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The Properties of the Tilts of Bipolar Solar Regions

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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 that 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. The time–latitude distribution of small bipoles differs substantially from that for large bipoles. Such a behaviour in terms of dynamo theory may indicate that small and large bipoles trace different components of the solar magnetic field. The other possible explanation 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 that occurs somewhere inside the solar convective zone. In turn, the solar dynamo is based on two processes.

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The differential rotation produces a toroidal magnetic field $\mathbf{B}_\mathrm{T}$ from a poloidal magnetic field $\mathbf{B}_\mathrm{P}$. The details of this process look 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 $\mathbf{B}_\mathrm{P}$ from the toroidal field. Several solar dynamo models have suggested various physical mechanisms that might be responsible for this regeneration. In particular, the regeneration might involve sunspot formation and diffusion at the solar surface (Babcock–Leighton mechanism), or it might be associated with cyclonic motions in only a more or less deep layer of the convective zone (the Parker mechanism). However, a combined action of these two mechanisms is possible as well (see *e.g.* the review by Pipin, 2013). The relative importance of these two mechanisms for the solar cycle remains a topic of intense debate.

Of course, an observational clarification of the details of the regeneration process is a useful contribution to this 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 bipole is inclined with respect to the solar equator. If this inclination angle systematically differs from zero, this would mean that the poloidal field is produced from the toroidal field 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, therefore we use below the wording 'α-effect' for brevity to refer to this effect.

Tilt studies were made 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 antisymmetric with respect to the solar equator and growing linearly with $\sin\theta$ (θ is the 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 more complicated, however. 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 to make the results of independent analyses comparable. This is probably why experts in solar dynamo theory did not pay attention to the tilt data for quite some time.

The methods available to isolate bipoles in magnetograms and the database of the tilts gradually grew until they became convincing, at least for some of the dynamo community. To us, the breakthrough was achieved by Stenflo and Kosovichev (2012). They confirmed Joy's law in a convincing way and did not recognise any cyclic slope variations in the relation between tilt and $\sin\theta$ (see also Li and Ulrich, 2012).

The tilt data were investigated in depth again by Tlatov *et al.* (2013), who broadly confirmed the conclusions of Stenflo and Kosovichev (2012) for the bipoles that can be mainly identified with bipolar sunspot groups. The 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; some very small variations were isolated, however. The point is that the analysis of Tlatov *et al.* (2013) included substantially more small bipoles than the analysis 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. We recall that in Tlatov *et al.* (2013) we defined small bipoles as those with areas smaller than 300 millionths of the solar hemisphere (MSH[1]), which are mostly ephemeral regions (note that we measured an area of domains with a magnetic field exceeding the threshold level $B_{\min} = 10$ 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 the northern hemisphere, for example, is of the opposite sign to that of the large bipoles. Stenflo (2013) stressed again that the analysis of Stenflo and Kosovichev (2012) did not identify any difference between the tilts of small and large bipoles. However, this analysis was 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 the parameters of their algorithm were only optimised for large bipoles, which made the sample of small-scale bipoles rather incomplete. Moreover, taking into account the higher smoothing level applied by the authors to magnetograms and the different type of structures that were recognised as bipoles, we conclude that the sample of small bipoles used in Tlatov *et al.* (2013) cannot be compared directly with the bipoles that were referred to as "small" in Stenflo and Kosovichev (2012) – and they are of particular interest.

The aim of this article is to extend the analysis of the different behaviour of small and large bipoles to various quantities associated with bipoles. It generalises 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 extracted bipoles is large enough 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, assuming that the bipoles trace the toroidal magnetic field is straightforward for large bipoles at least, because they are sunspots that are considered as a tracer for the large-scale magnetic field generated by solar dynamo somewhere in the convective shell. It might be assumed that the small bipoles represent a poloidal magnetic field, for example, and this solves the controversy. Of course, this is only an option, and other explanations, including even a demonstration that the algorithm used becomes somehow inapplicable for small bipoles, have to be considered.

These 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 the bipole, *e.g.* its flux, instead of its area. This is the motivation of the research discussed here.

Broadly speaking, we conclude that the distinction between small and large bipoles can be recognised in various physical quantities and confirms to some extent that small and large bipoles trace different magnetic field components.

