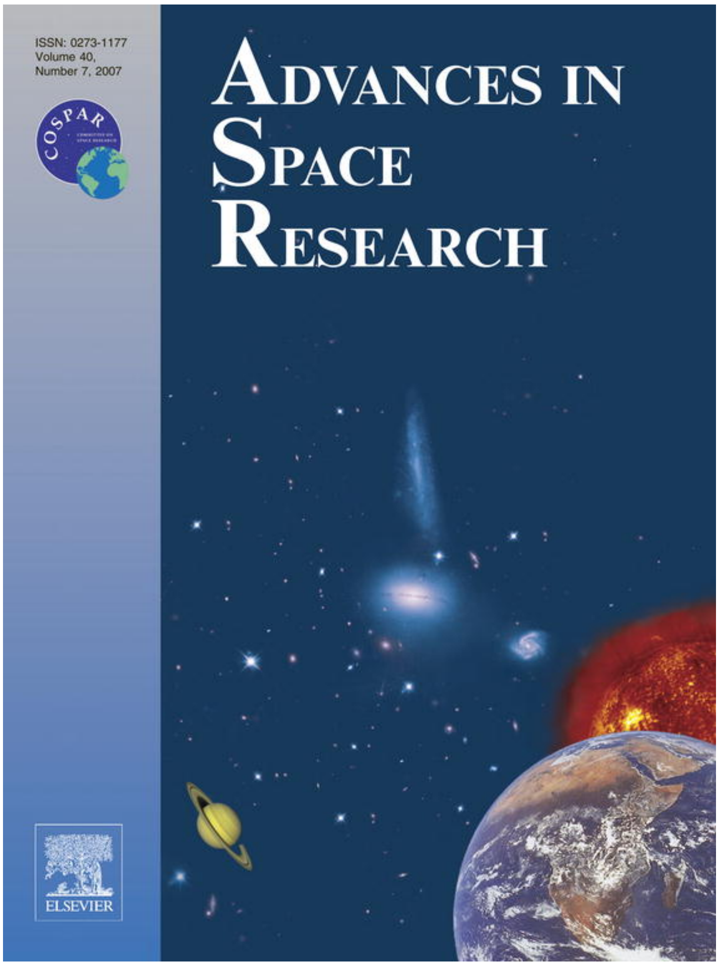
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Long-term persistence of solar active longitudes and its implications for the solar dynamo theory

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Abstract

We present an overview of the observational results related to the existence of long-lived sunspot active longitudes. These are affected by the solar differential rotation. The existence of such migrating active longitudes imposes an important constraint on the dynamo theory. We review different approaches to model non-axisymmetry in solar dynamo models and find that, in principle, plausible mechanisms exist to reproduce the observed non-axisymmetry. The most favorable interpretation is suggested by the 'stroboscopic effect', where a quasi-rigidly rotating non-axisymmetric mean-field can produce seemingly migrating active longitudes in sunspots. Other scenarios are less favorable but cannot yet be excluded.

Keywords: Solar activity; Dynamo; Active longitudes

1. Introduction

The subject of solar active longitudes has a long history. Carrington (1863) had already noticed that sunspots were not distributed randomly over solar longitudes but were concentrated in certain longitudinal zones of enhanced solar activity. Such zones are particularly evident during the declining phase of the solar cycle. When found in different indices they were given different names, for example: 'active longitudes' (Vitinskij, 1969), 'activity sources' (Bumba and Howard, 1969), 'Bartels active longitudes' (Bumba and Obridko, 1969), 'streets of activity' (Stanek, 1972), 'sunspot nests' (Castenmiller et al., 1986), 'hot spots' (Bai, 1990), 'helicity nests' (Pevtsov and Canfield, 1999), or 'complexes of activity' (Benevolenskaya et al., 1999). Long-lived active zones were found at different Carrington longitudes in the Northern and Southern hemispheres, and often rotated with a period different from that of the Carrington system (e.g., Vitinskij et al., 1986). Here we call these structures 'active longitudes' which better reflects the non-uniform longitudinal distribution of solar activity. Active longitudes on the Sun leave their imprint on all the outer layers penetrated by magnetic fields, including the photosphere, chromosphere, corona and heliospheric magnetic field (HMF). They have been found in the distribution of sunspots (e.g., Vitinskij, 1969; Bumba and Howard, 1969; Balthasar and Schüssler, 1983; Balthasar and Schüssler, 1984; Berdyugina and Usoskin, 2003; Juckett, 2006), surface magnetic fields (e.g., Benevolenskaya et al., 1999; Bumba et al., 2000) and the HMF (e.g., Ruzmaikin et al., 2001; Takalo and Murusla, 2002; Mursula and Hiltula, 2004). They influence the distribution of chromospheric faculae (Mikhailutsa and Makarova, 1994) and major flares (Jetsu et al., 1997; Bai, 2003; Zhang et al., 2007). More recently they have been found to modulate coronal

