The Properties of the Tilts of Bipolar Solar Regions

E. Illarionov$^1$ · A. Tlatov$^2$ · D. Sokoloff$^3$

© Springer

Abstract We investigate various properties associated with the tilt of isolated magnetic bipoles in magnetograms taken at the solar surface. We show that bipoles can be divided into two groups which have tilts of opposite signs, and reveal similar properties with respect to bipole area, flux and bipolar moment. Detailed comparison of these physical quantities shows that the dividing point between the two types of bipoles corresponds to a bipole area of about 300 millionths of the solar hemisphere (MHS). The time-latitude distribution of small bipoles differs substantially from that for large bipoles. Such behaviour in terms of dynamo theory may indicate that small and large bipoles trace different components of the solar magnetic field. The other possible viewpoint is that the difference in tilt data for small and large bipoles is connected with spectral helicity separation, which results in opposite tilts for small and large bipoles. We note that the data available do not provide convincing reasons to prefer either interpretation.

Keywords: Solar Cycle, Observations; Magnetic Fields, Photosphere; Active Regions, Magnetic Fields

1. Introduction

The solar magnetic cycle is believed to be associated with dynamo action which occurs somewhere inside the solar convective zone. In turn, the solar dynamo is based on two processes. The differential rotation produces toroidal magnetic field $B_T$ from poloidal magnetic field $B_P$. Details of this process looks quite clear following the modern development of helioseismology (see e.g. the review by Kosovichev, 2008). On the other hand, another process has to regenerate poloidal magnetic field $B_P$ from toroidal. There are several solar dynamo models which

---

$^1$ Department of Mechanics and Mathematics, Moscow State University, Moscow 119991, Russia
email: illarionov.ea@gmail.com

$^2$ Kislovodsk Mountain Astronomical Station of the Pulkovo Observatory, 357700, Box-145, Kislovodsk, Russia
email: tlatov@mail.ru

$^3$ Department of Physics, Moscow State University, Moscow 119992, Russia
email: sokoloff.dd@gmail.com
suggest various physical mechanisms underlying this regeneration. In particular, the regeneration can involve sunspot formation and diffusion at the solar surface (Babcock-Leighton mechanism), or can be associated with cyclonic motions in a more or less deep layer of the convective zone only (the Parker mechanism). However a combined action of both mechanisms looks possible as well (see e.g. the review by Pipin, 2013). The relative importance of both mechanisms for the solar cycle remains a topic of intensive debate.

Of course, an observational clarification of the details of the regeneration process is a useful contribution to the above discussion and the tilt angle of solar bipolar regions provides direct observational information for this regeneration. Indeed, the tilt data show how the direction between the two poles of a magnetic dipole is inclined with respect to the solar equator. If this inclination angle differs systematically from zero, this would mean that poloidal field is produced from toroidal by a physical process, which is exactly the effect under discussion. It is still not the whole story, and various physical mechanisms acting alone or jointly can provide the non-vanishing tilt. Of course, the intention of deducing the tilt from the observational data is to clarify the physics underlying the link between toroidal and poloidal fields. However it is preferable not to assume any choice in advance, so we use below the wording ‘α-effect’ for brevity to refer to this effect.

Tilt studies originated as early as in 1919 (Hale et al., 1919) and resulted in Joy’s law, simultaneously with formulation of the well-known Hale polarity law. According to Joy’s law, the average tilt is a non-vanishing quantity anti-symmetric with respect to the solar equator and growing linearly with sin θ (θ is solar co-latitude). This result is fully in accordance with expectations from solar dynamo theory, and it encourages the use of the tilt data as a valuable observational source to constrain the governing parameters of the solar dynamo. The reality is however more complicated. The point is that the tilt is quite small (several degrees only) and rather noisy. Moreover, the very concept of bipoles and their identification from magnetograms requires an algorithmic formalism in order to make comparable the results of independent analyses. This is probably why experts in solar dynamo theory did not pay attention to the tilt data for quite some time.

The methods available for isolation of bipoles in magnetograms and the database of the tilts grew gradually until they became convincing, at least for some of the dynamo community. To us, the breakthrough was by Stenflo and Kosovichev (2012). This paper confirms Joy’s law in a convincing way and does not recognize any cyclic variations of the slope of the relation between tilt and sin θ (see also Li and Ulrich, 2012).

