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North–South Asymmetry in the Distribution of Solar Background Magnetic Field

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Abstract The aim of this article is to investigate how the background magnetic field of the Sun behaves in different hemispheres. We used SOHO/MDI data obtained during a period of eight years from 2003 to 2011 to analyze the intensity distribution of the background magnetic field over the solar surface. We find that the background fields of both polarities (signs) are more intense in the southern than in the northern hemisphere. Mixed polarities are observed in the vicinity of the equator. In addition to the main field, a weaker field of opposite polarity is always present in the polar regions. In the declining phase of the cycle, the main field dominates, but at the minimum and in the rising phase of the cycle, it is gradually replaced by the growing stronger secondary field.

Keywords N–S asymmetry · Large-scale solar magnetic field

1. Introduction

To understand the solar dynamo mechanism it is important to simultaneously analyze the properties of magnetic fields in the equatorial and polar regions. It is commonly assumed that the polar magnetic field is quasi-unipolar and occupies an extensive area and that the field strength is relatively weak (0.1 – 0.5 mT). This region has the largest extension during solar minimum and changes its polarity in the maximum phase (Babcock, 1959). The most commonly used model of the field reversal is the one by Babcock (1961) and Leighton (1964). According to this model, the leading parts of the active regions move to the equator and are annihilated by the leading fields of opposite polarity from the other hemisphere. The weaker trailing parts of the active regions, in contrast, move to the poles and form the polar field. In the process, the new polar field interacts with the old one and gradually replaces it (Zirin, 1988; Fox, McIntosh, and Wlison, 1998; Snodgrass, Kress, and Wilson, 2000; Benevolenskaya, 2004). This scheme does not explain the mechanism of the

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poleward migration of the active-region field itself. This is explained in more detail by including dynamo waves or meridional flows (Wang, Sheeley, and Nash, 1991; Choudhuri, Schussler, and Dikpati, 1995; Kuzanyan and Sokoloff, 1997; Dikpati *et al.*, 2004; Hathaway and Rightmire, 2010): A possible scenario for the polar-field behavior of the solar cycle within the framework of the dynamo theory can be visualized as a traveling wave that propagates from the mid-latitudes and travels towards the poles, attaining its maximum magnitude during sunspot minimum. At the sunspot maximum, the polar activity passes through a minimum, after which the polarity reverses. Such a wave can probably be visualized by monitoring polar faculae or bright points, although the background radial fields may also manifest in this polar wave. Because the dipolar, axially symmetric field prevails in the global magnetic field of the Sun (*e.g.*, Stenflo, 1988), we expect that the polar regions have magnetic flux of opposite polarities, but one or the other sign dominates alternately in each consecutive cycle. This concept is generally consistent with recent high-resolution *Hinode* observations of polar areas of the Sun (*e.g.*, Shiota *et al.*, 2012).

The notion of two traveling waves in a solar activity cycle has a long history and became clear in the seminal work of Makarov and Sivaraman (1989), who studied the statistics of polar faculae together with the statistics of sunspots. The theoretical co-existence of the two waves can be described in a simplest way by a dynamo model that allows for the solar internal differential rotation (Belvedere, Kuzanyan, and Sokoloff, 2000), which yields both low-latitude equatorward and high-latitude poleward waves.

The reversal process is not yet fully understood. In particular, it is unclear how the new field replaces the old one and which role the fine structure of the background field plays in this process.

The analysis of the background field is closely related to the problem of the fine structure or "quantization" of solar magnetic fields. In the early 1960s, many authors claimed that small-scale magnetic fields are ubiquitous (Sheeley, 1966, 1967; Harvey, 1971). Important indirect evidence was provided by the analysis of different magnetic splitting of several spectral lines (Harvey and Livingston, 1969; Livingston and Harvey, 1969). The term "quantization of the magnetic field" was coined. This concept was corroborated by Stenflo (1973), who also analyzed magnetographic observations in two lines to show that the field is concentrated in individual tubes with a diameter of 100 – 300 km and a field intensity on the order of 2000 gauss (G). The kilogauss tubes fill only 1 % of the area of a quiet Sun with an average field of 10 G, for example. It was unclear whether the entire flux is concentrated in these tubes or if there is a nonzero magnetic field between the flux tubes. The contribution of concentrated tubes to the total flux from the solar surface is higher than that of active regions (*e.g.*, Zirin, 1987; Wang *et al.*, 1995).