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emission (Benevolenskaya et al., 2002; Badalyan et al., 2004; Sattarov et al., 2005), total solar irradiance (Benevolenskaya, 2002; Mordvinov and Willson, 2003), and surface helicity (Bao and Zhang, 1998; Pevtsov and Canfield, 1999; Kuzanyan et al., 2000). The active longitudes are undoubtly related to the generation of the solar global magnetic field. Explaining their presence, endurance and evolution represents a great challenge, and can be expected to provide strong observational constraints on the development of solar dynamo theory – which so far mostly has been strictly axisymmetric (on large-scales).

A recent observational analysis of sunspot distribution undertaken by Berdyugina and Usoskin (2003, hereafter BU03) and Usoskin et al. (2005, hereafter UBP05) demonstrated that sunspot active longitudes rotate differentially, i.e., with different angular velocity at different latitudes. Although the level of the non-axisymmetry is low (about 10%), the active longitude structure was found to persist during the entire period studied, about 11 solar cycles, with amazing phase coherence from cycle to cycle. This had been previously noticed for cycles 22 and 23 by Benevolenskaya et al. (1999) and Bumba et al. (2000). Berdyugina et al. (2006, hereafter BMSU06) discussed implications of such phase coherence for dynamo theory.

Persistent active longitudes migrating in longitude due to the star's differential rotation have been detected in different types of active stars, including young solar analogues (Berdyugina and Tuominen, 1998; Berdyugina et al., 2002; Berdyugina and Järvinen, 2005; Järvinen et al., 2005). Although active longitudes endure for a long time, the active regions they consist of evolve in size: while one active longitude reduces its activity level, the other increases, which suggests a redistribution of the spotted area between the opposite hemispheres. When the active longitudes have about the same activity level a switch of the dominant activity from one longitude to the other occurs. Such a phenomenon was first observed on the rapidly rotating single giant FK Com (Jetsu et al., 1991) and was tentatively referred to as a 'flip–flop'. Berdyugina and Tuominen (1998) discovered that flip–flops on active stars are regularly repeated, thus indicating a new type of stellar cycle manifested in the behaviour of active longitudes.

Solar active longitudes also exhibit a flip–flop cycle, although weaker than detected on other stars. The sunspot activity shows an alternation of active longitudes in about 1–3 years, resulting in flip–flop cycles of 3.80 and 3.65 years in the Northern and Southern hemispheres, respectively (BU03). This is about 1/3 of the 11-year sunspot cycle and is consistent with the results obtained for young solar analogues (Berdyugina and Järvinen, 2005). The discovery of flip–flops on the Sun provides the opportunity to study this phenomenon in detail.

In this review we discuss the observational signatures of sunspot active longitudes and their implications for dynamo theory.

2. Active longitudes on the Sun

2.1. The dynamic reference frame

Although the existence of active longitudes in various solar activity indices has been long recognized, they do not persist for very long in the Carrington coordinate reference frame. On the other hand, there are indications that the active longitudes may migrate continuously in Carrington longitude, whilst persisting over long timescales (see Section 2.3). Therefore, a new reference frame, in which the active longitudes remain constant, has been suggested by UBP05 and BMSU06, as briefly described below.