Further investigation of the tilt data was undertaken by Tlatov et al. (2013) who broadly confirmed the conclusions of Stenflo and Kosovichev (2012) for those bipoles which can mainly be identified with bipolar sunspot groups. A time-latitude (butterfly) diagram for the tilt averaged over appropriate time-latitude bins obtained in Tlatov et al. (2013) demonstrates that the tilt is indeed almost independent of the cycle phase: however some rather minor variations were isolated. The point however is that the analysis of Tlatov et al. (2013) included substantially more small bipoles than that of Stenflo and Kosovichev (2012) and the behaviour of the small bipoles is almost opposite to that of the large bipoles,
which correspond to sunspots. Recall that in Tlatov et al. (2013) we referred to small bipoles those with areas below 300 millionths of the solar hemisphere (MSH), which are mostly ephemeral regions (note that we measure in MSH an area of domains with magnetic field exceeding the threshold level $B_{\text{min}} = 10 \, \text{G}$ isolated in solar magnetograms). In particular, the tilt angle of small bipoles is antisymmetric with respect to the solar equator, whereas the tilt of small bipoles in, say, the northern hemisphere is of the opposite sign to that of the large bipoles. Stenflo (2013) stressed again that the analysis of Stenflo and Kosovichev (2012) does not identify any difference between the tilts of small and large bipoles. However this analysis is not focused on the small bipoles and the situation deserves further investigation and clarification. Indeed, Stenflo and Kosovichev (2012) used a substantially different approach to bipole identification and parameters of their algorithm were optimized for large bipoles only, thus the sample of small-scale bipoles was rather incomplete. Moreover taking into account the higher smoothing level applied by the authors to magnetograms, and the different type of structures, which were recognized as bipoles, we conclude, that the sample of small bipoles, used in Tlatov et al. (2013), cannot be compared directly with bipoles, referred as ”small” in Stenflo and Kosovichev (2012), and they are of particular interest.

The aim of this paper is to extend the analysis of the different behaviour of small and large bipoles to various quantities associated with bipoles. It generalizes the approach of Stenflo and Kosovichev (2012), who, following the idea of the earlier research, concentrated on the relation between tilt and latitude. The sample of the positions of bipoles extracted has sufficient size to proceed further and clarify a possible contribution of other factors to the tilt distribution.

We note that the different behaviour of small and large bipoles isolated at least from the sample of bipoles produced by the algorithm applied does not seem to represent fundamental problems for dynamo theory. In particular, an assumption that the bipoles trace the toroidal magnetic field looks straightforward for large bipoles at least, because they are sunspots which are considered as a tracer for the large-scale magnetic field generated by solar dynamo somewhere in the convective shell. It might be supposed that the small bipoles represent, for example, poloidal magnetic field and this solves the controversy. Of course, this is an option only and other explanations, including even a demonstration that the algorithm used becomes somehow inapplicable for small bipoles, have to be considered.

In our opinion, such considerations have to be based on an examination of the scaling between various physical quantities associated with bipoles. These could include in a plausible way the size of bipole, e.g. its flux, instead of its area. This is a motivation of the research discussed here.

Speaking broadly, we arrive at the conclusion that the distinction between small and large bipoles can be recognized in various physical quantities and confirms to some extent that small and large bipoles trace different magnetic field components.

---

1 MSH = $3.044 \times 10^6 \, \text{km}^2$. A round spot with area $S$ (in MSH) has a diameter of $d = (1969\sqrt{S}) \, \text{km} = (0.1621\sqrt{S})^\circ$ (see Vitinsky, Kopecky and Kuklin 1988).
2. The Data

We used a sample of bipoles identified by the algorithm of Tlatov, Vasil’eva and Pevtsov (2010). The method was applied to the magnetograms from Kitt Peak Vacuum telescope (KPVT) for the period 1975–2003, from the Solar and Heliospheric Observatory Michelson Doppler Imager (SOHO/MDI) (Scherrer et al. 1995; soi.stanford.edu/magnetic/Lev1.8/) for the period 1996–2011 and from the Helioseismic and Magnetic Imager (HMI) (Schou et al. 2012) for the period 2010–2013.