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 the *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/)

[1] 1 MSH $= 3.044 \times 10^6$ km^2. A round spot with area S (in MSH) has a diameter of $d = (1969\sqrt{S})$ km $= (0.1621\sqrt{S})^\circ$ (see Vitinsky, Kopecky, and Kuklin, 1986).

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 to recognise bipoles as Tlatov *et al.* (2013), and the two data samples are identical. In particular, we selected domains in which the magnetic field exceeds the threshold level $B_{\min} = 10$ G and an area exceeding 50 MSH. The parameters applied involve many small ephemeral regions, for which it is difficult to prove that each isolated region corresponds to a physical entity, and we can only operate with their statistical properties. The tests presented here and in Tlatov *et al.* (2013) do not show any evidence that these statistical properties 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 is highly desirable. Such an additional verification is obviously beyond the scope of this article.

To determine the bipole positions more correctly, 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 is true only in about 5 % of cases for bipolar sunspot groups (*e.g.* Sokoloff and Khlystova, 2010), but this fraction increases substantially for smaller areas.

The prevalent orientation was not prescribed in advance. The bipoles were distributed in two-year time bins and 5° latitudinal bins, and in each bin the prevalent orientation was defined as follows: For each of the two groups of bipoles with opposite leading polarity we computed the Gaussian approximation to the distribution of their tilt angles. The group with the largest amplitude thus defines the prevalent orientation in the bin. This normally is just the group with more bipoles. The obtained sample is the base for further investigations according to additional criteria.

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

The database gives the following parameters for the bipoles: the time t of observation, latitude θ of the centre of the bipole, the area S, flux F, distance d between the poles, and the tilt μ.

3. Results

We are interested mainly in correlations between the tilt μ and the other parameters describing a bipole. The dependence of the orientation of bipoles on the solar cycle is the well-known Hale polarity law, while the dependence of μ 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 the 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

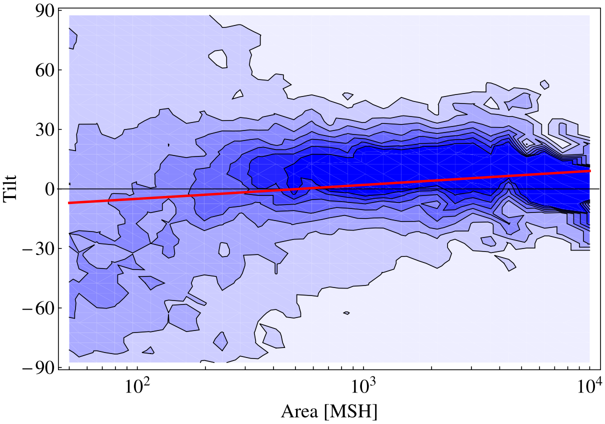

Figure 1 Distribution of bipoles in the combined area and tilt angle domains. The intensity of the colour indicates the number of bipoles relative to the total number of bipoles with the same areas (MDI data for the period 1998 – 2007, bipoles were selected from the latitudinal zone $|\theta| \geqslant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

the tilt angle distribution against the bipole area. Indeed, for large bipoles (we assumed that 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-squares fit confirms the visual trend and intersects the line of zero tilt exactly near 300 MSH. The difference of the mean tilt signs for these two bipole groups is confirmed by a simple statistical test based on Student's t-test. It gives $t_{\mathrm{eq}} = 22.9$ under the hypothesis that both samples have similar mean values, and $t_{\mathrm{op}} = 0.98$ under the hypothesis that the 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.

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

3.1. Cyclic Modulations of the Tilt

We started from a straightforward (and possibly not the most instructive) correlation property of the tilt angles, *i.e.* a correlation of the tilt averaged over two-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, MDI, and HMI data appear to agree more or less, at least at the epoch when the data overlap. This apparently confirms the self-consistency of the bipole database. In contrast, the large and small bipoles demonstrate opposite behaviour for each set of observational data.

The plot also shows a pronounced cyclic modulation for both types of bipoles. Remarkably, the absolute value of the large bipole tilts decreases during the cycle, while for small bipoles we observe an increase. Strictly speaking, we need to consider the cycles for each type of bipoles separately, and we show below that there are some reasons for this.