Later, Stenflo (1982) inferred from the analysis of the Hanle effect that the space between the tubes is filled with an intricate and strongly turbulent field of intensity from 10 to 100 G. Therefore, he suggested the concept of a dual field-structure in the Sun (dichotomy). This concept was corroborated by high-resolution observations obtained from the *Hinode* mission, which also revealed that the size of the tubes is as small as 50 km (Stenflo, 2011). There are reasons to believe that it may be even smaller. However, magnetic elements of this size must be difficult to discern as photometric features, because this is the scale at which the horizontal optical thickness in the photosphere becomes equal to unity. Therefore, the horizontal optical transfer may significantly smooth any temperature irregularities.

It is still unclear how these smaller kilogauss tubes contribute to the cyclic variations of solar activity. White and Livingston (1981) and Trujillo Bueno, Shchukina, and Asensio Ramos (2004) found no significant cyclic variations. In contrast, other authors reported a correlation (Harvey and Harvey, 1974; Hagenaar, Schrijver, and Title, 2003) as well as an anti-correlation with sunspot numbers (*e.g.*, Golub, Davis, and Krieger, 1979; Muller and Roudier, 1984; Harvey, 1985).

It is very important to compare the behavior of the background fields at low and high latitudes. It is reasonable to assume that the similarity and distinctions in the correlation of small-scale fields with sunspot numbers may become clearer when we analyze their latitudinal dependence. To study this, we focused on the asymmetry of background fields. The clearly pronounced north-south asymmetry (N–S asymmetry) of solar activity and its role in generating the solar magnetic field (*e.g.*, see Vitinsky, Kopecky, and Kuklin, 1986; Badalyan *et al.*, 2005; Nagovitsyn *et al.*, 2010; Badalyan, 2011) urged us to examine a similar effect in the solar background field. The N–S asymmetry was revealed in many indices of solar activity, such as the sunspot numbers and areas, differential rotation, prominences and filaments, coronal mass ejections, and magnetic flux. The asymmetry is also observed in different phases of the solar cycle (onset, rise, maximum, fall, and minimum) in the northern and southern hemispheres. The asymmetry is a real and systematic phenomenon. However, some characteristic features of the solar periodicity are lost when the Sun is considered as a whole (Carbonell, Oliver, and Ballester, 1993; Oliver and Ballester, 1994; Ataç and Özgüç, 1996; Duchlev, 2001; Li *et al.*, 2002, 2009, 2010; Temmer, Veronig, and Hanslmeier, 2002; Temmer *et al.*, 2006; Knaack, Stenflo, and Berdyugina, 2004; Gigolashvili *et al.*, 2005; Gao, Li, and Shi, 2009; Sýkora and Rybák, 2010; Badalyan and Obridko, 2011 and references therein; Chowdhury, Choudhary, and Gosain, 2013).

Standard dynamo models primarily produce an equatorward wave that mostly appears symmetric in latitude with respect to the equator. Account of the N–S asymmetry additionally complicates the situation, because both waves become out of phase and show differences in magnitudes. Furthermore, the two dynamo mechanisms working in the two hemispheres are only partly synchronized over the equator and have an additional global modulation with the duration of a century-long cycle (the Gleissberg cycle). The simplest model with interaction of the dynamo waves over the equator was considered by Galitsky, Sokoloff, and Kuzanyan (2005). However, in contrast to this theoretical model, the level of interaction cannot be described quantitatively by mere penetration of the magnetic field across the equator. Therefore, the estimates based on the computations by Galitsky, Sokoloff, and Kuzanyan (2005) would yield a global dynamo-modulating cycle on the order of thousands of years. Therefore, other mechanisms of coupling of the northern and southern hemispheres may be suggested, such as an interaction of the global meridional flow field beyond the convection zone. An indication of this phenomenon can be seen in the existence of trans-equatorial coronal loops and the possible synchronization of observable current helicity patterns across the solar equator, as noted by Zhang *et al.* (2010) and references therein.

By the term "background field" we mean the global photospheric magnetic field excluding the fields of active regions (*i.e.*, with > 300 G in absolute value). The background field and solar radiation are currently widely studied (*e.g.*, see Jin, Wang, and Zhao, 2012; Linker *et al.*, 2012; Petrie, 2012; Shiota *et al.*, 2012).