We used the same parameters for recognition of bipoles as Tlatov et al. (2013) and both data samples are identical. In particular we selected domains with magnetic field exceeding the threshold level \( B_{\text{min}} = 10 \, \text{G} \) and area exceeding 50 MSH. The parameters applied involve a large amount of small ephemeral regions, for which it is difficult to prove that each isolated region corresponds to a physical entity and we can operate with their statistical properties only. The tests presented in this paper and in Tlatov et al. (2013) do not show any evidence, that they are caused by a bias in the computer algorithm (see in detail Tlatov, Vasil’eva and Pevtsov, 2010). We stress however that an independent verification of the result by another algorithm looks highly desirable. Such an additional verification is obviously out of the scope of this paper.

For a more correct determination of bipolar positions we exploited only the central part of the solar magnetogram within 0.7 of the solar disk radius, because projection effects near the solar limb may distort the result substantially. Some bipoles may have inverse polarity and violate the Hale polarity law. This happens only in about 5% of cases for bipolar sunspot groups (e.g. Sokoloff and Khlystova, 2010) but this quantity increases substantially in going to smaller areas.

Note that the prevalent orientation is not prescribed in advance. The bipoles are distributed in two-year time bins and 5° latitudinal bins and in each bin the prevalent orientation is defined as follows. For each of the two groups of bipoles with opposite leading polarity we compute the Gaussian approximation to the distribution of their tilt angles. The group with the largest amplitude defines thus the prevalent orientation in the bin. Normally this is just the group with the larger number of bipoles. The obtained sample is a base for further investigations according to additional criteria.

For our analysis we use all bipoles in both hemispheres. We combine them together in such way that final angular distribution has a single peak, i.e. we subtract 180° from the angles in the second and third quadrants, and reverse the distributions in the southern hemisphere. The combined sample contains tilt angles in the interval between \(-90^\circ\) to \(+90^\circ\). For both hemispheres the positive sign indicates that the domain of leading polarity is closer to the Equator than the trailing domain. The negative sign means on the contrary that the domain of trailing polarity is situated closer to the Equator. We use the median as a robust statistic to estimate a mean tilt, and the t-Student criterion for 95% confidence intervals.

The database used gives for the bipoles the following parameters: the time \( t \) of observation, latitude \( \theta \) of the centre of the bipole, the area \( S \), flux \( F \), distance \( d \) between the poles and the tilt \( \mu \).
3. Results

We are interested mainly in correlations between the tilt $\mu$ and the other parameters describing a bipole. The dependence of the orientation of bipoles on the solar cycle is the well-known Hale’s polarity law, while the dependence of $\mu$ on the latitude is given by Joy’s law. We recall that the verification of Joy’s law, based on an algorithmic procedure to recognise bipolar regions, confirms the law (Stenflo and Kosovichev [2012] Li and Ulrich [2012] Tlatov et al. [2013]).

Quite surprisingly Tlatov et al. [2013] found that tilt substantially depends on the area of bipoles and that the prevalent tilt for small bipoles has the opposite sign to that for large bipoles. This trend can be easily noticed in Figure 1, where we show the density of tilt angle distribution against bipole area. Indeed, for large bipoles (we assume the dividing point between large and small bipoles is the same as in Tlatov et al. [2013], i.e. 300 MSH) we observe a pronounced peak in the domain of positive tilts. With smaller areas the peak becomes blurred (the distribution becomes rather non-gaussian), but the domain of increased bipole density turns smoothly down to the domain of negative tilts. The linear least-square fit confirms the visual trend and intersects the line of zero tilt exactly near 300 MSH. Difference of mean tilt signs for these two groups of bipoles is confirmed by simple statistical test based on Student’s $t$-test. It gives $t_{eq} = 22.9$ under hypothesis that both samples have similar mean values and $t_{op} = 0.98$ under hypothesis that mean values have similar absolute values but opposite signs. However the noisy distribution for small bipoles restricts the abilities of the $t$-test in some ways.

![Figure 1. Distribution of bipoles in the combined area and tilt angle domains, intensity of the colour indicates number of bipoles relative to the total number of bipoles with the same areas (MDI data for the period 1998–2007, bipoles were selected from latitudinal zone $|\theta| \geq 10^\circ$). The red line corresponds to the linear least-square fit.](image)

Now, we analyse the a correlation between the parameters mentioned above and tilt on the basis of the observational data available. In particular, it is...
interesting to compare the correlations for large and small bipoles in order to gain a better understanding of the physical nature of the difference in behaviour between these bipoles which was found in [Tlatov et al. (2013)].

