Interpretation of Solar and Stellar Activity in terms of Dynamo Modes

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Abstract. The magnetic activity on active, cool stars and on the Sun is spatially organized on large scales and exhibits cyclic behavior on various time scales. In particular, the biggest active regions tend to appear mainly at two preferred longitudes on opposite sides. Therefore, a physical mechanism has to exist that breaks the axial symmetry of the global magnetic field. This implies that in addition to the axisymmetric dipole a non-axisymmetric dynamo mode should be excited in the Sun. We discuss possible dynamo mode configurations that can explain the patterns observed both on stars and the Sun.

1. Introduction

The typical activity phenomena that are familiar from solar physics, such as spots, flares or activity cycles, are common also on cool, rapidly rotating stars. The level of the activity is strongly enhanced on these stars as compared to the Sun. The large sample of such stars enables us to investigate the properties of magnetic activity in a much broader parameter space than the Sun, as a single example, would allow. The Sun, on the other hand, reveals details not accessible on stars. Therefore, the comparison of solar and stellar activity is of mutual benefit to enhance our understanding of magnetic phenomena and the underlying dynamo.

The magnetic activity of cool stars can be followed to a large degree by photometry. These stars can be covered by huge spot regions that extend often over 10 to 20\% of the visible stellar surface (e.g. Strassmeier 1999). The spots modulate the brightness on the time scale of the rotation period typically by 0.1 to 0.2 mag (e.g. Henry, Eaton, & Hamer 1995). Therefore, stellar spot patterns can be inferred just from the time variation of photometric observations. The Doppler Imaging Technique (e.g. Berdyugina 2005b) for reconstructing the stellar surface would in principle contain more information but photometric data are available for much more stars and for longer time series.

The biggest active regions tend to appear always at about the same longitude, called “active longitude”, which drifts slowly due to differential rotation. There exist usually two active longitudes separated by 180° that become more active alternately and quasi-periodically every few years (for a review see Berdyugina 2005b,a). This switching of the dominant active longitude from one side to the other is known as “flip-flop”, a phenomenon first observed by Jetsu et al. (1991) on FK Com. Cyclic activity related to flip-flops was first reported by Berdyugina & Tuominen (1998). Active longitudes and flip-flops have been identified also on
the Sun, where they were found to be persistent on the century scale (Berdyugina & Usoskin 2003).

The origin of active longitudes and flip-flops is still under discussion. It is generally believed that these phenomena are related to the non-axisymmetric component of the large-scale magnetic field. With the recent advances both in observations (Berdyugina 2005b) and in non-axisymmetric dynamo calculations (Moss 2004) the topic gains more and more attention.

In this paper we present a qualitative interpretation of active longitudes and flip-flops on cool, active stars and the Sun. The goal is to determine the large-scale structure of the magnetic field and to identify the relevant dynamo modes that are necessary to produce the observed data on active longitudes and flip-flops.

2. Method

The connection between dynamo modes, spot distribution and active longitudes is established with the method introduced by Fluri & Berdyugina (2004). A given surface distribution of the magnetic field is translated into an intensity map based on the rule that spots appear most probably at the locations of the strongest magnetic fields. This intensity map, which corresponds to a surface distribution of the spot filling factor, is then used to obtain the corresponding light curve.

The surface magnetic field that serves as input to the whole procedure is built from a superposition of five different dynamo modes. We employ two axisymmetric modes, A0 and S0, and three non-axisymmetric modes, A1, S1, and the spherical harmonic $Y_{22}$ with $\ell = m = 2$.

By varying the relative strength of the different dynamo modes, this method allows us to study the long-term behavior of active longitudes and of global activity patterns including the properties of activity cycles.

3. Modeling Active Longitudes and Flip-flops

In this section we consider different global magnetic field configurations that lead to active longitudes and flip-flops. After explaining the basic idea we discuss realistic time-dependent superpositions of dynamo modes that can reproduce the observed global activity patterns on stars and the Sun.