The aim of this article is to investigate how the background magnetic field of the Sun behaves in different hemispheres.

2. Analysis Method

The analysis of the asymmetry uses a single index that is not directly related to the magnetic field distribution in magnitude; such an index includes the number of sunspots or flares, the intensity of the polar magnetic field, or the mean background field. However, there are reasons to believe that the asymmetry value may be different for fields of different strengths. Therefore, we analyzed the asymmetry of the field density distribution $f(B)$.

Let a given region on the map contain N pixels, N_b of which has the value $b = B \pm \Delta B$. Then, $f(B) = N_b/(2\Delta BN)$ (*i.e.*, the integral $f(B)$ over all B is equal to one). The map usually has no gaps, and the value $2\Delta N$ for the given region remains constant on different days. The $f(B)$ values obtained are averaged over a series of days. Function $f(B)$ is estimated over the intervals $(2\Delta B \cdot K - \Delta B, 2\Delta B \cdot K + \Delta B)$, where $2\Delta B = 4.5$ G, $K = 0, \pm 1, \ldots, \pm 67$.

Function $f(|B|)$ is estimated in a similar way. If among N points in a region there are $N|b|$ points with $|b| = B \pm \Delta B$ where $B > \Delta B > 0$, then $f(|B|) = N|b|/(2\Delta B \cdot N)$.

Let us introduce the following notations:

$f_{\mathrm{N}}(B)$ is the density of distribution of the background fields in the northern hemisphere and

$f_{\mathrm{S}}(B)$ is the same for the southern hemisphere.

The index chosen to characterize the N–S asymmetry of the background field is the ratio

$$q\big(|B|\big) = f_{\mathrm{S}}\big(|B|\big)/f_{\mathrm{N}}\big(|B|\big), \tag{1}$$

where $f(|B|)$ is the density of distribution of the absolute value of the field of intensity B.

We also consider the ratios of the distribution functions for the positive and negative fields in the northern and southern hemispheres:

$$q(B)_{+} = f_{\mathrm{S}}(B)/f_{\mathrm{N}}(B), \tag{2}$$

$$q(B)_{-} = f_{\mathrm{S}}(-B)/f_{\mathrm{N}}(-B), \tag{3}$$

where $B > 0$.

SOHO/MDI data (daily maps of the solar magnetic field B – 1-minute magnetograms of Level 1.8.2, http://soi.stanford.edu/magnetic/index5.html) were studied to analyze the difference between the solar hemispheres in the density of distribution $f(B)$ of the background magnetic field B. The series of the magnetic maps processed covers a period of eight years from 2003 to 2011 when the SOHO pointing was "tumbling" (every quarter, the image of the northern hemisphere appeared alternately at the top or bottom of the field of view). This effect was used to compensate for the spatial irregularities of sensitivity and noise in the MDI detector when comparing $f(B)$ values for the northern and southern hemispheres ($f_{\mathrm{N}}(B)$ and $f_{\mathrm{S}}(B)$). The distribution density $f(B)$ of the field intensity B was calculated daily at a step of 4.5 G in three latitudinal ranges (0 – 30°, 30 – 45°, 45 – 70°) separately for the northern and southern hemispheres. The estimates of f obtained were averaged over the time intervals, which include approximately the same number of normal and inverted images of the Sun.

When determining $f(B)$ and, ultimately, q, q_{+}, and q_{-}, the choice of the parameters $\Delta B = 4.5$ G and the maximum field strength $B_{\mathrm{Max}} \approx 300$ G was determined for the sake of compromise between two competing objectives: to obtain more details (*i.e.*, smaller ΔB and larger B_{Max}) and reduce the computation errors (*i.e.*, larger ΔB and smaller B_{Max}).

Except for 2003, we used annual estimates of $q(|B|)$, $q(B)_{+}$, and $q(B)_{-}$, which were averaged over various intervals of $|B|$.

If the background magnetic field consists of fine elements (flux tubes), the values $q(|B|)$, $q(B)_{+}$, and $q(B)_{-}$ may be interpreted as ratios of the number of these elements in different hemispheres of the Sun.

