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Invited Review

NON-AXISYMMETRIC MAGNETIC FIELDS AND FLIP-FLOPS ON THE SUN AND COOL STARS

S. V. BERDYUGINA[1,2]
[1]*Institute of Astronomy, ETH Zentrum, 8092 Zurich, Switzerland*
[2]*Astronomy Division, P.O. Box 3000, 90014 University of Oulu, Finland*
(e-mail: sveta@astro.phys.ethz.ch)

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Abstract. The modulation of solar activity closely follows the solar rotation period suggesting the existence of long-lived active regions at preferred longitudes. For instance, two preferred active longitudes in both southern and northern hemispheres are found to be persistent at the century time scale. These regions migrate with differential rotation and periodically alternate their activity levels showing a flip-flop cycle. The pattern and behaviour of active longitudes on the Sun is similar to that on cool, rapidly rotating stars with outer convective envelopes. This suggests that the magnetic dynamo, including non-axisymmetric magnetic fields and flip-flop cycles, is also similar in these stars. This allows us to overview the phenomenon of stellar magnetic activity and to study it in detail on the Sun.

1. Introduction

The multitude of activity phenomena on the Sun are related to magnetic fields which are generated by cyclonic turbulence in the outer convective zone and penetrate the solar atmosphere forming sunspots, plages, network, etc. They further expand into the outer atmosphere and exhibit themselves as highly dynamic coronal loops. Therefore, a detailed study of solar activity phenomena reveals the structure of underlying magnetic fields and provides valuable constraints for solar dynamo theory. These same activity phenomena are observed on cool stars with outer convective zones.

Here I review the properties of large-scale magnetic fields on cool active stars and compare them with those observed on the Sun. Rapidly rotating cool stars show a much higher level of activity over the Sun and may differ from the Sun in their dynamo mechanisms (Section 2.1). For instance, they show prominent large-scale non-axisymmetric magnetic fields in the form of active longitudes. The dominant activity in such stars switches periodically from one active longitude to the opposite one exhibiting flip-flop cycles (Section 2.2). A recent study of sunspot distribution has revealed similar behaviour on the Sun (Section 3). It appears that there are more similarities between solar and stellar dynamos than was previously thought.

2. Non-Axisymmetric Magnetic Fields on Cool Stars

2.1. The phenomenon of stellar activity

Studying magnetic activity on stars other than the Sun provides an opportunity for detailed tests of solar dynamo models. Using only solar observations limits the range of the global stellar parameters for such tests, while an extensive sample of stars of various activity levels provides key constraints for stellar and solar dynamo theory.

Stellar activity similar to that of the Sun was first discovered on red dwarfs, a fraction of which exhibit remarkable magnetic activity registered through observations of extremely strong optical flares (UV Cet-type stars). Periodic brightness variations were observed in binary systems of red dwarfs (BY Dra-type) as distortions of the light curves outside eclipses. Kron (1952) was seemingly the first who considered the hypothesis that spottedness of the stellar surface was causing these distortions. Later, light-curve variations due to starspots and other magnetic phenomena were discovered on other types of stars.

It was suggested by Skumanich (1972) that rotation plays a crucial role in the generation of stellar activity. Later this became evident from the strong correlation of magnetic activity indicators with rotational velocities and periods. Such relations have been reported between rotation and coronal emission (Pallavicini *et al.*, 1981; Walter and Bowyer, 1981), chromospheric Ca II and Hα emission (Middelkoop, 1981; Mekkaden, 1985), ultraviolet line fluxes (Vilhu, 1984; Simon and Fekel, 1987) and radio emission (Drake, Simon, and Linsky, 1989). Therefore, stars with more rapid rotation are expected to show a higher level of magnetic activity. Such active stars are the best choice for testing and developing stellar dynamo theory. Among single stars these are pre-main-sequence stars (T Tau-type) and early-age main-sequence stars of solar type. Evolved binary components which are tidally locked at fast rotation by a close companion are also strongly magnetically active (RS CVn-type and BY Dra-type systems). Rapidly rotating single giants of FK Com-type which are probably formed from coalesced binaries complete the selection of magnetically active stars.