3.1. Cyclic Modulations of the Tilt

We start from a straightforward (and possibly not the most instructive) correlation property of the tilt angles, i.e. a correlation of the tilt averaged over 2-year bins with the phase of the cycle. The correlation calculated separately for large and small bipoles is presented in Figure 2. There are two messages from the plot. First of all, the KPVT data, MDI data and HMI data look to be more or less in agreement, at least at the epoch when the data overlap. This appears to confirm the self-consistency of the bipole database used. In contrast, the large and small bipoles demonstrate opposite behaviour for each set of observational data.

![Figure 2. Tilt (in degrees) averaged over 2 years time bins. Solid line is for large bipoles with areas $S > 300$ MSH, dashed line is for small bipoles with areas $50 < S < 300$ MSH. Black colour shows KPVT data, blue is for MDI data, green is for HMI data.](image)

The other message from the plot is a pronounced cyclic modulation visible for both types of bipoles. A remarkable feature is that in the course of the cycle the absolute value of tilts of large bipoles decreases, while for small bipoles we observe an increase. Strictly speaking we have to distinguish cycles for both types of bipoles and as it will be shown later there are some reasons to suppose it.

An interpretation of the correlation for the large bipoles looks quite straightforward and is consistent with the suggestion of [Stenflo and Kosovichev (2012)] that the slope in Joy’s law is independent of the phase of the cycle. Indeed, Joy’s law tells us that $\mu \propto \sin \theta$ where $\theta$ is the colatitude of the bipoles, which decays on average with the phase. This results in a decay of $<\mu>$.

Obviously, this interpretation does not explain the behaviour of the small bipoles. In order to clarify the situation we present in Figure 3 the behaviour of the tilt for small bipoles averaged in various latitudinal zones versus time, and
the distribution of the small bipoles compared with that of the large. We see from this figure that the small bipoles demonstrate some kind of cyclic behaviour which is, however, quite different from that of the large. The time-latitude distribution of small bipoles demonstrates an equatorward propagating pattern as well as poleward. The cycle described by small bipoles looks shifted from that of the large. The tilt angles of the small bipoles are, as expected, determined mainly by bipoles located in the middle latitudes. In general, it looks plausible that small bipoles represent a different component of the solar magnetic field to that traced by the large ones.

![Figure 3](image)

**Figure 3.** Upper figure: time-latitude diagram for tilt according to KPVT data for bipoles with areas $50 < S < 300$ MSH. Blue shows negative tilt, red is for positive. The yellow points show the sunspot distribution. Lower figure: tilt evolution for bipoles with areas $50 < S < 300$ MSH in different latitudinal zones: black represents bipoles with $|\theta| < 10^\circ$, green with $10^\circ \leq |\theta| < 20^\circ$, red with $20^\circ \leq |\theta| < 30^\circ$, and blue with $30^\circ \leq |\theta| < 40^\circ$.

### 3.2. Violations of Hale’s Law

Now we examine how Hale’s polarity law works for large and small bipoles. Of course, there is a small fraction of bipoles which violate Hale’s law. It is natural to compare this fraction with the fraction of sunspot groups which violate the law (according to Sokoloff and Khlystova [2010] this fraction is about $5 - 7\%$).

The fraction of bipoles which follow the Hale polarity law *versus* the bipole area is presented in Figure 4. The plot is organized as follows. We divide the bipole sample in bins according to their area. Dots in the plot correspond to centres of a bin. Then the fraction of bipoles in a bin which follow Hale’s law is shown by the vertical coordinate in the plot. In our analysis we used the MDI
data at the maximum stage of the Cycle 23 (period 1998–2007). At the end of this cycle the overlap of bipoles with opposed orientations occurs because of the extended solar cycle at high latitudes (Tlatov, Vasil’eva and Pevtsov, 2010).

For the largest bipoles the fraction which follow Hale’s law exceeds 90%. Such bipoles correspond to bipolar sunspot groups and the result, as expected, agrees with the estimate of Sokoloff and Khlystova (2010).