3.1. Basic Idea

The basic mechanism resulting in active longitudes and flip-flops is illustrated in Figure 1. Let us consider the superposition of an axisymmetric A0 mode and a non-axisymmetric S1 mode resulting in an inclined dipole field (top row of Figure 1). The corresponding intensity image or spot filling factor distribution is shown in the right-most panel of Figure 1.

It is immediately clear that the introduction of the S1 mode breaks the axial symmetry and defines two longitudes, separated by 180°, where the spots are predominantly concentrated. These are the active longitudes, one in the northern and one in the southern hemisphere. When changing the polarity of the
Figure 1. Simple configuration for creating active longitudes and flip-flops. In both rows the first three images illustrate the magnetic field distribution at the surface, while the last image on the right gives an intensity map, corresponding to a spot probability distribution. The only difference between the two rows is the sign of the A0 mode. The sign change results in a flip-flop, i.e. in a 180° shift of the active longitudes.

A0 mode (bottom row of Figure 1) the active longitudes shift by 180°. Thus, a flip-flop occurs in this configuration whenever A0 changes its sign.

Obviously a flip-flop would also result from a sign change of the S1 mode. However, in \(\alpha-\omega\) dynamos the non-axisymmetric field is generally believed to be steady in some rotating frame, while the axisymmetric component is expected to oscillate.

3.2. Stellar Case

To obtain realistic activity patterns we make the energy of the dynamo modes time-dependent in the following.

As a first example we consider the superposition of A0 and S1 as in Figure 1. We assume that A0 oscillates e.g. with a period of 22 years and with a sign change every 11 years, as it is the case on the Sun. Together with a constant S1 mode we would observe a flip-flop every 11 years. A full flip-flop cycle, consisting of two flip-flops, is therefore twice as long as the spottedness cycle (i.e. the sunspot-like cycle). This is the typical ratio seen on cool, active binaries (Berdyugina 2004). Furthermore, the resulting long-term variations of the light-curve matches stellar observations. Out of a sample of 11 active binaries Henry et al. (1995) found 3 stars with this behavior.

The majority of the active binaries (8 out of 11) exhibit a second type of activity pattern with a long-term light curve behavior as plotted in the middle panel of Figure 2. To get this type of variations we have assumed the time-dependent superposition of four dynamo modes given in the top panel of Figure 2: the axisymmetric modes A0 and S0 remain constant while the non-axisymmetric modes A1 and S1 vary periodically in anti-phase.
Figure 2. Flip-flop mechanism due to varying non-axisymmetric modes in anti-phase. Top panel: Time-dependence of the dynamo modes, which serves as input. Middle panel: Of the resulting light curves we show the maximum, mean, and minimum value of the magnitude. Bottom panel: The phase of the minimum of the light curves switches by 0.5 whenever the A1 and S1 modes are of equal strength. We assumed an inclination of the stellar rotation axis of 60°.

Despite none of the modes ever changes its sign, the flip-flops do occur when the A1 and S1 modes are of equal strength (Figure 2). The time between two flip-flops is not always identical and could be modified by changing the relative strength of the A1 and S1 modes. This gives us the possibility to fine-tune the configuration of dynamo modes when fitting the model to photometric data of stars. Note however that with current mean field dynamos it seems harder to achieve this mechanism than the first type discussed above with the sign change of A0.

### 3.3. Solar Case

On the Sun and single, active cool stars the flip-flop cycle is typically 3 to 4 times shorter than the spottedness cycle (Berdyugina 2005a). The question is whether the solar pattern of flip-flops can be reproduced by the same mechanisms
as described in Sect. 3.2, or whether the dynamo working in single stars might differ form the one in binaries.

We could first try to combine the two types of flip-flop mechanisms described in Sect. 3.2.. For this purpose we would assume the superposition of dynamo modes shown in Figure 2 and set the period of A1 and S1 to about 3.6 years, corresponding to the flip-flop cycle on the Sun (Berdyugina & Usoskin 2003). In addition we would select A0 to oscillate with sign changes every 11 years as we know it happens on the Sun. Indeed, such a magnetic field configuration would really produce active longitudes and flip-flops both in the northern and southern hemispheres with the observed frequency.