Since the active longitudes of sunspots do not define a quasi-rigidly rotating pattern, the new frame is dynamic, i.e., it follows the differential rotation, which is approximated by

$$\Omega_i = \Omega_0 - B \sin^2 \psi_i, \tag{1}$$

where Ω_0 corresponds to the equatorial angular velocity, B is the rotational shear between the equator and the pole, and ψ_i is the mean latitude of sunspot formation in the ith Carrington rotation (CR). (Only the first appearance of each spot is considered here.) The Carrington longitude of a point fixed in the dynamic frame during CR i is defined as [1]

$$\Lambda_i = \Lambda_0 + T_C \sum_{j=N_0}^{i} (\Omega_j - \Omega_C), \tag{2}$$

where T_C and Ω_C are the Carrington period and rotation rate, respectively. The sum is taken over all Carrington periods elapsed since the beginning of sunspot data starting in the CR N_0, and Λ_0 is a constant up to which the longitude is defined. The observed Carrington longitude of the kth spot group in the ith CR, λ_{ki}, can be reduced to the new frame:

$$\zeta_{ki} = \lambda_{ki} - \Lambda_i - n\, 360^\circ, \tag{3}$$

where longitude ζ_{ki} corresponds to the dynamic reference frame, and n is chosen to keep the value of ζ between 0 and 360°. The effect of the dynamic frame is illustrated in Fig. 1. The longitudinal distribution of sunspot areas suggests two active zones, 180° apart, whose continuous migration in Carrington longitude (upper panel) closely follows the dynamic reference frame ($B = 3.40$ and $\Omega_0 = 14.33°/\text{day}$). After reducing all spots to this dynamic frame, the longitudinal distribution shows two clear, persistent active zones which quasi-periodically (see Section 2.2) alternate in relative magnitudes of their activity.

Using this approach and all the available sunspot data for 1874–1996, UBP05 and BMSU06 found that a system of two oppositely located active longitudes persists

[1] Note that the corresponding Eq. (3) in UBP05 contains a typographical error: Ω_j and Ω_C are interchanged. However, all the computations were done using the correct formula (see Usoskin et al., 2007).

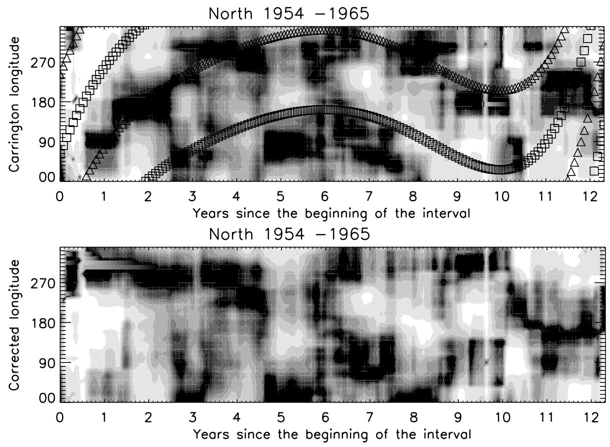

Fig. 1. The longitudinal distribution of the sunspot area during cycle # 19 in the Carrington (upper panel) and dynamic (lower panel) reference frames. Paths corresponding to $\zeta = 0$ and 180° are shown by squares and triangles in the upper panel. Adopted from Usoskin et al. (2005).

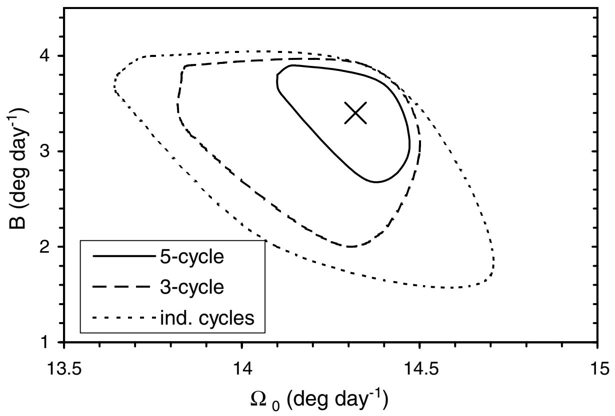

Fig. 2. The region occupied by the parameters of the differential rotation in the Northern hemisphere, defined using the entire studied time series (large cross) as well as from sub-intervals: individual cycles (dotted), 3-cycle intervals (dashed) and 5-cycle intervals (solid). Adopted from Usoskin et al. (2005).