Since the discovery of rotationally modulated brightness variations due to starspots, a large amount of data has been collected for different types of stars. Parallel brightness and colour variations, i.e., the faintest state being accompanied by the reddest colour, imply that spots are significantly cooler than the unspotted photosphere, on average by 500 K to 2000 K. Large variations in amplitude, up to 0.6 mag, indicate that the spotted areas are huge compared to that of sunspots, up to 30% of the whole stellar surface. Such large cool spots when passing over stellar disks cause strong line profile distortions in the spectra of rapidly rotating stars. Analysis of a time series of spectral line profile variations using Doppler imaging techniques provides the spot distribution over the visible stellar surface. Doppler images reveal that spots on cool rapidly rotating stars are preferably formed at higher latitudes, from 30° up to the visible pole, which is in contrast with sunspots which on average appear at latitudes below 30°. For a detailed overview of starspot properties and analysis techniques see Berdyugina (2004).

2.2. Stellar magnetic activity patterns

Chromospheric plages produce flux variations in the emission cores of Ca II H&K lines as observed on the Sun and Sun-like stars. Monitoring Ca II emission on solar-type dwarfs, pioneered by O. Wilson at Mt. Wilson Observatory, has led to the detection of solar-like activity cycles in such stars (Baliunas *et al.*, 1995). The chromospheric cycles appear to be more regular among cooler dwarfs with lower activity level, suggesting an evolution of the behaviour from young active stars varying irregularly to older less active stars with regular cycles such as the Sun. In addition, the luminosity variation of young stars anti-correlates with their variation in chromospheric emission (Radick *et al.*, 1998), i.e., young stars become fainter near their activity maxima, while older stars, including the Sun, become brighter at maximum activity. This suggests a shift from spot-dominated to faculae-dominated activity as stars evolve along the main sequence. Such an evolution implies that activity cycles on young stars should be more prominent in spot patterns rather than in chromospheric plages. This is confirmed by the recent analysis of photometric observations of young solar analogs (Amado *et al.*, 2001; Berdyugina, Pelt, and Tuominen, 2002; Messina and Guinan, 2002; Jarvinen *et al.*, 2004) which has revealed sunspot-like cycles on these stars. Variations of the total spottedness, analogous to the sunspot cycle, are also found on other types of cool active stars, including the components of binary systems (e.g., Henry *et al.*, 1995).

Time series of Doppler images suggest that large active regions on cool magnetically active stars can last for several years (Vogt *et al.*, 1999). Moreover, it is often two active regions at opposite longitudes that persist for a long time (Berdyugina *et al.*, 1998, 1999). An analysis of long-term photometric observations clearly confirm the existence of *persistent active longitudes* on stars of the RS CVn-type (Berdyugina and Tuominen, 1998; Lanza *et al.*, 1998; Rodono *et al.*, 2000) and FK Com-type (Korhonen, Berdyugina, and Tuominen, 2002) as well as on young solar analogs (Berdyugina, Pelt, and Tuominen, 2002; Jarvinen *et al.*, 2004). Two examples are shown in Figure 1.

Although active longitudes endure for a long time, the active regions they consist of evolve in size, indicating possible cyclic variations as first observed in Doppler images (Berdyugina *et al.*, 1998, 1999). 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 opposite one occurs. Such a phenomenon was first observed on FK Com (Jetsu *et al.*, 1991) and was tentatively called flip-flop. Berdyugina and Tuominen (1998) have analyzed long-time series of photometric data for four RS CVn stars and discovered that flip-flops are regularly repeated and thus indicate a new type of stellar cycle which is related to active longitudes, i.e., *a flip-flop cycle*.

Long-term photometric observations reveal that active longitudes can migrate in phase with respect to the chosen reference frame. In binaries, this is usually the orbital ephemerid, while in single stars it represents an average epoch obtained over several years. If the migration is linear, a phase difference accumulates due to the constant difference between the assumed and true periods of the spot rotation. This is more common for the binary components of RS CVn-type stars. A non-linear migration suggests the presence of differential rotation and changes in mean spot latitudes as, e.g., on the Sun (Section 3). Such a behaviour is typical for single stars, young solar type dwarfs and FK Com-type giants (Figure 1).