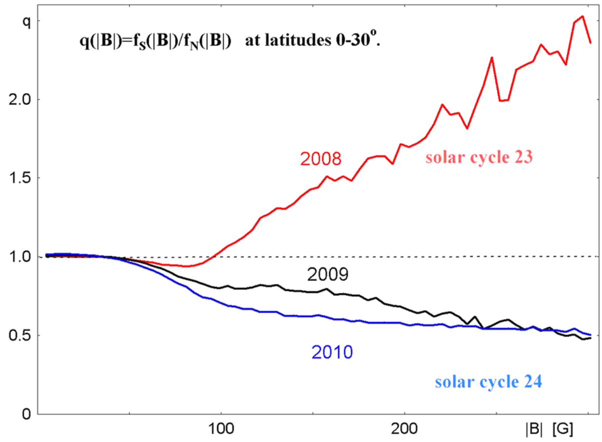

Figure 1 The $q(|B|)$ variation corresponding to latitudes $0-30°$ in 2008, 2009, and 2010.

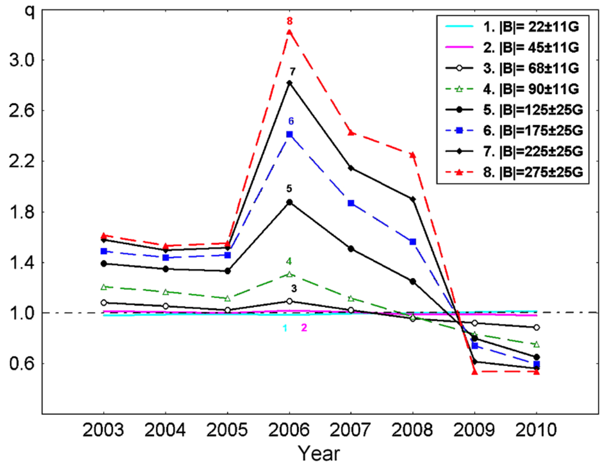

Figure 2 The time variation of index $q(|B|)$ corresponding to latitudes $0-30°$ for eight ranges of $|B|$.

3. The Background Field Asymmetry at Low Latitudes

The basic properties of N–S asymmetry of the background magnetic field at low latitudes ($\varphi = 0-30°$) are represented in Figures 1, 2, and 3.

Figure 1 illustrates variation of $q(|B|)$ for the period 2008 – 2010. At $|B| > 60$ G, $q(|B|)$ differs from unity over time and with variation of B. These changes do not allow us to explain the inequality $q \neq 1$ by peculiarities of the measurement techniques. It also confirms that the background magnetic field of the Sun is asymmetric. This asymmetry is insignificant for weak magnetic fields with $|B| < 60$ G, which suggests the existence of at least two components in the background-field structure. Figure 1 clearly shows the transition from cycle 23 to cycle 24 (or from the paired cycles 22 – 23 to 24 – 25). In cycle 23, $q(|B|)$ increases with the increase of B, and in cycle 24 it, varies in the opposite manner.

The time variation of $q(|B|)$ is seen in more detail in Figure 2. One can see two types of the $q(|B|)$ dependence. For weak magnetic fields with $|B| < 60$ G (curves 1 – 2), the N–S asymmetry is insignificant, dominated by solar and instrumental noises. For stronger fields (curves 3 – 8), the asymmetry is definitely present, the values of q differ significantly from unity, and all time variations in $q(\mathrm{yr})$ have the same pattern, which shows the max-

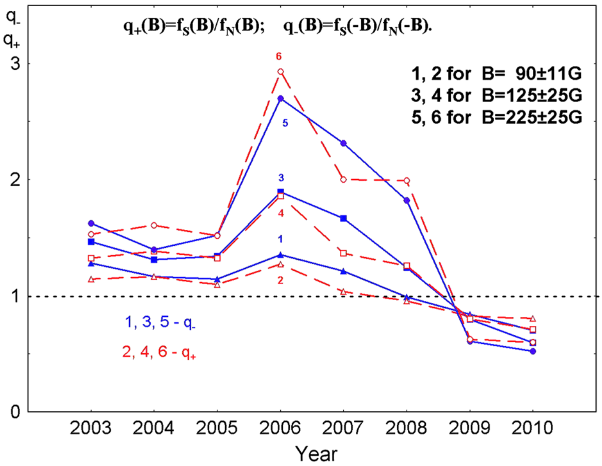

Figure 3 The time variation of indices q_+ and q_- corresponding to latitudes 0 – 30° for three ranges of B.