throughout the entire period in the dynamic frame with $B = 3.40(3.39) \pm 0.03°$/day and $\Omega_0 = 14.33(14.31) \pm 0.01°$/day for Northern (Southern) hemispheres, respectively. Note that these figures are consistent with a uniquely determined equatorial angular velocity. These differential rotation parameters are significantly different from those obtained for sunspots, indicating that spots are detached after formation from the originating non-axisymmetric structure. The corresponding measure of the asymmetry Γ (defined as the ratio of the non-axisymmetric part to the sum of the axisymmetric and non-axisymmetric components in the sunspot area, see UBP05 for details) is 0.11 (0.09) for the Northern (Southern) hemispheres, respectively. More prominent activity indices yield a higher measure of the asymmetry, e.g., $\Gamma = 0.15$ for the case when only the largest spot group is considered in each CR (BUP05), and $\Gamma \approx 0.4$ for the occurrence of major solar flares (Zhang et al., 2007). This indicates that the non-axisymmetry manifests itself more clearly in more energetic phenomena, while weaker magnetic structures display a noisier pattern (cf. Ivanov, this issue). Using shorter time intervals yields the same result but with a wider range of possible parameter values, which however "tightens" to the best fit parameters for the entire series, as illustrated in Fig. 2. The differential rotation corresponding to the dynamic frame, in which the active longitudes persist, is systematically slower than that obtained for individual sunspots, but is close to the differential rotation of either the immediate sub-surface matter or deep layers of the convection zone.

2.2. The flip–flop cycle

The relative activity level of the active longitudes varies in time, since sunspots are preferably concentrated in one of the two active longitude, which is thus dominant at a given time (BU03). Moreover, the location of the dominant longitude alternates periodically, on about 1.8–1.9 years on average. The individual duration of one longitude's dominance may last from 1 to 3 years, while the switch of dominance from one longitude to the other is rather rapid and may happen within a month. Thus the phenomenon is very similar to the flip–flop effect observed on active cool stars (e.g., Berdyugina and Tuominen, 1998). On average six switches of the activity occur during the 11-year sunspot cycle and, thus, the 3.7-year flip–flop cycle is about 1/3 of this. It is known however that the length of the sunspot cycle varies on a century timescale. Similarly the flip–flop cycle appears also shorter for shorter solar cycles (cf. Mursula and Hiltula, 2004). This suggests, therefore, that the ratio 1/3 might be a fundamental feature preserved on a long-time scale.

There is a statistically significant difference between the flip–flop cycle lengths in the Northern and Southern hemispheres: 3.80 and 3.65 years respectively. This difference persists for all cycles studied and provides a beating period between the two frequencies on a century timescale. This may be related to the centennial oscillations in the North–South asymmetry detected in solar activity (e.g., Verma, 1993; Knaack et al., 2004).

2.3. Comparison with other studies

The results discussed above suggest that a persistent non-axisymmetry in sunspot activity does not display a quasi-rigid rotation with the Carrington period, but seems to be affected by the differential rotation. This important conclusion is consistent with numerous earlier and recent results. For example, an indication of migrating solar active longitudes was first presented by Lopez Arroyo (1961). Later, Stanek (1972) analyzed sunspot data since 1962 and found that the Northern and Southern hemispheres behave independently, and that the "streets of activity" follow the differential rotation. Using a cell-counting method, which deals with spatially and temporarily averaged sunspot data for the last 120 years, Pelt et al. (2006) also found that sunspot active longitudes migrate in the Carrington system and are affected by the differential rotation, although depict a limited persistence. (However, they disagree significantly with some of the conclusions of BMSU06 and earlier papers.) This pattern is also observed in other solar magnetic indices. For example, Bobova and Stepanian (1994) studied active longitudes in the background magnetic field in different latitudinal belts for the period 1969–1980 and found that their rotational period follows the differential rotation law, which is however different from that for sunspots. A differentially rotating component of active longitudes has also been reported in large-scale solar magnetic fields for the period 1965–1994 (Ivanov et al., 2001). A very strong degree of non-axisymmetry (about 40%) has been observed in the occurrence of major solar flares during the period of 1975–2005, in a differentially rotating reference frame (Zhang et al., 2007). All these studies imply the existence of active longitudes in various solar magnetic indices, with a life time exceeding that of any single active region, i.e., longer than a year. Being affected by the differential rotation, they could be found in rigidly rotating frames only over short timescales, and could not be detected in time intervals longer than one solar cycle without taking account of the nonlinear migration.

