^{15} \text{ Mx} (see Table 1). The peak distribution of granular area is 0.93 Mm\(^2\), taking the mean unsigned longitudinal apparent flux density of 28 Mx cm\(^{-2}\) in the quiet region into account, and the magnetic flux within
Figure 2. Distributions of the Doppler velocity (displayed by triangles) and the continuum intensity (shown by asterisks). The Doppler velocity is shown on the top scale, while the continuum intensity on the bottom scale. The continuum intensity is the relative intensity to the mean photosphere.

Figure 3. Unsigned magnetic flux distribution of the granules.

Table 1
The Properties of Granulation

| Term                                      | Average | Range       |
|-------------------------------------------|---------|-------------|
| Continuum intensity (n-dim)               | 1.07    | 0.97–1.14   |
| Doppler velocity (km s\(^{-1}\))         | −0.82   | −3.3–2.0    |
| Total magnetic flux (10\(^{16}\) Mx)     | 14.2    | 0.1–334.4   |
| Unsigned longitudinal apparent flux density (Mx cm\(^{-2}\)) | 12      | 0–212       |
| Transverse apparent flux density (Mx cm\(^{-2}\)) | 79      | 4–218       |
| Inclination to the surface being vertical to the LOS (deg) | 27.1    | 4.8–76.7    |

the scale of granular size is \(2.6 \times 10^{17}\) Mx, which is within the range of magnetic flux of internetwork magnetic elements according to the mean flux obtained by Wang et al. (1995).

The apparent flux density distributions are shown in Figure 4. It is apparent from the figure that the unsigned longitudinal apparent flux density of granules is weak with a mean apparent flux density of 12 Mx cm\(^{-2}\), and the granular transverse apparent flux density spans the range from almost 0 to 218 Mx cm\(^{-2}\) with a mean apparent flux density of 79 Mx cm\(^{-2}\). Comparing with the average apparent flux densities, 28 and 98 Mx cm\(^{-2}\), of the whole three regions, the magnetic fields in granules are obviously weaker. This reflects the fact that the longitudinal and
transverse fields within the granule are weaker than those in the intergranular lanes. Another reason comes from the fact that our statistics have excluded the abnormal granules which certainly have much stronger apparent flux densities than the normal granules. Moreover, the range of inclination with respect to the surface that is perpendicular to the LOS is from 4.8 to 76.7 degrees with a peak distribution around 25 degrees.

Considering the continuum intensity and inferred Doppler velocity, the intergranular lanes are separated from the granules. The mean unsigned longitudinal and transverse apparent flux densities in the intergranular lanes are 29 Mx cm$^{-2}$ and 117 Mx cm$^{-2}$, respectively, and the corresponding inclination to the surface that is perpendicular to the LOS is only 20 degrees. Therefore, in the quiet region, the magnetic vectors of the granule are more longitudinal than those of intergranular lanes. The strong preference for a longitudinal field resides in the intergranular lanes, which confirms the conclusion drawn by Domínguez et al. (2003). Furthermore, the transverse field also preferentially occurs in the intergranular lanes.

3.2. Correlations Among the Granular Apparent Magnetic Flux Density, Intensity and Doppler Velocity

The correlation between the granular Doppler velocity and continuum intensity is studied. In order to show the relationship clearly, we divide the granules into 100 equally populated bins according to granular intensity, and compute the mean Doppler velocity and the mean intensity in each bin. We find that there is a negative correlation between the Doppler velocity and the continuum intensity, with a correlation coefficient of $-0.83$, well above the confidence level of 99.9%. We fit their relationship by a linear function, just as displayed in Figure 5,

$$V_{\text{los}} = A_0 + A_1 \times I_C,$$

(1)

where $A_0 = 8.9 \pm 0.6$ and $A_1 = -9.0 \pm 0.6$. Therefore, we find that the larger the spectral blueshift is, the brighter the granule becomes.

In addition, in the same way, we also analyze the relationship between the granular unsigned longitudinal apparent flux density $B_{\text{app}}^L$ and the corresponding transverse apparent flux density $B_{\text{app}}^T$. Our statistics show that there is a positive correlation between them. We fit their relationship by the polynomial function, just as displayed in Figure 6,

$$B_{\text{app}}^L = A \times \left( B_{\text{app}}^T \right)^2,$$

(2)

where $A = 0.00164 \pm 0.00005$.

However, the statistics exclude the abnormal granulation because the convective elements are modified by the stronger magnetic field. In order to compare the properties of the abnormal granules with those of normal granules, we arbitrarily select three abnormal granules manually in the plage region. It is found that the mean unsigned longitudinal apparent flux density in the abnormal granules is larger than 300 Mx cm$^{-2}$, while the transverse apparent flux density is around 100 Mx cm$^{-2}$. Their magnetic fluxes exceed $1.0 \times 10^{19}$ Mx, which supports the conclusion of Cheung et al. (2007). Their maximum intensities are higher than the average photospheric intensity by a factor of 1.1. Furthermore, due to the modification of the stronger magnetic fields, the Doppler velocity of abnormal granules is very small.