The fraction of bipoles which follow Hale’s law drops with the bipole area. This seems natural because it is more difficult to isolate small bipoles than the large ones, and the noise level in determination of the bipole orientation is larger for the small bipoles. The point however is that the plot in Figure 4 shows specific slopes for large, $S^{0.05}$, and small, $S^{0.2}$, bipoles. This confirms that small and large bipoles represent physical entities of different natures. The slopes match near $S = 500$ MHS. This confirms the validity of the area threshold chosen to separate small and large bipoles. The data for bipoles in these groups are shown in blue and red in Figure 4. The fraction of bipoles which follow the Hale’s law becomes as small as 50% near $S = 50$ MHS and, then, it becomes fruitless to consider smaller bipoles.

Thus the estimate $5 \sim 7\%$ for the number of reversed bipoles is valid mainly for bipoles with areas greater than 1000 MSH.

3.3. Flux and Tilt

We now investigate in more detail the link between the size of a bipole and the tilt. There are two natural measures for the size of a bipole, its area $S$ and its magnetic flux $F$ (here and below $F$ is measured in $10^{20} \text{ Mx}$). Fortunately, both these quantities are closely interrelated (Figure 5). $F(S) \sim S^{1.25}$ (blue line). This means that it is sufficient to study only the dependence on $F$. In the same figure we show that the large bipoles give the main contribution to the total magnetic flux. More precisely we plot with a black line a function $\Phi(S)$ which gives the contribution to the total flux of bipoles with areas greater than $S$. The line is fitted well by $\Phi(S) = \exp[-S/(2 \times 10^3)]$. 

![Figure 4](#) The fraction of bipoles oriented according to Hale’s polarity law (MDI data). Blue marks the segment with the slope of the line 0.2, red marks the segment with the slope 0.05.
Figure 5 shows that about 90% of total flux comes from bipoles with areas $S > 300$ MSH. However, we appreciate that such an estimate does not, for instance, take into account that the lifetime of small bipoles (ephemeral regions) is shorter than that of large bipoles (sunspots). Thus, the contribution of the smaller bipoles to the total flux may be underestimated, and a more detailed analysis is required. In particular, a measure of the flux regeneration rate would seem to be more suitable here.

![Figure 5](image1)

**Figure 5.** Black line shows the contribution of bipoles to the total flux according to MDI data (graphics of $\Phi(S)$). Blue dots indicate the mean flux for bipoles with different areas, the fitted line has a slope of 1.25.

Figure 6 shows that a negative tilt value is predominant for $F < 10$. With $F > 30$ it becomes positive. Comparing the plot with the previous Figure 5, we conclude that the dividing point $F = 20$ corresponds to an area $S = 300$ MSH. The tendency of increasing tilt seems to remain for larger values of $F$.

The investigation of the correlation between flux and tilt is interesting in the first place for estimating the contribution of bipolar moments to the formation of the poloidal component of magnetic field (Stenflo, 2013). We recall that the bipolar moment is $B_m = F \cdot d$, where $F$ is the flux of a bipole and $d$ is the distance between the unipolar regions in the bipole. Furthermore, $d$ is another natural measure of the bipole size.

![Figure 6](image2)

**Figure 6.** Tilt against flux $F \times 10^{20}$ Mx for MDI data.
The distance $d$ is defined as the distance in heliographic degrees between the geometrical centres of monopoles in a given bipole. This definition includes indirectly a contribution from the area of the bipole (a part of $d$ comes from the radii of the two opposite polarities of the bipole) and is strongly affected by the shape of the domains (complex configurations can even give zero $d$). Indeed, a simplistic presentation of bipoles as two near circular domains leads to $d$ increasing as $\sqrt{S}$, where $S$ is a measure of area of a bipole.

![Figure 7. Mean distance $d$ against size of the domains given by $\sqrt{S}$.](image1)

In fact Figure 7 shows the slope of $d$ as function of $\sqrt{S}$ to be significantly less than one. This means that domain sizes increase faster than the distance between them. Again, behaviour of the plot is different for large and small bipoles (however the slope is almost the same), and the dividing point is close to $S = 300$ MHS (note that the plot shows $\sqrt{S}$ rather than $S$).