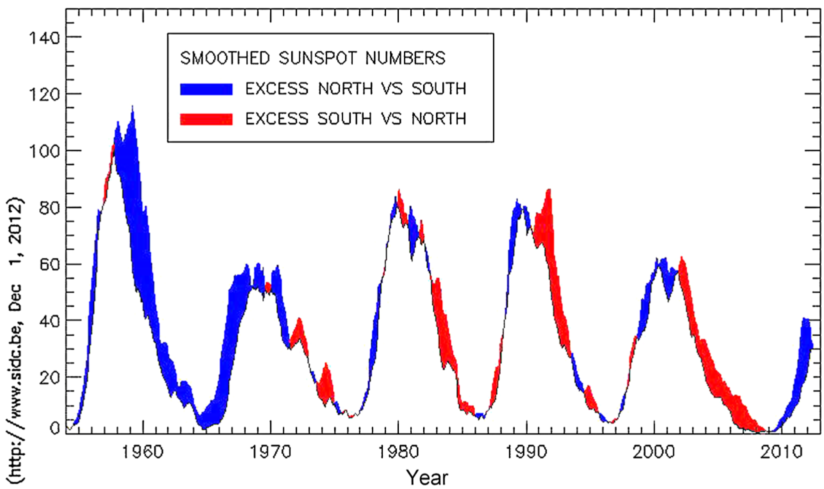

Figure 4 The comparison of sunspot numbers in different hemispheres.

imum asymmetry in 2006 followed by the minimum asymmetry in 2009 – 2010. Around 2008 – 2009, the field predominance in the southern hemisphere ($q > 1$) changed by its predominance in the northern hemisphere ($q < 1$).

The N–S asymmetry in the distribution of $|B|$ at latitudes of 0 – 30° can also be seen when the positive and negative polarities are considered separately (see Figure 3). We found that $q_- \approx q_+$ and $f(-B)/f(B) \approx 1$, *i.e.* the background magnetic field remains quasi-neutral for each year and each field value.

Figure 4 shows a comparison of the sunspot numbers in different hemispheres (downloaded from http://sidc.oma.be/sunspot-index-graphics/sidc_graphics.php). Figures 5a and 5b illustrate the difference of sunspot numbers in the southern and northern hemispheres and their normalized difference (*i.e.*, the difference of sunspot numbers in the two hemispheres divided by their sum). From these figures we conclude the following:

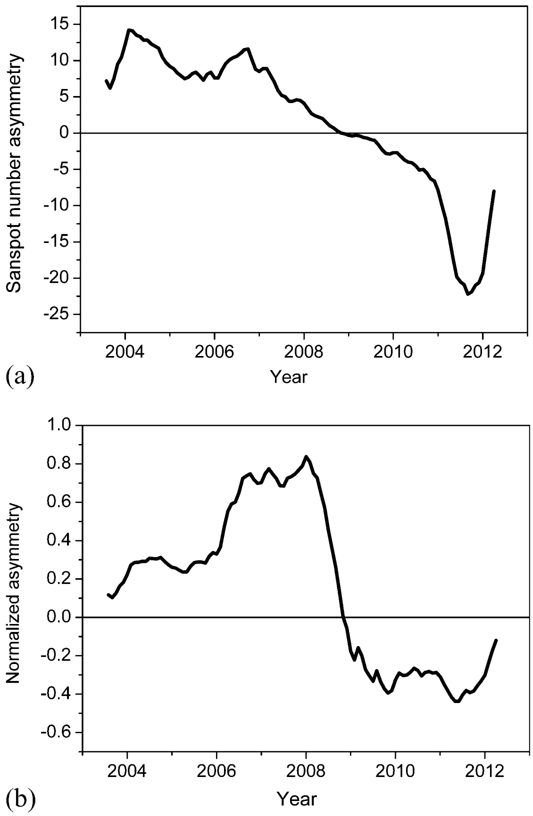

Figure 5 The difference of sunspot numbers in the southern and northern hemispheres (a) and their normalized difference (b).

i) The time variation of the background field asymmetry is similar to the behavior of the asymmetry in sunspot numbers. During the recent solar cycles, the asymmetry of sunspot numbers changed its sign at the minima and maxima of the cycles. The same occurred with the asymmetry of the background field, which changed at the minimum between cycles 23 and 24.

ii) The asymmetry in the distribution of background fields increases with the increase in the field magnitude. The physical nature of this effect is still unclear because it is unclear whether the increase persists for strong fields.