The differential rotation on the surfaces of active stars is most accurately measured from Doppler images (Petit, Donati, and Collier Cameron, 2002). Recent results suggest that the intensity of differential rotation probably weakly depends on the rotation period and the stellar mass (Petit, Donati, and Collier Cameron, 2004; Reiners and Schmitt, 2003). Knowing the differential rotation and the phase migration of active longitudes allows us to recover mean spot latitudes during the course of sunspot-like cycles, i.e., stellar butterfly diagrams (Berdyugina, 2005). Alternatively, the mean spot latitudes can be recovered either from light curve modelling or Doppler images. The former provides longer time scales but less reliable latitudes, while the latter gives more reliable output but is usually limited in time coverage. For young dwarfs the butterfly diagrams are reminiscent of the solar case, although the limited amount of collected results does not yet allow for any conclusions.

The two cycle types, the spottedness cycle and flip-flop cycle, have been recovered on different types of stars. A sample of stars with different rotation rates and cycle frequencies thus provides an opportunity to investigate the likely evolution of the stellar dynamo, as was done by, e.g., Saar and Brandenburg (1999). However, in such an analysis it is important to distinguish between the two cycle types as they can be associated with different dynamo modes, as discussed by Moss (2004) and Fluri and Berdyugina (2004). The frequency ratio for the two cycle types appears to be different for binary components and single stars. In RS CVn-type stars exhibiting both types of cycles, flip-flops appear to occur at the frequency of the spottedness cycle (Henry *et al.*, 1995; Berdyugina and Tuominen, 1998). In young dwarfs flip-flop cycles are 3 – 4 times shorter than the sunspot-like cycle (Berdyugina, Pelt, and Tuominen, 2002; Jarvinen *et al.*, 2004).

Summarizing the above, the following main activity patterns are observed on cool active stars, namely the components of binary systems, young single dwarfs and single rapidly rotating giants:

- total spottedness variations: sunspot-like cycles (Figure 1, low panels);
- persistent active longitudes 180° apart: non-axisymmetric magnetic fields (Figure 1, upper panels);