4. AN AVERAGE SOLAR GRANULAR CELL

The variations of the apparent magnetic flux density, the Doppler velocity, and the continuum intensity from the granular center to the intergranular lane are useful constraints for modeling the solar granule. We construct a model of an average solar granular cell.

We first defined the granular size. Generally speaking, the granular size has two measures to be defined. One is the distance between the centers of two adjacent granules; this size is called the “cell size” (Stix 2002). Another is the granular “diameter,” defined as follows (see Bray et al. 1984): let $A$ be the granular area over which granular intensity is larger than a certain value; the area generally is not circular, so an effective diameter is $D = 2(A/\pi)^{1/2}$. Using the 2100 granules manually selected, we find that the peak distribution of granular “diameter” $D$ is...
relationship between the granular relative intensity (nondimensional) and the granular Doppler velocity (km s\(^{-1}\)). In order to show their relationship clearly, the granules are divided into 100 equal-population bins according to the magnitude of relative intensity, and the mean intensity and mean velocity in each bin are calculated. The solid line shows the linear fit on the granular intensity and the Doppler velocity.

Figure 6. Relationship between the granular transverse apparent flux density, \(B_{\text{app}}^\perp\), and the unsigned longitudinal apparent flux density, \(B_{\text{app}}^\parallel\). The solid line represents the linear fit.

1\(^{\prime}\)50. In the image of continuum intensity in an enlarged scale, we plot a horizontal line (from east to west) and a vertical line (from south to north), and both of them span the granular center and the corresponding intergranular lanes. We define the positions with the minimum intensity in intergranular lanes as the outer edge of a granular cell, and the distance between the outer edges on both sides of the granular cell as the size of granular cell \(D_g\), which is larger than \(D\) by definition. The \(D_g\) is almost the same as the “cell size,” the distance between the centers of two adjacent granules.

Afterward, we divide the \(D_g\) into 26 equally populated bins along the two lines mentioned above, and compute the mean intensity in each bin. The measurements along the two orthogonal lines are averaged to get the intensity changes from the granular center to the corresponding intergranular lanes. Making use of the same method, we analyze 100 granules which are, more or less, regular with almost all of the well inverted Stokes profiles. Moreover, in order to reduce the asymmetry from the south–north cut, we select 50 granules in the quiet region (0\(^{\prime}\), \(-200^{\prime}\)) and 50 granules in the quiet region (0\(^{\prime}\), 200\(^{\prime}\)) to construct the average solar granular cell. Finally, we average the intensity of 100 granules in each bin, and obtain the intensity variations with the distance from granular center to its corresponding intergranular lanes for an average solar granular cell. In the image of continuum intensity, we can see that there is a distinct boundary, i.e., great contrast of intensity, between the granule and the corresponding intergranular lanes. Therefore, from the granular center to intergranular lanes, we can also find two adjacent bins with largest contrast of intensity, and define the bin with less intensity as the inner edge of the average solar granular cell. We define the distance between the inner edges as the effective diameter \(D\) of the average solar granular cell, and this distance is bounded by the two dashed lines in Figure 7. For the average solar granular, the diameter \(D\) is equal to 1\(^{\prime}\)50 according to the peak distribution of granular effective diameter, and the size \(D_g\) of the granular cell is 2\(^{\prime}\)16 based on the ratio between \(D\) and \(D_g\) of the average solar granular cell.

Finally, in the same way, we obtain the average Doppler velocity, and both the unsigned longitudinal and transverse magnetic flux densities of 100 granules in each bin; the variations of apparent magnetic flux densities and Doppler velocity with the distance from granular center are obtained. The detailed distribution of apparent flux densities, convective flow, and intensity for the average solar granular cell is schematically drawn in Figure 7. It is interesting to note that the MHD parameter distributions of the average granular cell are not exactly symmetric. Furthermore, we find that there is also asymmetry when we use only the results from the east–west cuts for the average solar granular cell.

For the average solar granular cell that we construct, the mean unsigned longitudinal and transverse apparent flux densities in intergranular lanes are 22 Mx cm\(^{-2}\) and 102 Mx cm\(^{-2}\) respectively, whereas in the granule they are only 7 Mx cm\(^{-2}\) and 61 Mx cm\(^{-2}\), respectively. The apparent flux density distributions of the average solar granular cell confirm the
previous results that there is a preference for longitudinal and transverse fields to reside in the intergranular lanes. The magnetic flux of the surrounding dark lanes of the average solar granular cell is $2.2 \times 10^{17}$ Mx, while the magnetic flux of the average solar granule excluding the dark lanes is only $6.5 \times 10^{16}$ Mx.