The above results suggest that the phenomenon is persistent on the time scale of at least a single cycle and possibly even longer. BU03, UBP05 and BMSU06 suggested that the active longitudes are persistent, in the dynamic reference frame described above, throughout the entire period of observations, i.e., about 120 years. The statistical significance of this finding has been recently disputed by Pelt et al. (2005, 2006) who, using surrogate data and Monte-Carlo simulations as well as a wide parametric range search, have concluded that the observed centennial persistence of active longitudes can be a coincidence of random fluctuations rather than a real phenomenon. However, the most important thing for this study is that active longitudes are persistent in a dynamic reference frame for times comparable or exceeding one solar cycle. Another claim by Pelt et al. (2006) that we used a "contra-moving" frame in our earlier studies, is not correct and is most likely based on a confusion caused by the typographical error in UBP05 (see Usoskin et al., 2007). In this paper as well as in all our earlier studies we used a "co-moving" reference frame (following the terminology of Pelt et al., 2006). An independent study of the same sunspot data by Juckett (2006), based on spherical harmonics decomposition, clearly confirmed the presence of the active longitudes with the azimuthal number $m = 2$ as well as mode oscillations with frequency $\sim$0.3 year^{-1}, i.e., the flip–flop cycle. Furthermore, this study revealed a whole spectrum of various non-axisymmetric modes oscillating with frequencies between 5 and 35 months, thus indicating a high degree of complexity of the active longitude phenomenon.

2.4. Summary of observational results

The bulk of observational results discussed above can be summarized as follows.

- There are two active longitudes approximately 180° apart that can persist, maintaining their phase, over long periods. While the exact lifetime is still a matter of debate, in the context of dynamo modelling the important feature is that the period of phase persistence is much longer than the lifetime of an active region and even longer than a solar cycle.
- The active longitudes depicted by sunspots are affected by differential rotation and migrate in any rigidly rotating frame but are persistent in a dynamic frame related to the mean latitude of sunspot formation.
- The differential rotation of the frame in which active longitudes persist is different (slower and steeper) from that obtained using individual spots as tracers.
- The level of non-axisymmetry increases with the intensity of manifestation of the activity indicator. It varies from 10% for all sunspots (15% if only larger spots are considered) up to 40% for major solar flares.
- At any given time, one of the two active longitudes is more active (dominant), and the dominance switches between them quasi-periodically: this is known as the 'flip–flop' phenomenon. The 'flip–flop' cycle forms 1/3 of the 11-year cycle.

These findings suggest the existence of a weak, persistent non-axisymmetric dynamo component, which provides new constraints for the development of solar dynamo models. In Section 3, we consider different possibilities to understand how the active longitude phenomenon can be understood in the terms of the solar dynamo.

3. Active longitudes and dynamo theory

The magnetic fields present in the Sun, and in broadly similar stars that have deep surface convection zones, are believed to be generated by a hydrodynamic dynamo. In a simple case, the global-scale magnetic field is considered to be axisymmetric, consisting of two parts – poloidal and toroidal. According to the conventional scenario, twisting by differential rotation converts poloidal field into toroidal and, in turn, the effect of cyclonic turbulence generates poloidal field from toroidal. Thus differential rotation of the convective envelope is a key ingredient of both these processes, with rotational energy compensating for diffusive losses. More details can be found in, e.g., monographs by Moffatt (1978), Parker (1979), Mestel (1999), and Stix (2004). A full description of the dynamo action would require solving, at high spatial resolution, the MHD and energy equations in a highly stratified medium. Such a task is at or beyond the limits of current computational capabilities. This leads to a wide use of parametrization of small scale processes, known as the mean field dynamo theory, which nevertheless is recognized to have a number of unsatisfactory features and lacks true predictive power. In this formulation the key parameters are the α-coefficient, which represents the action of the cyclonic eddies, and the turbulent diffusivity. In what follows we use the mean field theory description.

Here we try to analyse the results of sunspot observations described above as two interlinked parts. The first fact is that preferred and long-lived active longitudes can be associated with sunspot formation/emergence, and the second that the relative strengths of these features varies with time (the flip–flop phenomenon).