iii) A separate analysis of positive and negative polarities (Figure 3) reveals that the sign of asymmetry of the background field does not depend on the field polarity. In the declining phase of cycle 23, the fields of both polarities were stronger in the southern hemisphere, and their asymmetry changed sign at the cycle minimum simultaneously with the asymmetry of sunspot groups. In cycle 23, the leading sunspot in the southern hemisphere has S (negative) polarity. Correspondingly, the polarity of the following sunspots is N (positive). Since the background field is formed by remnants of the trailing parts of active regions, one can expect that the asymmetry of the background field of N (positive) polarity replicates the asymmetry of sunspot numbers, and, hence, q_+ would be greater than unity. However, $q_- \approx q_+$; *i.e.*, it is also more than unity. Thus, the number of elements of the background field, whatever their sign, is larger in the hemisphere in which the leading sunspot is of S (negative) polarity. This is, probably, because in the context of the Babcock–Leighton mechanism, the two polarities of active regions undergo de-

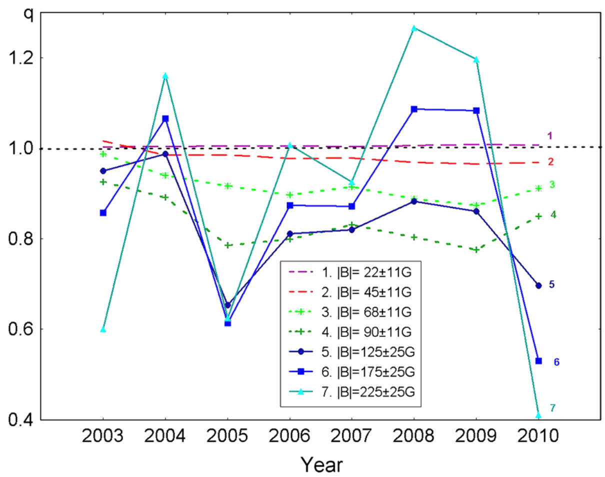

Figure 6 The time variation of index $q(|B|)$ corresponding to latitudes $45-70°$ for seven ranges of $|B|$.

cay and disperse by fluid motions such as turbulent diffusion and differential rotation, which are independent of the polarity of the field. Therefore, generally more fields of all strengths with both polarities are expected in the hemisphere that produces more active regions, and this is what is seen here.

iv) For each year and each value of the magnetic field, $q_- \approx q_+$, and the background magnetic field remains quasi-neutral: $f(-B)/f(B) \approx 1$. This implies that the background fields close within one hemisphere. Since the above expression only approximates unity, some quantity of the magnetic flux in each hemisphere may be open, connecting the large-scale fields in the two hemispheres.

4. The Quantities q, q_-, and q_+ at Latitudes $|\varphi| > 30°$

To compare the effect of the asymmetry within and outside the activity zone ($\varphi = 0-30°$), we have plotted the estimated values of q, q_-, and q_+ in two latitudinal ranges: $45-70°$ and $30-45°$ (Figures 6, 7, and 8).

Figure 6 illustrates the time variation $q(\mathrm{yr})$ at latitudes of $45-70°$. Three types of curves are clearly detected: curves $1-2$ ($|B| < 60$ G), curves $3-4$ ($|B| \approx 60-100$ G), and curves $5-7$ ($|B| > 100$ G). For curves $1-2$, the mean value $\langle q\rangle$ differs from unity by less than 2 %, and the standard deviation sq is $1-2$ %. Thus, the magnetic field for levels $|B| < 60$ G is dominated by natural and instrumental noise, and the N–S asymmetry cannot be detected. This agrees well with our results for weak fields at latitudes $0-30°$ (Figure 2).

Corresponding to curves $3-4$, q changes marginally with time and is always smaller than one. Curves $5-7$ correspond to the condition $|B| > 100$ G and vary almost synchronously in a wide range ($q \approx 0.4-1.2$). A comparison of Figures 6 and 2 reveals a radical difference between the variations of q at latitudes $45-70°$ and $0-35°$ for $|B| > 100$ G. In particular, in the first interval, the eight-year mean values of q are much lower than unity, while in the second interval they are much larger.