The correlation for the large bipoles appears to be quite clear 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. According to Joy's law, $\mu \propto \sin\theta$, where θ is the colatitude of the bipoles, which decays on average with the phase. This results in a decay of $\langle\mu\rangle$.

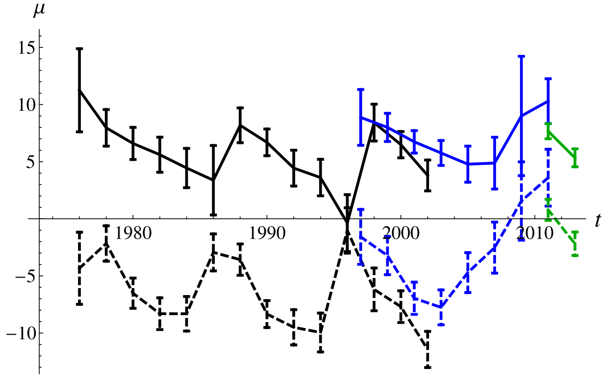

Figure 2 Tilt (in degrees) averaged over two-year time bins for the period 1975 – 2013. The solid line depicts large bipoles with areas $S > 300$ MSH, the dashed line small bipoles with areas $50 < S < 300$ MSH. The KPVT data are shown in black, the MDI data in blue, and the HMI data in green.

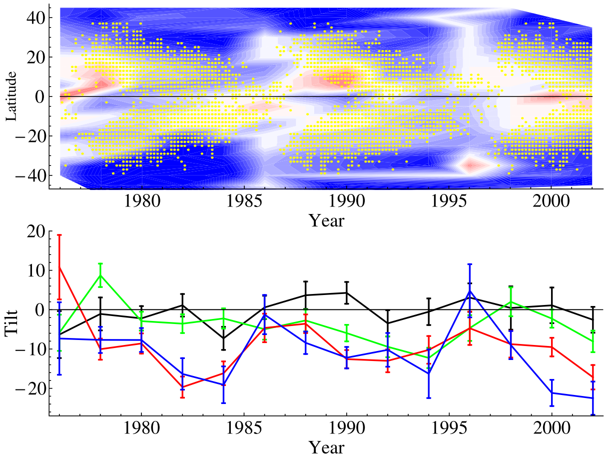

Figure 3 Upper panel: time–latitude diagram for the tilt according to KPVT data for bipoles with areas $50 < S < 300$ MSH. Blue shows the negative, red the positive tilt. The yellow points show the sunspot distribution. Lower panel: tilt evolution for bipoles with areas $50 < S < 300$ MSH in different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

Obviously, this interpretation does not explain the behaviour of the small bipoles. To clarify this, 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 the distribution of the large bipoles. This figure shows that the small bipoles demonstrate some kind of cyclic behaviour that is, however, quite different from that of the large bipoles. The time–latitude distribution of small bipoles demonstrates an equatorward propagating pattern as well as a poleward pattern. The cycle described by the small bipoles is shifted from that of the large bipoles. The tilt angles of the small bipoles are, as expected, determined mainly by bipoles located in the middle latitudes. In general, it is plausible to assume that small bipoles represent a different component of the solar magnetic field from that traced by the large bipoles.

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 that violate Hale's law. It is natural to compare this fraction with the fraction of sunspot groups that violate the law (according to Sokoloff and Khlystova (2010), this fraction is about 5 – 7 %).

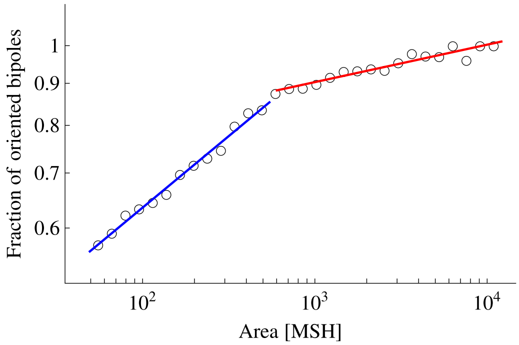

Figure 4 The fraction of bipoles oriented according to Hale's polarity law (MDI data). Blue marks the segment with a slope of the line of 0.2, red marks the segment with a slope of 0.05.