3.1. Traditional approaches

The Sun appears approximately axisymmetric on a global scale, although there is clear evidence for small-scale non-axisymmetries (sunspots, coronal holes, etc). Correspondingly, most solar dynamo models are axisymmetric. However, it has been known for a decade or more, perhaps surprisingly, that non-axisymmetric mean fields can be generated by an axisymmetric dynamo system, especially if the angular velocity Ω is not constant but varies with latitude and depth in the convection zone (e.g., Moss et al., 1995; Moss, 1999; Bassom et al., 2005). As shown by helioseismology the predominant variation of Ω near the solar surface is latitudinal. Assuming that the dominant axisymmetric component of the solar field is related to a dipole aligned with the rotation axis, together with the associated azimuthal field, it can be seen that a non-axisymmetric component, whose symmetry is either a dipole or a quadrupole with axis in the equatorial plane, will provide perturbations to the surface field, centered on the equator and separated by 180°. However it is not straightforward to interpret the active longitude phenomenon in terms of dynamo models – below we will consider several possibilities.

Solar dynamo models can demonstrate a small degree of intrinsic non-axisymmetry (e.g., Moss, 1999), but it is difficult to explain the active longitude phenomenon solely by this ‘spontaneous’ non-axisymmetric field generation. Another possibility is that non-axisymmetry in the solar field can be driven by non-axisymmetric large-scale hydrodynamic processes, e.g., an instability of the solar tachocline – the thin rotational shear layer at the base of the convection zone where the rotation law changes from that of the envelope to the solid body rotation of the radiative core. Dikpati et al. (2004) suggested that an $m = 1$ instability can be excited in this region, which could result in a $m = 1$ perturbation to α (this feature oscillates about the rotational equator). Dikpati and Gilman (2005) presented an interpretation of the instability in terms of a “shallow-water theory” to explain solar active longitudes. It has been shown by BMSU06 that this can produce a non-axisymmetric field near the surface whose strength is a few percent of the axisymmetric component.

It is also possible that the preferred longitudes could be related to a relic, equatorial dipole field, anchored in the Sun’s radiative core. The presence of such a field of about 1 G is consistent with the uniform rotation of the core, but its strength would be much reduced at the solar surface. More fundamentally, this field necessarily rotates with the core angular velocity, which is not observed for the active longitudes.

We also note that the observed reversals of the solar magnetic field are related to the tilt of the global magnetic dipole, which automatically selects preferred longitudes. However, solar dynamo models do not consider such a process in the solar cycle. Neither of these last two mechanisms would exhibit phase mixing (see Section 4.2 below).

Thus, there are several mechanisms that might generate a small degree of non-axisymmetry in the mean field produced by conventional dynamo models. However in these cases, the preferred zones are expected to appear either sporadically or to rotate quasi-rigidly, in disagreement with the observed results. In Section 4, we will consider a possible scenario where a quasi-rigidly rotating non-axisymmetry in the mean field may lead to seemingly migrating active longitudes in sunspot formation.

4. Possible scenarios

4.1. The stroboscopic effect

As we can conclude from the previous discussion, non-axisymmetric magnetic structures can be consistent in various ways with the concept of magnetic field self-excitation in the basically axisymmetric Sun. The question is how similar are the non-axisymmetric structures suggested by dynamo theory to those deduced from observations? Making such a comparison however turns out to be a rather nontrivial task. The point is that theoretical models provide information on the spatial distribution of the large-scale magnetic field, while the observational data are mainly based on its manifestation as various forms of solar activity at the solar surface. These manifestations are proxies for the interior magnetic field, and the causal link is usually not known in detail. The observational feature of the active longitudes which forms the main challenge for dynamo theory, is that the active longitudes are affected by differential rotation and migrate in Carrington longitude according to the mean latitude of sunspot formation/emergence. On the other hand, the scenarios outlined above to explain the surface magnetic field all produce rigidly rotating non-axisymmetric magnetic structures. It would be a little foolhardy to insist that all possible dynamo generated structures must necessarily rotate rigidly, but BMSU06 found no plausible exceptions.