The difference in the asymmetry of the background magnetic fields at latitudes $45-70°$ and $0-30°$ becomes even more evident if we consider the positive and negative polarities separately using indices $q_+(\mathrm{yr})$ and $q_-(\mathrm{yr})$ (*cf.* Figures 7 and 3). For the given values of $|B|$ at latitudes $0-30°$, we find $q(\mathrm{yr}) \approx q_+(\mathrm{yr}) \approx q_-(\mathrm{yr})$, while at latitudes $45-70°$, we usually see $q_+(\mathrm{yr}) > 1$ and $q_-(\mathrm{yr}) < 1$ in 2003–2009 (all data ranges except 2010–2011).

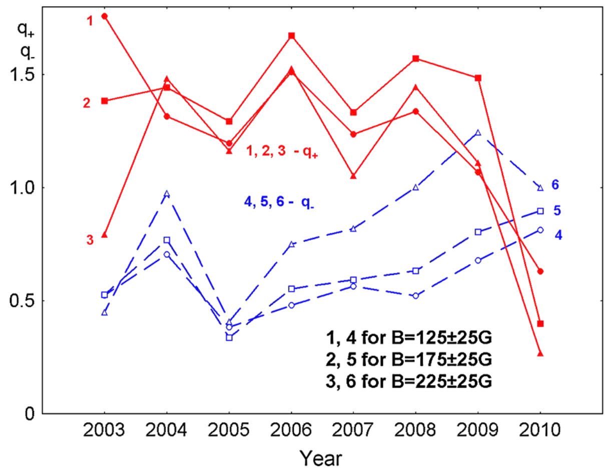

Figure 7 The time variation of indices q_+ and q_- corresponding to latitudes $45-70°$ for three ranges of B.

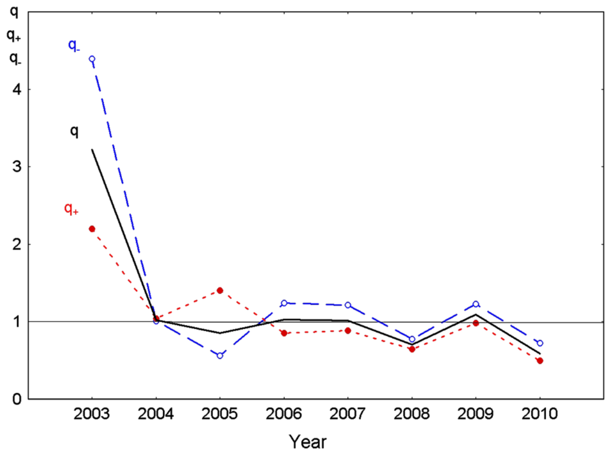

Figure 8 Time variation of indices q, q_+, and q_- corresponding to latitudes $30-45°$ for $B = 100-250$ G.

Thus, at latitudes $0-30°$, the N–S asymmetry in the density of distribution of the background magnetic field ($f(B)$) is revealed in the indices $q(|B|)$, $q(B)_+$, and $q(B)_-$, while at high latitudes $45-70°$, the field amplitude changes. As seen from the plots, the positive polar field in the southern hemisphere appears stronger than in the northern one until 2009, and the negative field appears stronger in the northern hemisphere.

Figure 8 shows time variations of q(yr), q_+(yr), and q_-(yr) at middle latitudes of $30-45°$. The deviations of q from 1 are not as strong as in Figure 2 (if we ignore 2003) and often change their sign. Moreover, the extrema of the q_+(yr) and q_-(yr) variations do not always coincide, and their heights in 2003 differ by a factor of two. Thus, the existence of a *regular* N–S asymmetry at latitudes $30-45°$ is not evident. The cause of the q(yr) peak in 2003 is not clear, because no data in this parameter are available before 2003. It might be generated by the cycle maximum that occurred in 2002.

5. Discussion of the Results

We established the existence of an N–S asymmetry in the distribution density of the solar background magnetic field (with amplitudes $|B| = 100 - 300$ G). The asymmetry is manifested by a significant difference of the distribution density $f(B)$ in the two solar hemispheres. The background photospheric field has a different spatial structure at different latitudes. At low latitudes ($0 - 30^\circ$) and for $|B| > 60$ G, the N–S asymmetry of the field distribution density $f(B)$ is represented by the parameters $q(|B|)$, $q(B)_+$, and $q(B)_-$ irrespective of the sign of the magnetic field.