The fraction of bipoles that *follow* the Hale polarity law *versus* the bipole area is presented in Figure 4. The plot is organised as follows: We divided 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 that 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 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 that follow Hale's law exceeds 90 %. These bipoles correspond to bipolar sunspot groups, and the result, as expected, agrees with the estimate of Sokoloff and Khlystova (2010).

The fraction of bipoles that follow Hale's law decreases with the bipole area. This seems natural because it is more difficult to isolate small bipoles than large ones, and the noise level in the determination of the bipole orientation is higher for the small bipoles. The point is, however, 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 change of slope occurs near $S = 500$ MHS. This is in agreement with an area threshold 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 that follow Hale's law decreases to 50 % near $S = 50$ MHS, and after this, it becomes fruitless to consider smaller bipoles.

Thus the estimate 5 – 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 the link between the size of a bipole and the tilt in more detail. 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} 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 the function $\Phi(S)$ that 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 5 shows that about 90 % of total flux comes from bipoles with areas $S >$ 300 MSH. However, we appreciate that this estimate does not, for instance, take into account that the lifetime of small bipoles (ephemeral regions) is shorter than that of the large bipoles (sunspots). Thus the contribution of the smaller bipoles to the total flux may be un-

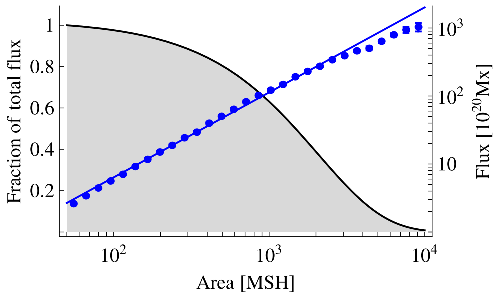

Figure 5 The black line shows the contribution of bipoles to the total flux according to MDI data (graphics of $\Phi(S)$). Blue dots indicate the mean flux for bipoles with different areas, the fitted line has a slope of 1.25.

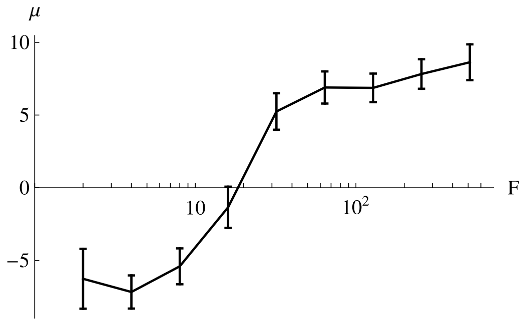

Figure 6 Tilt (in degrees) against flux F [in units of 10^{20} Mx] for MDI data.

derestimated and a more detailed analysis is required. In particular, a measure of the flux regeneration rate would seem to be more suitable here.

Figure 6 shows that a negative tilt value is predominant for $F < 10$. For $F > 30$ 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 higher values of F.

Investigating 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 $Bm = F \cdot d$, 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.

The distance d is defined as the distance in heliographic degrees between the geometrical centres of monopoles in a given bipole. This definition indirectly includes 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 almost circular domains leads to d increasing as $\sqrt{S}$, where S is a measure of the area of a bipole.

Figure 7 shows that the slope of d as a function of $\sqrt{S}$ is significantly smaller than one. This means that domain sizes increase faster than the distance between them. Again, the behaviour of the plot is different for large and small bipoles (but the slope is almost the same), and the dividing point is close to $S = 300$ MHS (note that the plot shows $\sqrt{S}$ and not S).

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

Figure 7 Mean distance of the center of gravity of opposite polarities d against the size of the domains given by $\sqrt{S}$.

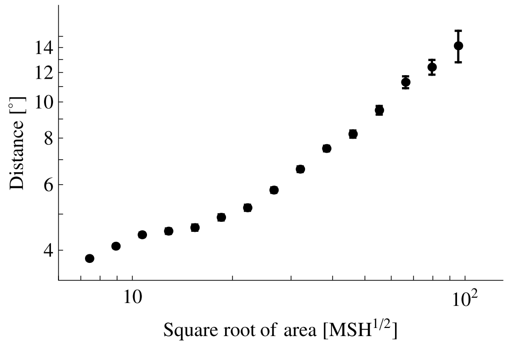

Figure 8 Bipolar moment against the area of bipoles, MDI data. The fitted line has a slope of 1.5.