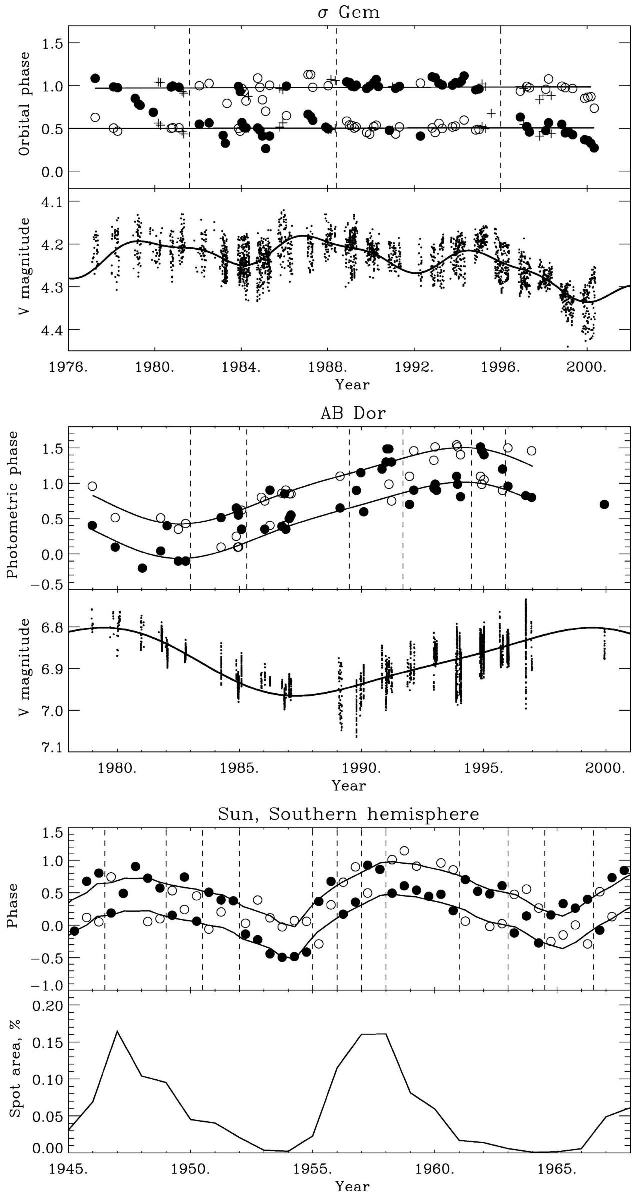

Figure 1. Active longitudes, flip-flops and sunspot-like cycles on the RS CVn star σ Gem (Berdyugina and Henry, in preparation), young solar analog AB Dor (after Järvinen *et al.*, 2004), and the Sun (after Berdyugina and Usoskin, 2003). In the three plots *upper panels* show phases of spot concentrations (*filled* and *open circles* denote primary and secondary regions, respectively). The migration paths of active longitudes are emphasized by *solid lines*. Flip-flops are marked by *vertical dashed lines*. They occur when the primary region jumps to the opposite longitude. For the Sun, only half-year average phases are shown and a linear drift of the active longitudes in the Carrington system is subtracted for better visibility. *Lower panels* in the plots show variations of the stellar brightness and sunspot area. Note that minimum brightness corresponds to maximum spotted area (e.g., Amado *et al.*, 2001.)

- switching of dominant activity between active longitudes: flip-flop cycles (Figure 1, upper panels);
- cycle frequency ratio (spottedness to flip-flop): larger in binaries, smaller in single stars;
- migration of active longitudes: differential rotation and butterfly diagrams (Figure 1, upper panels in plots for the Sun and AB Dor; Berdyugina, 2005).

These phenomena seem to differ from the activity patterns observed on the Sun and need to be explained by stellar dynamo theory. However, a closer look at solar activity reveals many similarities between the Sun and more active stars as discussed in the following section.

3. Non-Axisymmetric Magnetic Field on the Sun

The Sun is the only star whose magnetic activity can be observed and studied in detail. It exhibits 11- and 22-year spot and magnetic cycles which are explained by an oscillatory magnetic dynamo. The distribution of sunspots in the solar photosphere reflects the distribution of magnetic fields in the convection zone and provides strong observational constraints on solar dynamo theory. Sunspots are known to preferably appear in narrow latitudinal belts and approach the equator as the solar 11-year cycle advances, a pattern known as the Maunder butterfly diagram.

The longitudinal behaviour of sunspot activity also shows a noticeable pattern (Berdyugina and Usoskin, 2003) and indicates the presence of a non-axisymmetric dynamo mode. Large sunspot groups in both northern and southern hemispheres are preferably formed around two active longitudes which are separated by 180° and persistent for at least 120 years. Similar to young solar-type dwarfs, the two active longitudes on the Sun are long-lived quasi-rigid structures which are not fixed in any reference frame due to differential rotation. They continuously migrate, with a variable rate, with respect to the chosen reference frame (Figure 1). In the Carrington system, the migration results in a phase lag of about 2.5 solar rotations per sunspot cycle. The migration of active longitudes is caused by changes in the mean latitude of the sunspot formation and differential rotation. Sunspots are first formed at higher latitudes and approach the equator as the solar cycle advances, in the Carrington reference frame the migration is more rapid at the beginning of the cycle and slows down towards the end. The rate of differential rotation obtained from the active longitude migration is in agreement with measurements by SOHO/MDI (Berdyugina and Usoskin, 2003).

Major spot activity alternates the active longitudes in about 1–3 years, which results in flip-flop cycles of 3.8 and 3.65 years in the northern and southern hemispheres, respectively. This is about 1/3 of the 11-year sunspot cycle and agrees with the results obtained for young solar analogs (Section 2.2). The difference between flip-flop cycle lengths in the north and south is significant and produces an oscillating effect in the north–south asymmetry on a century time scale. This may indicate a relationship between the north–south asymmetry and the active longitudes which is also suggested by the presence of 1.7 and 3.6 year periodicities in the asymmetry (Knaack, Stenflo, and Berdyugina, 2004). Evidence of active longitudes can be found in the distribution of solar flares, in the solar corona, solar wind and interplanetary magnetic field (IMF) (Bumba and Obridko, 1969; Jetsu *et al.*, 1997; Benevolenskaya, Kosovichev, and Scherrer, 1999; Neugebauer *et al.*, 2000). The alternation of the active longitudes may be responsible for, e.g., phase variations of the IMF with the 3.2-year period found by Takalo and Mursula (2002).