At higher latitudes ($45 - 70^\circ$) and for $|B| > 100$ G, the effect of the polar field can be seen. As inferred from $q(B)_+$ and $q(B)_-$ data before 2009, the positive polar field was found to be stronger in the southern hemisphere, while the negative field was found to be stronger in the northern hemisphere. At intermediate latitudes ($30 - 45^\circ$), no clearly pronounced effects were noted.

Thus, we confirm the existence of an N–S asymmetry in the distribution density of the solar background magnetic field (with $|B| = 100 - 300$ G). This asymmetry is shown by the substantial difference of $f(B)$ estimates in the two solar hemispheres. The asymmetry of the background magnetic field is characterized by the indices q, q_-, and q_+, which depend on latitude, time, and field intensity B. In particular, in the period of 2006 to 2010, the value of q at latitudes $0 - 30^\circ$ decreased several times; *i.e.*, the relative contribution of the northern latitudes to the low-latitude background field increased significantly. Note that this decrease occurred at the transition of two 22-year magnetic cycles (between the pairs of cycles 22–23 and 24–25). However, it is unclear whether this was caused by the transition from one 22-year cycle to another or by the possible onset of a secular minimum of solar activity. The available series of observational data is insufficient to conclude about this.

The analysis of the N–S asymmetry of the distribution density $f(B)$ became possible with the advent of the SOHO/MDI regular measurements and was associated with a periodic maneuver of the spacecraft. From mid-2003, the SOHO spacecraft has been turned over by 180° quarterly every year. Thus, every three months, the image of the northern hemisphere of the Sun appeared alternately at the top or at the bottom of the field of view. This effect made it possible to eliminate the spatial irregularities of sensitivity and noise of the MDI detector by comparing $f(B)$ values for the northern and southern hemispheres.

The behavior of the high-latitude field is also characterized by some particular features. Until 2009, the positive polar field was found to be stronger in the southern hemisphere and the negative field stronger in the northern hemisphere. At the same time, we found that the former exceeds the secondary positive field in the northern hemisphere. For the negative field, the situation is reverse. This agrees with observations of the polar field (*e.g.*, Shiota *et al.*, 2012) and the general pattern of magnetic field reversal.

Note that the asymmetry of background fields at high latitudes changes sign not at the maximum of the cycle, when a reversal of the polar field occurs, but in 2008–2009, *i.e.*, at about the cycle minimum and, accordingly, the maximum of the polar field.

Figure 9 illustrates the asymmetry of the mean large-scale polar field as inferred from the Wilcox Observatory data (http://wso.stanford.edu/Polar.html). In 2008–2009, the asymmetry of the polar field changed sign, and the total field at the south pole became stronger than that at the north pole.

The results presented here are in general consistent with those obtained from the *Hinode* high-resolution spectro-polarimeter observations carried out in September and November 2007 (Ito *et al.*, 2010; Shiota *et al.*, 2012). In these images, the magnetic field can be resolved into separate clusters of different polarity, which can be interpreted as the kilogauss

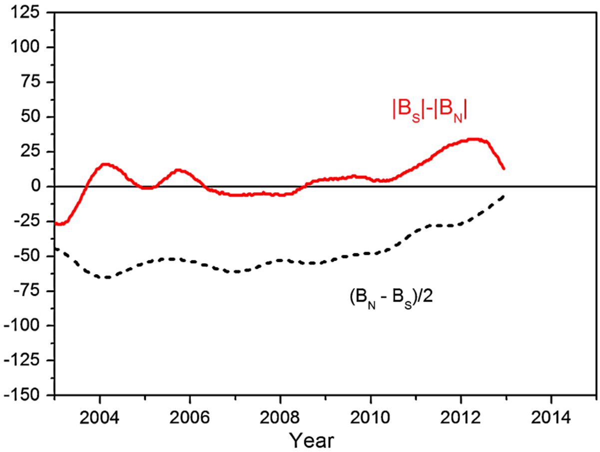

Figure 9 The asymmetry of the mean large-scale polar field as inferred from the Wilcox Observatory data.

flux tubes, as mentioned earlier in Section 1. The field between the flux tubes has been neglected when plotting the histograms. It turned out that the distribution of the clusters in quiet regions is absolutely symmetric about zero and, therefore, the fluxes of both polarities are balanced. On the other hand, the histograms near the north pole are clearly asymmetric, suggesting predominance of the negative polarity during 2003 – 2011. The number of clusters of positive polarity increases with time, which eventually results in the polarity reversal of the mean large-scale field.

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