![Figure 8. Bipolar moment against area of bipoles, MDI data. The fitted line has a slope of 1.5.](image2)

For investigation of the bipolar moment, $B_m$, we consider first its dependence on the area of the bipoles. Figure 8 shows that $B_m$ is proportional to $S^{1.5}$. The mean tilt versus $B_m$ is shown in Figure 9. We see that the tilt of small bipoles...
behaves again in the opposite way to that of the large bipoles and the dividing point \( B_m = 90 \) lies between 200 – 300 MSH (Figure 8).

![Figure 9. Tilt against bipolar moment \( B_m \) [10^{20} Mx°] for MDI data.](image)

Figure 9 shows a moderate growth of the tilt with increasing bipolar moment for large bipoles. Note that Stenflo and Kosovichev (2012) did not find any significant variations of tilt angle with flux or bipolar moment.

Now we can calculate the averaged effect of the tilt as follows. We consider the bipoles which follow Hale’s polarity law, multiply the tilt by the polarity \( p = \pm 1 \) of the leading component of the bipole, and sum \( F \sin(p \mu) \) over all bipoles (for the period 1998–2007 using MDI data). The quantity obtained is 10% of the total magnetic flux and shows which part of the toroidal magnetic field is converted to poloidal one. In other words, it is an estimate of the ratio \( \alpha/v \), where \( v \) is the r.m.s. velocity of the convection and \( \alpha \) is the magnitude of the alpha-effect. The estimate is robust in sense that it remains stable if the large bipoles only are taken into account (small bipoles give only a minor contribution to the estimate), or if we consider bipolar moments instead of magnetic fluxes. The estimate is remarkably close to the order-of-magnitude estimate in Tlatov et al. (2013) and corresponds to a traditional expectation from dynamo theory.

4. Discussion and Conclusions

Summarizing, we conclude that we can recognize specific properties of small and large bipoles, which are represented mainly by ephemeral regions and sunspot groups respectively. The dividing point between the groups is located near a bipole area \( S = 300 \) MSH. However the separation of the groups can be based on other relevant quantities, i.e. bipolar moment, magnetic flux, distance between the bipole domains. All ways of separating the groups give similar results. The main difference between the two groups in the context of our research is the opposite sign of the bipole tilt. However specific properties of two groups of bipoles are visible in other respects as well.

We note several other remarkable features in the results obtained.

The time-latitude diagram for small bipoles (Figure 3) seems to agree with the concept of the extended solar cycle (Wilson et al., 1988). In particular the wings
of the butterfly diagrams for the tilt of small bipoles start at high latitudes 1 – 2 years earlier than the corresponding sunspot cycle, and then propagate towards the solar equator.

For the large bipoles (S > 300 MSH), the tilt becomes larger for larger bipoles. The tendency is visible if the flux is considered as a measure of the size of bipoles (Figure 6) as well as if the bipole moment is considered as the measure (Figure 9).

Separation of bipoles into small and large with opposed properties seems to support the idea of Choudhuri and Karak (2012) that the regimes of dynamo action in the presence of sunspots (i.e. large bipoles) and in their absence are substantially different. Probably, this illuminates a difference between solar dynamo action during the Maunder minimum and in contemporary solar cycles. Of course, a simple explanation is that the fields responsible for the large and small bipoles just originate from different depths where the fields have different properties.

Pragmatically, the contribution of large bipoles to the total $\alpha$-effect (that parametrizes solar dynamo action) dominates and it seems possible to ignore small bipoles when quantifying it. A deeper understanding of the processes underlying solar dynamo action deserves however a physical interpretation of the opposed properties of the large and small bipoles with respect to the tilt.

First of all, we have to note that our research is inevitably based on a complicated algorithmic procedure leading to the isolation of bipoles from magnetograms. Our analysis does not show any trace of a bug in the algorithm used which could produce a difference between small and large bipoles. It is difficult however to exclude such an option completely based on the results of the application of just one algorithm for isolation of the bipoles. We thus stress the desirability of comparing our results with those from other algorithms which can isolate small bipoles from large. Future research in this direction is needed.

