Origin of Helicity in the Quiet Sun

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Abstract. It has been suggested that a substantial fraction of the weak magnetic field outside of active regions may be generated by the local dynamo action driven by granular flows. Because of their small characteristic size and lifetime, the Coriolis force should have no significant effect on these flows and hence, granules will show no hemispheric dependence of their kinetic helicity. Magnetic field generated by such (non-helical) dynamo should exhibit no hemispheric helicity rule either. On the other hand, if magnetic field originates deep in the convection zone, one can expect that interaction with turbulent convection (Σ-effect) will introduce hemispheric asymmetry with positive helicity in southern hemisphere and negative in northern hemisphere.

Using vector magnetograms from the Advanced Stokes Polarimeter we measure current helicity \( \alpha_z = J_z/B_z \) of photospheric field in the quiet Sun at few fixed latitudes. Our results indicate a weak hemispheric asymmetry in distribution of \( \alpha_z \) with a tendency for averaged helicity to be negative in the northern hemisphere and positive in the southern hemisphere. We interpret this asymmetry in a framework of the sub-photospheric origin of the photospheric field in the quiet Sun. There is also a more pronounced inverse relationship between latitude and the scatter in \( \alpha_z \), which may be attributed to the photospheric dynamo action.

1. Introduction

Magnetic field on the Sun plays a key role in the solar activity on all spatial scales. It is believed that the strong magnetic field (active regions) is generated at the base of the convection zone (e.g., DeLuca & Gilman 1991, Parker 1993). The weak magnetic fields outside of solar active regions are thought to be the remnants of dissipating active regions. Recent observations, however, have shown that this classical picture may be incorrect. The lifetime of the photospheric magnetic fields outside active regions is very short (minutes to hours), while the active regions may exist for several months. Title & Schrijver (1998) have shown that the weak network magnetic field on the Sun is replaced within \( \sim 40 \) hours. Recently, Cattaneo (1999) has proposed that substantial fraction of
the weak magnetic field on the Sun is generated by the local motions at or near the photosphere. How is it possible to distinguish between the photospheric and sub-photospheric dynamos? Disregarding specific details, every dynamo should employ a non-axisymmetric motions to generate magnetic field (Cowling 1968). In “convection zone” dynamos (α − Ω, mean-field, overshoot region dynamos) the helical motions of the convective flows play such a role. Because of the Coriolis force, the kinetic helicity $h_k = (\nabla \times \mathbf{v}) \cdot \mathbf{v}$ (where $\mathbf{v}$ is velocity) of the convective flows will have a hemispheric sign preference. Magnetic helicity of the fields generated by these helical flows will also exhibit a hemispheric sign asymmetry. Thus, for instance, in the case of the overshoot region dynamo, magnetic helicity will be negative in the northern hemisphere and it will be positive in the southern hemisphere. Such hemispheric helicity rule has been observed in active regions magnetic fields (e.g., Seehafer 1990; Pevtsov, Canfield & Metcalf 1995; Abramenko, Wang & Yurchishin 1997; Longcope, Fisher & Pevtsov 1998; Bao & Zhang 1999). On the other hand, the symmetry can also be broken by the random motions. Cattaneo (1999) has developed a numerical model of such a “chaotic” dynamo and has shown that it can successfully operate in the solar photosphere. The evolution of the magnetic fluxes from his numerical simulations resembles very well the observations. Still it is unclear if the magnetic field in the quiet Sun is, in fact, generated by the photospheric granular motions or they simply recycle the field that has been generated by a sub-photospheric dynamo.

In this paper we suggest that a helicity approach can be used to distinguish between the photospheric and sub-photospheric dynamos. Because the granular flows in the individual cells have significantly shorter lifetime (8–10 minutes) in comparison with the solar rotation period (25 days), the effect of the Coriolis force on these flows should be negligible. The mean kinetic helicity of these flows (averaged over large number of granules) and the magnetic field helicity should be near zero everywhere, independent of the hemisphere. On the other hand, if the magnetic field is generated by the sub-photospheric dynamo, whose kinetic helicity is affected by the Coriolis force, the magnetic helicity should exhibit the hemispheric sign asymmetry. Below we search for the observational evidence of the hemispheric helicity rule in the quiet Sun magnetic field.