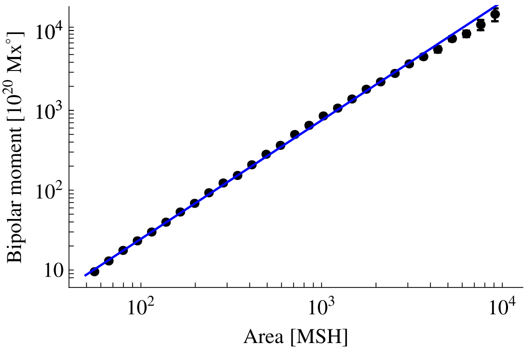

Figure 9 Tilt against bipolar moment Bm [10^{20} Mx°] for MDI data.

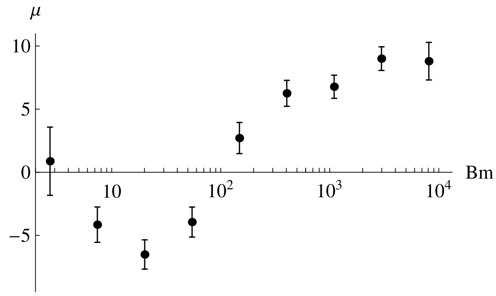

Figure 9 shows a moderate growth of the tilt with increasing bipolar moment for large bipoles. Note that Stenflo and Kosovichev (2012) did not find any significant variations of the tilt angle with flux or bipolar moment.

Now we can calculate the averaged effect of the tilt as follows: We consider the bipoles that 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 into a poloidal field. In other words, it is an estimate of the ratio α/v, where v is the r.m.s. velocity of the convection and α is the magnitude of the α-effect. The estimate is robust in the sense that it remains stable when only the large bipoles are taken into account (small bipoles contribute only mildly 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 the traditional expectation from dynamo theory.

4. Discussion and Conclusions

To summarise, we conclude that we can recognise specific properties of small and large bipoles, which are mainly represented 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 such as bipolar moment, magnetic flux, and 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 the two bipole groups are visible in other respects as well.

We note several other remarkable features in our results.

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 one to two years earlier than the corresponding sunspot cycle, and then propagate towards the solar equator.

For the large bipoles ($S > 300$ MSH), the tilt increases with the size of the bipoles. This tendency is visible when the flux is considered as a measure of the bipole size (Figure 6) and also when the bipole moment is considered as the measure (Figure 9).

When the bipoles are separated according to size with opposed properties, the emerging pattern 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. This probably shows 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.

At first glance, the contribution of large bipoles to the total α-effect (that parametrises solar dynamo action) dominates, and it seems possible to ignore small bipoles when quantifying this contribution. A deeper understanding of the processes underlying solar dynamo action, however, deserves 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 that isolates bipoles from magnetograms. Our analysis does not show any trace of a bug in the algorithm that might produce a difference between small and large bipoles. It is difficult, however, to exclude this option completely based on the results of applying just one algorithm to isolate the bipoles. We therefore stress that it is desirable to compare our results with those from other algorithms that can isolate small from large bipoles. 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 to indicate that large bipoles represent a toroidal magnetic field, while the small bipoles are connected with a poloidal magnetic field. Figure 3 seems to support this interpretation. Indeed, interpreting large bipoles, *i.e.* sunspot groups, as tracers of a 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 quite similar to corresponding patterns of the large-scale surface magnetic field (Obridko *et al.*, 2006), however, which presumably trace the solar poloidal magnetic field. The fact that we see specific slopes for small and large bipoles in the other plots seems to agree with this interpretation. However, one might 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 a toroidal magnetic field is substantially stronger than a poloidal field, which would be expected to result in jumps.

Another possible interpretation might be based on the idea that the α-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 of helicity of the opposite sign in the other range. The moderate growth of the tilt with bipolar moment for large bipoles in Figure 9 seems to be consistent with the idea of the helicity separation in Fourier space (Seehafer, 1996): the point is that the Coriolis force is stronger for larger bipoles. A continuous behaviour of the plots in figures that do not directly involve tilt becomes natural with this interpretation: all bipoles now represent a 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 these interpretations do not seem convincing enough for us to prefer one over the other.

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