Tlatov et al. (2013) suggested that the opposite sign of tilt for small and large bipoles can be understood as indicating that large bipoles represent toroidal magnetic field while the small ones are connected with poloidal magnetic field. Figure 3 seems to support this interpretation. Indeed, the interpretation of large bipoles, i.e. sunspot groups as tracers of toroidal magnetic field, is standard and the problem is to identify what is traced by the small bipoles. Figure 3 shows that the tilt patterns in the time-latitude diagram for small bipoles are pronouncedly dissimilar to the sunspot wings in the diagram. They are however quite similar to corresponding patterns of the large-scale surface magnetic field (Obridko et al., 2006) which presumably trace the solar poloidal magnetic field. The fact that we see specific slopes for small and large bipoles in other plots presented above seems to agree with this interpretation. However one could expect even more dramatic events at transitions in the plots between small and large bipoles, such as jumps. The point is that dynamo modelling predicts that toroidal magnetic field should be substantially stronger than the poloidal, which would be expected to result in jumps.

Another possible interpretation might be based on the idea that the $\alpha$-effect is associated with hydrodynamic and magnetic helicities, which are inviscid invariants of motion (Seehafer 1996; Krivodubskii 1998). Then accumulating helicity in one range of scales (or spatial region) would have to be compensated by growth
Properties of tilt of bipolar solar regions

of helicity of the opposite sign in the other range. A moderate growth of the tilt with bipolar moment for large bipoles in Figure 3 seems to be consistent with the idea of the helicity separation in Fourier space (Seehafer, 1996): the point is that the Coriolis force is larger for larger bipoles. A continuous behaviour of the plots in figures which do not involve tilt directly becomes natural with this interpretation: all bipoles now represent toroidal field. In contrast, the form of the time-latitude diagrams in Figure 3 now requires an explanation.

We stress that the arguments in favour of either of the above interpretations do not seem convincing enough for us to prefer one to the other.

Acknowledgments The paper is supported by RFBR under grants 12-02-00170, 13-02-91158, 12-02-00884, 12-02-31128, 13-02-01183, 12-02-00614. We are grateful to D. Moss for a critical reading of the paper.

References

Choudhuri, A.R., Karak, B.B.: 2012, Phys. Rev. Lett. 109, 171103
Hale, G.E., Ellerman, F., Nicholson, S.B., Joy, A.H.: 1919, Astrophys. J. 49, 153
Kosovichev, A.G.: 2008, Adv. Space Res. 41, 830
Krivodubskii, V.N.: 1998, Astron. Rep. 42, 122
Li, J., Ulrich, R.K.: 2012, Astrophys. J. 758, 115
Ohridko, V.N., Sokoloff, D.D., Kuzanyan, K.M., Shelting, B.D., Zakharov, V.G.: 2006, Mon. Not. Roy. Astron. Soc. 365, 827
Pipin, V.V., in Kosovichev, A.G., de Gouveia Dal Pino, E.M., Yan, Y. (eds.), Solar and Astrophysical Dynamos and Magnetic Activity, Proc. IAU Symp. 294, 375
Scherrer, P.H., Bogart, R.S., Bush, R.I., Hoeksema, J.T., Kosovichev, A.G., Schou, J., et al. and the MDI Engineering Team: 1995, Solar Phys. 162, 129
Schou, J., Scherrer P.H., Bush, R.I., Wachter, R., Couvidat, S., Rabello-Soares M.C., Bogart R.S., Hoeksema J.T., Liu, Y., Duvall, T.L., Akin, D.J., Allard, B.A., Miles, J.W., Raiden, R., Shine, R.A., Tarbell, T.D., Title, A.M., Wolfson, C.J., Elmore, D.F., Norton, A.A., Tomczyk, S.: 2012, Solar Phys. 275, 229
Seehafer, N.: 1996, Phys. Rev. E 53, 1283
Sokoloff, D.D., Khlystova, A.I.: 2010, Astron. Nachr. 331, 82
Stenflo, J.O.: 2013, Astron. Astrophys. Rev. 21, 66
Stenflo, J.O., Kosovichev, A.G.: 2012, Astrophys. J. 745, 129
Tlatov, A.G., Illarionov, E.A., Sokoloff, D.D., Pipin, V.V.: 2013, Mon. Not. Roy. Astron. Soc. 432, 2975
Tlatov, A.G., Vasil’eva, V.V., Pevtsov, A.A.: 2010. Astrophys. J. 717, 357
Vitinsky, Yu.I., Kopecky M., Kuklin G.V.: 1986, Statistics of the Sunspot Activity, Nauka, Moscow
Wilson, P.R., Altrocki, R.C., Harvey, K.L., Martin, S.F., Snodgrass, H.B.: 1988, Nature 333, 748