From Figure 7, we see clearly that the plasma motion corresponding to the LOS in the granular center is fastest, and there is a negative correlation between the continuum intensity and the Doppler velocity. The maximum intensity contrast of the average solar granule is $9 \pm 0.3$, and the Doppler velocity. The maximum intensity contrast of the average solar granule excluding the dark lanes is only $6 \pm 0.5$.

If we define the radius $Dg/2$ of the granular cell as unit one, then the apparent flux densities can be expressed as the function of the distance from granular center, $d$. The relationship between $B_{\text{app}}$ and the distance $d$ can be fitted by a two-peak Gaussian function, just as that shown in Figure 8 and described by:

$$B_{\text{app}}^T = B_{T0} + \frac{B_{T1}}{e^{\frac{-(d-d_0)^2}{2\sigma_1^2}}} + \frac{B_{T2}}{e^{\frac{-(d-d_2)^2}{2\sigma_2^2}}}.$$ 

where $B_{T0} = 33.9 \pm 0.8$, $B_{T1} = -17.9 \pm 0.6$, $\sigma_1 = 0.66 \pm 0.03$, $\mu_1 = -0.41 \pm 0.02$, $B_{T2} = -28.4 \pm 0.6$, $\sigma_2 = 0.84 \pm 0.03$, and $\mu_2 = 0.37 \pm 0.02$. The effective half-width of $B_{\text{app}}^T$ is 0.765.

The relationship between $B_{\text{app}}^T$ and the granular diameter $d$ can be fitted by a single Gaussian function, just as that shown in Figure 9:

$$B_{\text{app}}^L = B_{L0} + \frac{B_{L1}}{e^{\frac{-(d-d_0)^2}{2\sigma_1^2}}} + \frac{B_{L2}}{e^{\frac{-(d-d_2)^2}{2\sigma_2^2}}}.$$ 

where $B_{L0} = 35.8 \pm 0.8$, $B_{L1} = -17.9 \pm 0.6$, $\sigma_1 = 0.66 \pm 0.03$, $\mu_1 = -0.41 \pm 0.02$, $B_{L2} = -28.4 \pm 0.6$, $\sigma_2 = 0.84 \pm 0.03$, and $\mu_2 = 0.37 \pm 0.02$. The half-width of $B_{\text{app}}^L$ is 0.73.

In addition, the Doppler velocity $V_{\text{Los}}$ and the continuum intensity $I_c$ can also be expressed as functions of $d$ by the two-peak Gaussian fit:

$$V_{\text{Los}} = V_0 + \frac{V_1}{e^{\frac{-(d-d_0)^2}{2\sigma_1^2}}} + \frac{V_2}{e^{\frac{-(d-d_2)^2}{2\sigma_2^2}}},$$ 

where $V_0 = 1.26 \pm 0.07$, $V_1 = -1.7 \pm 0.2$, $\sigma_1 = 0.67 \pm 0.04$, $\mu_1 = 0.39 \pm 0.04$, $V_2 = -1.9 \pm 0.3$, $\sigma_2 = 0.73 \pm 0.05$, and

**Figure 7.** Model of average solar granular element. Note that the apparent flux densities (solid line and dotted line) are displayed on the left scale, while the Doppler velocity (dash-dot line) and the relative intensity (dash-dot-dot line) on the right scale. The unsigned longitudinal apparent flux density has been scaled by a factor of 2. The two vertical dashed lines represent the edge between granule and intergranular lanes, and $D$ is the effective diameter.

**Figure 8.** Variation on unsigned longitudinal apparent flux density with granular diameter in the average solar granular element. The squares display the longitudinal apparent flux densities of the reconstructed average solar granular element. The solid line shows the multipeaks Gauss fit. The radius $Dg/2$ is defined as unit one.
\[
\mu_{32} = -0.28 \pm 0.04;
\]

\[
I_c = I_0 + \frac{I_1}{\sqrt{2}\sigma_{41}} e^{-2(\frac{d-\mu_{41}}{\sigma_{41}})^2} + \frac{I_2}{\sqrt{2}\sigma_{42}} e^{-2(\frac{d-\mu_{42}}{\sigma_{42}})^2},
\]

where \(I_0 = 0.887 \pm 0.004, I_1 = 0.16 \pm 0.01, \sigma_{41} = 0.74 \pm 0.03, \mu_{41} = -0.33 \pm 0.02, I_2 = 0.16 \pm 0.01, \sigma_{42} = 0.73 \pm 0.02, \) and \(\mu_{42} = 0.37 \pm 0.02.\)