Fortunately, the concepts of a rigidly rotating magnetic structure and a differentially rotating active longitude are not inevitably incompatible (BMSU06). The point is that the sunspot data as used to determine active longitudes represent only the behaviour of the strongest part of the solar activity wave, and give no direct information concerning the form of the magnetic field throughout the entire convective zone. We know from the sunspot data (as a function of time t) the migration law at the latitude $\psi(t)$ and the longitude $\lambda(t)$ where the activity wave is strongest at time t. We assume the latitudinal migration law to be axisymmetric. Let us suppose that the center of the migration wave is at latitude $\psi(t)$ at time t – this is the latitude that the active longitude analysis samples. Thus, if $\lambda^*(\psi,t)$ is the longitude at which the magnetic field is maximum at latitude ψ at time t, then $\lambda(t) = \lambda^*(\psi(t),t)$ is the derived active longitude. It is important to note that we cannot completely reconstruct the dependence of λ^* on ψ from $\lambda(t)$ and $\psi(t)$ alone. A dynamo interpretation of the phenomenon of active longitudes requires some hypothesis concerning the general shape of the function $\lambda^*(\psi,t)$. It can be assumed that the rotation rate ω of the longitude λ^* at various latitudes is specific, i.e., $\partial\lambda^*/\partial t = \omega(\psi)$ and $\omega(\psi_1) \neq \omega(\psi_2)$. Then we identify $\omega(\psi)$ with the rotation rate Ω, and conclude that a latitudinal migration of the point where the toroidal magnetic field is strongest in a rigidly rotating non-axisymmetric magnetic structure can be manifested by a differentially rotating proxy. Therefore, it is possible to observe seemingly differentially rotating active longitudes in sunspots, even if the mean field non-axisymmetry is quasi-rigidly rotating.

The possibility of obtaining seemingly migrating active longitudes from rigidly rotating non-axisymmetry can be referred to as the stroboscopic effect, which is illustrated in Fig. 3. Let us assume that the non-axisymmetry of the mean field is a quasi-rigid structure (hatched area in the Figure), which is not necessarily meridionally aligned but can be stretched by the shear. When an axisymmetric dynamo wave (grey band) propagates equatorwards, it highlights the latitudinal zone where the axisymmetric field is maximal, producing seemingly migrating active longitudes in sunspot formation. It is important that the parameters of these active zones, that seemingly migrate in longitude, are defined by the instantaneous angular velocity of the highlighted area, and will yield an overall rotation law that is different from that of the sunspots.

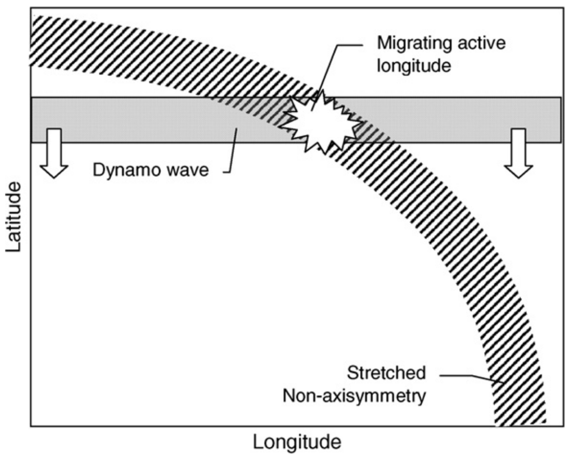

Fig. 3. An illustration of the stroboscopic effect. A coexistence of equatorwards moving dynamo wave and a rigidly rotating non-axisymmetry can produce seemingly migrating active longitudes in sunspot formation.

This idea seems to be the most plausible in the context of dynamo theory and allows reconciliation of all observed features (including sunspots and other tracers) with theoretical expectations.

4.2. Phase mixing

Let us turn now to the possibility that the magnetic structure underlying differentially rotating active longitude is differentially rotating as well. It means that neighbouring magnetized latitudinal layers rotate with respect to one another and the magnetic field is stretched because of this differential rotation. The spatial scale of the magnetic field decreases because of the stretching, and the role of diffusion effects increases. This situation is known as phase mixing (e.g., Bassom et al., 2005). Phase mixing usually results finally in a rapid decay of magnetic field. Therefore, the non-axisymmetric magnetic structures excited by various dynamos are expected to rotate rigidly.