2. Observations

We use a set of vector magnetograms of the quiet Sun areas observed on April 16, 2000 using the Advanced Stokes Polarimeter (ASP). Each magnetogram covers $\approx 30 \times 70^\circ$ and has $0.6 \times 0.37^\circ$ pixel size. The magnetograms have been observed at 6 different areas of the quiet Sun centered at N00W00, N10W00, S10W00, N40W00, S40W00, S40W10, outside the active regions (c.f., Fig. 1). For each of these 6 positions we have recorded 5 consecutive magnetograms with $\sim 4$ minute per magnetogram. The image has been stabilized using a correlation tracker. AO-system was not available. The seeing is very good at the beginning of the observations and it gradually deteriorates to the end of the day (Figure 2). The magnetograms are reduced following standard ASP data reduction. To resolve the $180^\circ$ ambiguity in azimuths of transverse field we have chosen the orientation that gives the most vertical magnetic field.
Figure 1.  Kitt Peak magnetogram for the day of observations.

Figure 2.  White light images of two quiet Sun areas with the best (left, 10S00W) and worst (right, 40S00W) seeing. Time cadence between consecutive magnetograms in each series is $\sim 4$ minutes.
3. Helicity distribution

For each vector magnetogram we have computed the maps of force-free field parameter $\alpha_z(x, y) = \left( \frac{\partial B_y(x,y)}{\partial x} - \frac{\partial B_x(x,y)}{\partial y} \right) B_z(x, y)^{-1} = J_z(x, y)/B_z(x, y)$. The pixels with weak polarization (where the line-profile fitting procedure has failed) were excluded from this study. Figure 3 shows the histograms of $\alpha_z$ for each magnetogram of the series observed at N40W00. Other areas show similar distributions. Approximating these distributions by gaussian function we find mean value of $\alpha_z$ and its standard deviation $\sigma \alpha_z$.

![Histograms of $\alpha_z$ for 5 magnetograms observed at N40W00. Solid line is Gaussian fit, vertical dashed line is the mean value $<\alpha_z>$. Mean $<\alpha_z>$ and the standard deviation $\sigma \alpha_z$ are given in the right-upper corner of each panel.](histograms.png)
Figure 4. Averaged helicity $<\alpha_z>$ and its standard deviation $\sigma\alpha_z$. Left: $<\alpha_z>$ as function of solar latitude. Values from ASP observations are shown as triangles with error bars. Solid (dashed) line shows mean (st. deviation) helicity of a $3 \times 10^{21}$ Mx flux tube resulting from the $\Sigma$-effect (Longcope et al, 1998). Right: $\sigma\alpha_z$ (triangles) as a function of latitude. First degree polynomial approximation is shown as dashed line.

Typical $\alpha_z$ distribution has the width of $2 \cdot 10^{-7} m^{-1}$ and much smaller offset of $\sim 2 \cdot 10^{-8} m^{-1}$. Next, we combine all 5 magnetograms of the same region to compute a single distribution of $\alpha_z$ for each observed area. Figure 4 shows $<\alpha_z>$ (left) and $\sigma\alpha_z$ (right) of these distributions as a function of solar latitude.

4. Discussion

The histograms of the $\alpha_z$ (Fig. 3) show small, but persistent offset. With one noticeable exception (discussed below), the offsets are negative in the northern hemisphere and positive in the southern hemisphere. Such hemispheric pattern is in agreement with the hemispheric helicity rule found for the active regions, which implies that the helicity of the quiet Sun magnetic field has sub-photospheric origin. The photospheric "chaotic" dynamo should exhibit no hemispheric preference in its helicity. Although the width of the histograms is an order of magnitude larger than the offset, the same offset is present on all 5 magnetograms of each series and hence appears to be real. The offsets are in qualitative agreement with the $\Sigma$-effect predictions. Figure 5 shows the results of the Monte-Carlo simulations of the interaction between the horizontal thin flux tubes and the turbulent convection ($\Sigma$-effect, Longcope et al. 1998). The histogram of $\alpha$ exhibits very similar properties (small offset and significantly larger width) as the distributions shown on Fig. 3. Figure 4 (left panel) shows the latitudinal variation of $\alpha$ and its scatter as expected from the $\Sigma$-effect computed for a $3 \times 10^{21}$ Mx flux tube. The observed helicity is in qualitative agreement with Longcope et al. (1998) results. We should note, however, that the Long-
Figure 5. Histogram of twist $\alpha$ for N=1000 realizations of a $3 \times 10^{21}$ Mx flux tube. Dotted line shows mean value of $\alpha$. Right panel shows scatter plot of twist $\alpha$ vs. tilt $\phi$. (Adopted from Longcope et al. (1998), reproduced by permission of the AAS).

copulo et al. (1998) calculations were done for stronger active region fields. The calculations for a weaker field remain to be done, although we expect that they will result in slightly larger values of $\alpha$ and its dispersion ($\sigma\alpha$). Longcope et al. (1998) numerical simulations have shown that the turbulent flows in the upper part of the convection zone give the major contribution into the helicity of the magnetic fields observed at the photosphere. Extending their findings on our present observations leads us to a speculation that the quiet Sun magnetic field helicity may also have its origin in the upper part of the solar convection zone, but not in the photosphere.