However, there are big problems with this configuration that even rule it out as a possible solution. The non-axisymmetric modes would have to be chosen rather strong, i.e. of the same order of magnitude as the A0 mode. In addition, the S0 mode would not only have to oscillate as well but would even have to be stronger than A0, analogous to the case illustrated in Figure 2. These are serious contradictions to the observations, since the dipole mode A0 clearly dominates on the Sun. Furthermore, the north-south asymmetry of the unsigned magnetic flux would continuously favor the same hemisphere. Analysis of solar data reveals however that the unsigned flux is alternately larger in both hemispheres and even undergoes cyclic behavior on several time scales (Knaack, Stenflo, & Berdyugina 2004). Therefore, a simple combination of the previously discussed configurations cannot be applied to the Sun.

To reproduce solar observations we have to find a new flip-flop mechanism. A promising possibility is sketched in Figure 3. Here we have introduced a new mode, namely the spherical harmonic $Y_{22}$ with $\ell = m = 2$. The superposition of A0 and $Y_{22}$ results already in two active longitudes (Figure 3, top row) regardless
Figure 4. Possible flip-flop mechanism on the Sun due to varying non-axisymmetric modes in anti-phase. Top panel: Time dependence of the dynamo modes, which serves as input. The non-axisymmetric modes S1 and $Y_{22}$ have the same strength and are represented by the same dotted line. Middle panel: North-south asymmetry of the unsigned magnetic flux. Bottom panel: Phase of the minimum of the light curves, separately for the northern (solid) and southern (dotted) hemispheres. The jumps indicate flip-flops.

of the strength of the non-axisymmetric mode $Y_{22}$. If we add to this combination S1 as a second non-axisymmetric mode then S1 selects which of the two active longitudes dominates (Figure 3, bottom row). When assuming that S1 rotates relative to $Y_{22}$ both active longitudes will dominate in turns.

A possible solution for the Sun with this flip-flop mechanism is illustrated in Figure 4. The dominant mode is now really A0 (top panel). Flip-flops occur both in the northern and southern hemispheres (Figure 4, bottom panel). They are controlled by the two modes S1 and $Y_{22}$ according to the basic mechanism explained above (Figure 3). One advantage of this configuration is that the non-axisymmetric modes S1 and $Y_{22}$ can be very weak as long as they are present. The stronger they are the more pronounced become the active longitudes. The fact that the solar active longitudes appear to be rather weak indicates that the non-axisymmetric modes should be weak as well, which allows for considerable scatter in the longitudes of sunspots. The presence of S0 does not influence the flip-flops but controls the north-south asymmetry of the unsigned magnetic flux.
(Figure 4, middle panel). The cyclic behavior of the north-south asymmetry can now be obtained simply from different harmonics. Therefore, observed periodicities in the north-south asymmetry (Knaack & Stenflo 2005) provide constraints for the S0 mode in our model. Alternatively, these short-term variations would also result from harmonics of the basic 22 year period of A0. And such harmonics are clearly present on the Sun as indicated by the difference in the rise and fall time of the sunspot number.

4. Conclusions

We have presented a method that allows us to interpret activity patterns observed on cool stars including the Sun in terms of dynamo modes and to test results of dynamo calculations. Starting from a surface magnetic field distribution, which is given as a superposition of a few basic dynamo modes, we can calculate maps of the spot filling factor and light curves.

We have discussed several configurations of dynamo modes that naturally lead to active longitudes and flip-flops. This allowed us to reproduce the two types of brightness variations found on cool, active binaries. The solar active longitudes and flip-flops can however only be explained by a different mechanism. This could be an indication that the underlying dynamos in binaries and single cool stars might differ, but further analysis is necessary to clarify this issue.

For the Sun we have presented a possible dynamo mode configuration that reproduces the observed behavior of flip-flops. Active longitudes and the quasi-periodic flip-flops are determined by two non-axisymmetric dynamo modes (S1 and $Y_{22}$ with $m = 1$ and $m = 2$, respectively). The stronger these two modes the better visible become the active longitudes. Interestingly, the north-south asymmetries of the unsigned magnetic flux and thus probably of many features related to magnetic activity can be explained and are controled by the S0 mode.

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References