Comparing the observed properties of the non-axisymmetric magnetic field on the Sun and active stars, we can conclude that the activity patterns emphasized in Section 2.2 are also relevant for the solar case. There appears to be more similarity between different types of stars than it was thought previously. Thus, fine details of the stellar dynamo can be deduced by studying the Sun, while its global parameters, on an evolutionary time scale, are provided by a sample of active stars.

4. Dynamo Modes

The geometry and behaviour of solar and stellar magnetic fields are globally determined by the stability of dynamo modes with different symmetry (Brandenburg *et al.*, 1989). For instance, the sunspot cycle can be explained by an axisymmetric mean-field dynamo mode of $\mathcal{A}0$ type which is antisymmetric with respect to the equator (dipole-like). Similarly, spottedness cycles in other stars can be also associated with an axisymmetric mode of $\mathcal{S}0$ type which is symmetric with respect to the equator (quadrupole-like).

Persistent active longitudes separated by 180° on the Sun and cool active stars clearly indicate the presence of non-axisymmetric dynamo modes. They can be either symmetric with respect to the equatorial plane, a dipole-like $\mathcal{S}1$ mode (Moss *et al.*, 1995), or an antisymmetric quadrupole-like $\mathcal{A}1$ mode (Tuominen, Berdyugina, and Korpi, 2002). The magnetic field configuration in such modes consists of two magnetic spots of opposite polarities (active longitudes) 180° apart (see, e.g., Figure 1 in Fluri and Berdyugina, 2004).

Beside the symmetry of the modes, their oscillatory properties are important. The mean-field dynamo theory favours oscillating axisymmetric modes with a clear cyclic behaviour and sign changes (as in the sunspot cycle), while non-axisymmetric modes appear to be rather steady.

The switching of active longitudes and flip-flop cycles observed on the Sun and other active stars imply, however, the existence of apparently oscillating non-axisymmetric fields. As is suggested by Berdyugina, Pelt, and Tuominen (2002), perhaps the coexistence of oscillating axisymmetric and steady non-axisymmetric modes results in the appearance of flip-flop cycles. Then, the relative strengths of the two dynamo modes and the period of the oscillations of the axisymmetric mode should define the amplitudes and lengths of observed cycles. The possibility of such a mechanism was first demonstrated by the mean-field dynamo calculation of Moss (2004) who obtained a stable solution with an oscillating $\mathcal{S}0$ type mode and a steady, mixed-polarity non-axisymmetric mode. In this case flip-flops are quasi-periodic and as frequent as sign changes of the $\mathcal{S}0$ mode, which is reminiscent of the behaviour observed in some RS CVn stars. A similar mechanism involving an oscillating $\mathcal{A}0$ mode and a steady $\mathcal{S}1$ mode is discussed by Fluri and Berdyugina (2004).

More frequent flip-flops, compared to the sunspot-like cycle in single stars and the Sun, suggest a more complex field configuration. As shown by Fluri and Berdyugina (2004) flip-flops could also occur due to alternation of relative strengths of non-axisymmetric $\mathcal{S}1$ and $\mathcal{A}1$ modes without sign changes of any involved modes. If in addition a co-existing axisymmetric mode were changing its sign with a different frequency, it would result in the behaviour observed in solar-type stars. The stability of such a solution should however be tested by dynamo calculations.

5. Conclusions

Non-axisymmetric large-scale magnetic fields are persistent in various types of active stars including the Sun. Their continuous longitude migration implies the presence of differential rotation and provides an opportunity for studying stellar butterfly diagrams. Activity cycles revealed in variations of spot and plage area appear to accompany flip-flop cycles, i.e., periodic switching of dominant activity between opposite longitudes. An analysis of these phenomena can help to identify underlying dynamo modes. Cool stars, therefore, provide a pronounced example of solar activity, while the Sun is a proven laboratory for studying stellar magnetism.

Comparing the activity patterns of the present Sun and young solar analogs allows us to infer the possible evolution of the stellar dynamo on main sequence stars. First, the overall activity level is reducing while the star evolves along the main sequence and looses its angular momentum. Second, the activity is changing from spot-dominated to faculae-dominated. This implies that cycles on young stars are more prominent in spot patterns, while on stars of the solar age cycles become more apparent in chromospheric plages. Third, young stars show conspicuous non-axisymmetric fields, which coexist on the Sun and solar-age stars with a strong axisymmetric component.

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