5. DISCUSSIONS

So far, we only use the terms longitudinal and transverse apparent flux densities to describe the results of our statistics. Because the three quiet regions are not observed at disk center, there will appear to be some uncertainties that result from the effect of projection in the estimation of vertical and horizontal fields. Accordingly, the longitudinal and transverse apparent flux densities do not strictly mean the vertical and horizontal apparent flux densities. Thus, we make a simple estimation about the uncertainties. We find that the uncertainty is about 4 Mx cm\(^{-2}\) for the vertical field and 7 Mx cm\(^{-2}\) for the horizontal field. The uncertainties are within 3 times the standard deviations of magnetic flux density measurements. Therefore, it is quite acceptable to use the terms vertical and horizontal fields to describe our statistical results on the vector magnetic fields of solar granulation. Compared with the values of magnetic parameters from 2100 granules and the average solar granular cell, we find that the vertical fields are weaker than the corresponding horizontal fields in the whole quiet region. The vertical fields are concentrated in the intergranular lanes, which confirmed the conclusion about the distribution of vertical fields obtained by Lites et al. (2008). Moreover, we find that the horizontal fields also occur most commonly in the intergranular lanes. This conclusion is different from the result for the horizontal field distributions obtained by Lites et al. (2008). The reason for the difference may be the fact that the result shown by Lites et al. (2008) mostly emphasizes the fraction of the area of the bin occupied by the greater horizontal field for equally populated bins from the granular center to intergranular lanes, while our result stresses the magnitude of the horizontal field for each bin from the granular center to intergranular lanes.

On the other hand, the effect of projection could also result in uncertainties of less than 12 degrees in the estimation of magnetic inclination angle with respect to the horizontal solar surface. Compared with the magnetic inclination angles with respect to the image surface being perpendicular to the LOS, 27.1 and 20 degrees, for the granules and intergranular lanes, respectively, the uncertainty in the magnetic inclination angle makes it hard for us to affirm that the magnetic fields in the granules are more vertical than those in the intergranular lanes. Therefore, we select a quiet region observed at disk center on 2007 December 21, and divide the region into granular region and intergranular region according to the continuum intensity and the inferred Doppler velocity. The magnetic inclination angles are averaged over only the inverted pixels in the granular region and intergranular region. We find that the average magnetic inclination angle with respect to the LOS is 53.2 degrees in granules and 59.2 degrees in the intergranular lanes, i.e., 37.8 and 30.8 degrees with respect to the local solar surface. Therefore, we confirm that the magnetic fields in the granules are more vertical than those in the intergranular lanes. However, Orozco Suárez et al. (2007b) show that the fields are more horizontal in the granular region than elsewhere seen from the probability density functions (pdf’s) of magnetic inclination, which is opposite to our result. Indeed, more studies should be made to clarify the discrepancy.

6. CONCLUSIONS

Based on observations of the quiet Sun using SOT/SP aboard the Hinode spacecraft, we have statistically studied the distributions of granular magnetic flux, vector magnetic fields, the continuum intensity, and the Doppler velocity. Moreover, a model of an average solar granular cell is reconstructed.

The granular flux spans the range from 1.1 \times 10^{15} Mx to 3.3 \times 10^{15} Mx with a peak distribution at 1.6 \times 10^{16} Mx. The granular vertical apparent flux density is weaker than the corresponding horizontal apparent flux density, and there is a positive correlation between them. The range of granular inclination to the surface that is vertical to the LOS is from 4.8 to 76.7 degrees with a peak distribution at 25 degrees, and the magnetic vectors in the granules are more vertical than those in the intergranular lanes. There is a strong preference that the vertical and horizontal fields reside in the intergranular lanes. There is a range for the Doppler velocity from -3.3 km s\(^{-1}\) (blueshift) to 2.0 km s\(^{-1}\) (redshift) after removing the velocity components due to the oscillation. Some granules are darker than the quiet photosphere in intensity; the relative intensity of granules has a range spanning from 0.97 to 1.14. There is a linear correlation between the granular intensity and the Doppler velocity.

A model of an average solar granular cell has been built by analyzing 100 granules, and the variations of the vector magnetic fields, the Doppler velocity, and the continuum intensity from the intergranular lanes to the granular center are studied. For the average solar granular cell, it is also confirmed that the vertical and horizontal fields have a strong preference in the intergranular lanes. The changes of apparent flux densities, convection flow, and relative intensity with the distance from granular center to the corresponding intergranular lanes can be empirically formulated. Interestingly, the transverse apparent flux density distribution can well be formulated by a Gaussian function; however, the unsigned longitudinal field distributions can only be best fitted by double-peak Gaussian functions. These empirical formulation may serve as some quantitative constraints on the magneto-convection simulations.
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