Figure 4 (right panel) shows that the standard deviation of $\alpha$ distribution has a tendency to decrease with solar latitude. It is possible that the atmospheric seeing effects contribute toward such dependency. For a typical day, the atmospheric seeing is better during morning hours and it is worse later in the day. Because low latitude area were observed earlier than high latitude areas a correlation between the atmospheric seeing and $\sigma\alpha_z$ is possible. To test this idea we have computed an averaged contrast for the white light granulation images as a difference of $<I_b>$ and $<I_d>$, where $<I_b>$ is an average of all pixels with intensity $I \geq 90\% \times (I_{\text{max}} - I_{\text{min}})$, and $<I_d>$ is an averaged of all pixels with intensity $I \leq 10\% \times (I_{\text{max}} - I_{\text{min}})$. The higher contrast corresponds better seeing. Figure 6 shows lack of correlation between the image contrast and the $\sigma\alpha_z$ and so, the decrease of width of the distribution with the latitude is not related to the atmospheric seeing and may have solar origin.

We speculate, that a correlation between $\sigma\alpha_z$ and latitude shown in Fig. 4 (right panel) may be due to the photospheric dynamo action, recycling the mag-
Figure 6. Standard deviation $\sigma_{\alpha_z}$ as function of the image contrast.

magnetic field generated below the photosphere. Because the Coriolis force action is
stronger in high latitudes, the magnetic field that is of subphotospheric origin, will have stronger twist in high latitudes, and hence, will have better chance to
withstand the “chaotic” dynamo action. Thus, the width of the $\alpha$ distribution
will be narrower in high latitudes than that in the low latitudes. Another indi-
rect argument for a sub-photospheric origin of helicity of the magnetic fields in
quiet Sun, is the persistence of $<\alpha_z>$. A lifetime of a granular flow is about
8–10 minutes. The $\alpha_z$ histograms, however, show the same mean $<\alpha_z>$ dur-
ing 20 minutes (e.g., Figure 3). Thus, the averaged helicity has the same sign
despite the fact, that the granular pattern has been replaced several times.
Figure 4 (left panel) shows that 5 of 6 areas in our data set follow the hemispheric
helicity rule. However, one area disobeys the rule. In attempt to understand
this anomaly we have compared the active region helicity with $<\alpha_z>$ of nearby
quiet Sun areas. We used Haleakala Stokes Polarimeter (HSP, Mickey 1985)
data to compute active region helicity as in Pevtsov et al. (1995). The AR
NOAA8955 was situated at $\approx 22^\circ$ in southern hemisphere and had positive $\alpha$.
Two closest quiet Sun areas at 40W00 and 40W10 also had positive $\alpha$ (Figure
4). Active region NOAA 8953 was situated at $\approx 16^\circ$ in the southern hemisphere
and it had negative helicity on Apr. 14. The closest quiet Sun area at 10W00
had negative $\alpha$ on Apr. 16. Although this pattern seems to be consistent with
the idea that the magnetic helicity of nearby active region may affect the helicity
of quiet Sun areas, we do not have enough statistics to support it. Moreover,
the HSP magnetograms of AR NOAA 8953 are not consistent with each other:
on Apr. 12 the $\alpha$ was negative, on Apr. 13 it was positive and on Apr. 14 it was
negative again.

5. Conclusions

The results presented in this paper lead us to the following conclusions:

- the weak photospheric magnetic fields outside of active regions follow the
  same hemispheric helicity rule as strong magnetic field of active regions.
• the presence of the hemispheric helicity rule in the weak fields does not support the idea that those fields are generated by the photospheric "chaotic" dynamo.

• if the photospheric "chaotic" dynamo exists, as suggested by some numerical models and partially supported by selected observational properties of the magnetic field, the primary action of this dynamo is to redistribute the magnetic field generated somewhere below the photosphere.

• we find very limited observational evidence that the helicity of the photospheric weak magnetic fields may be related to the helicity of closest active region. If following independent observations confirm this finding, this will inevitably suggest that the quiet Sun photospheric fields are remnants of decaying active regions.

Acknowledgments. This work was supported by NASA through SR&T grant NAG5-6110.

References

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