We cannot however exclude a scenario for active longitudes with a phase mixing for the magnetic field. A naive idea would be that, because of some mean field non-axisymmetry (which is a quasi-rigid structure), the dynamo wave is also excited with a small degree of non-axisymmetry. After generation, the dynamo wave may become detached from the mean field and start propagating equatorwards being affected by the differential rotation. This could lead to seemingly migrating active longitudes in sunspot formation. We were however unable to reproduce this idea in the framework of mean field dynamo models because the detached non-axisymmetry damps rapidly (BMSU06). However, taking into account the unknown relation between the mean field approach and sunspots, it cannot be conclusively excluded.

4.3. The flip–flop phenomenon

Models for rapidly rotating stars with quasi-cylindrical (i.e., not solar-like) rotation laws have been shown to exhibit the flip–flop phenomenon (which does not necessarily require an oscillating non-axisymmetric field) – (Moss, 2004, 2005; Fluri and Berdyugina, 2004, 2005; Elstner and Korhonen, 2005; Korhonen and Elstner, 2005). However, flip–flops have not been found in the corresponding solar models, although it is at present unclear whether this remains true for the solar models that include effects of the tachocline instability discussed above. Possible effects of rigidly rotating non-axisymmetric modes on the sunspot distribution and the North–South asymmetry were studied by Fluri and Berdyugina (2005). It was found that a combination of an equatorial dipole and quadrupole ($l = m = 2$) rotating with respect to each other can reproduce the main features of the solar active longitudes. In the light of the recent findings by Juckett (2006), this model should be updated by the inclusion of a series of modes with higher azimuthal numbers.

That the 3.7-year flip–flop cycle is 1/3 of the 11-year sunspot cycle is probably of fundamental importance, as the same relation has been found in analogues cycles of very active, young solar analogues (Berdyugina and Järvinen, 2005; Berdyugina, 2005). A comparison of the Sun with young solar-type dwarfs enables the study of the evolution of solar magnetic activity since the Sun arrived at the Main Sequence. For instance, it is very plausible that the Sun has possessed both 11-year and 3.7-year cycles since the beginning of its evolution on the Main Sequence.

5. Conclusions

We have presented an overview of the observational results related to the existence of active longitudes (preferred zones) in sunspot formation:

- There are two long-lived active longitudes in sunspot formation, 180° apart.
- Sunspot active longitudes migrate in Carrington longitude and appear to be subject to differential rotation, whose parameters are different from those obtained from individual spots as tracers.
- The level of non-axisymmetry is small, about 0.1 of the dominant axisymmetric mode, for sunspots but is higher for more energetic indices.
- Active longitudes display the 'flip–flop' phenomenon with a period of about 1/3 of the solar cycle.

The existence of such migrating active longitudes imposes an important constraint on solar dynamo theory. We have reviewed different approaches to modelling non-axisymmetry in solar dynamos and found that the solar dynamo can in principle reproduce non-axisymmetric magnetic configurations, comparable in many respects with the observed features. Even though it appears conceptually difficult to explain the idea of true differential rotation of the active longitudes in the framework of the mean field dynamo, these two concepts are not inherently contradictory. Since sunspot formation is only very indirectly related to the mean field features, seemingly migrating active longitudes in sunspots can be produced even by quasi-rigid non-axisymmetry in the mean field dynamo. It is shown that the stroboscopic interpretation provides a natural explanation for the differential rotation of active longitudes. Other scenarios appear less favourable but cannot be excluded either.

Looking to the future we would like to emphasize the importance of studying other activity indices that more directly related to large-scale magnetic fields and thus to the dynamo action. This is particularly related to the surface magnetic field distribution, and such a study is under way. As the recent results show, studying the non-axisymmetry in strong energetic solar phenomena such as solar X-flares yields clearer results (Zhang et al., 2007). An important question awaiting investigation is whether the known non-axisymmetry in the heliospheric parameters is related to the active longitudes, or has a different origin.

Meanwhile, further theoretical developments are needed in order to better understand the observed non-axisymmetry. This should include both the further development of non-axisymmetric 3D models, of the solar dynamo and detailed modelling of the stroboscopic effect.

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