Mem. S.A.It. Vol. 78, 242

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Preferred longitudes in solar and stellar activity

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Abstract. An analysis of the distribution of starspots on the surfaces of very active stars, such as RS CVn- FK Com-type stars as well as young solar analogs, reveals preferred longitudes of spot formation and their quasi-periodic oscillations, i.e. flip-flop cycles. A non-linear migration of the preferred longitudes suggests the presence of the differential rotation and variations of mean spot latitudes. It enables recovering stellar butterfly diagrams. Such phenomena are found to persist in the sunspot activity as well. A comparison of the observed properties of preferred longitudes on the Sun with those detected on more active stars leads to the conclusion that we can learn fine details of the stellar dynamo by studying the Sun, while its global parameters on the evolutionary time scale are provided by a sample of active stars.

Key words. Stars: activity – starspots – Sun: activity – sunspots

1. Introduction

The motivation to study preferred longitudes in sunspot activity was based on the results obtained for very active cool stars, whose activity level exceeds significantly that of the Sun. In particular, a young solar analog LQ Hya was found to exhibit an activity cycle similar to that of the Sun but along with preferred longitudes of active regions and so-called flip-flops, switches of the dominant activity between the opposite longitudes (Berdyugina et al. 2002). This indicated that the young Sun may have also exhibited such activity patterns and, thus, raised the question whether the modern Sun has preserved these characteristics. In this paper I try to demonstrate connections between the sunspot and starspot activity and analyse the information on stellar and solar active longitudes acquired to date.

2. Preferred longitudes in stellar activity

Studying magnetic activity on other stars than the Sun opens the 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 levels of activity provides key constraints for the stellar and solar dynamo theory.

Decades of continuous photometric monitoring of RS CVn-type stars (binaries with cool active giants or subgiants) revealed that large spots (active regions) maintained their identities for years which was interpreted as a signature of one or two active longitudes. Berdyugina & Tuominen (1998) showed that active longitudes on these stars are persistent structures which can however continuously mi-

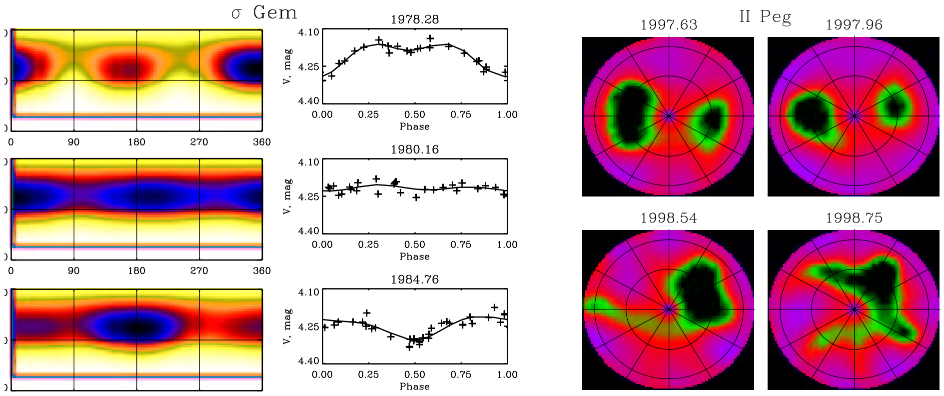

Fig. 1. Active longitudes and the flip-flop phenomenon on cool active binary components: on the left, as observed in light curves of σ Gem, and on the right, in Doppler images of II Peg. The images on the left show the distribution of the spot filling factor on the stellar surface obtained via inversions of the light curves (plots in the middle). The II Peg images obtained from inversions of spectral line profiles show the temperature distribution on the stellar surface as seen from the pole. Flip-flops appear as a switch of the dominant activity to the opposite longitude.

grate in the orbital reference frame. The active longitudes are separated by 180° on average and usually differ in their activity level.

Although active longitudes endure for a long time, active regions they consist of evolve in size, indicating possible cyclic variations as revealed first from Doppler images (Berdyugina et al. 1998). While one active longitude reduces its activity level, the other increases, which suggests for redistribution of the spotted area between the opposite hemispheres. At the moment 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. 1993) and was tentatively called flip-flop. Berdyugina & Tuominen (1998) have analyzed long 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 cycles which is related to active longitudes, i.e. flip-flop cycles. Two persistent active longitudes separated by 180° and flip-flop cycles seem to be typical patterns of stellar activity. In addition to RS CVn-type stars they have been found on FK Com (Korhonen et al. 2002) and very active young solar analogues (Berdyugina & Järvinen 2005; Järvinen et al. 2005a,b).

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 ephemeris, while in single stars it represents an average epoch over years. If the migration is linear, the phase difference is accumulated due to a constant difference between the assumed and true periods of the spot rotation. This is more common for binary components of RS CVn-type. A non-linear migration suggests the presence of differential rotation and changes of mean spot latitudes as, e.g., on the Sun (Sect. 3). Such a behaviour is typical for single stars, young solar type dwarfs and FK Com-type giants, with so far one exception, which is the RS CVn-type star HR 1099. An analysis of the migration of active longitude on this star combined with measurements of differential rotation from Doppler images provided the first stellar butterfly diagram (Fig. 2) without an assumption on spot shapes, numbers or distributions (Berdyugina & Henry 2007). It is interesting that the active regions at opposite longitudes occupy different latitudes, and when one drifts equatorward, the other approaches the pole. A similar behaviour was also noticed

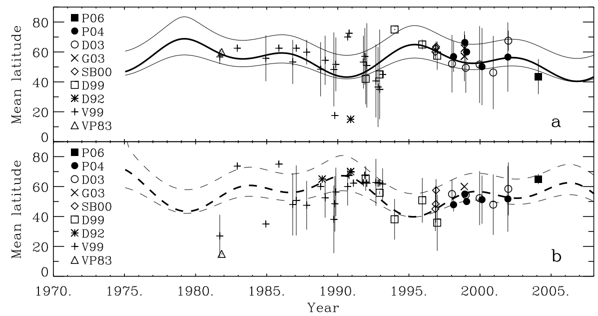

Fig. 2. Butterfly diagram of HR 1099. Mean latitudes recovered from the migration of two active longitudes are shown in two separate panels (solid and dashed curves). Mean latitudes of spots in the opposite hemispheres measured from Doppler images are shown with different symbols. Standard deviations of the mean Doppler imaging latitudes (if several spots were observed) are shown as vertical dashes. The thick curves are the solutions using the best parameters of the differential rotation law by Petit et al. (2004). The thin curves indicate the $\pm 1\,\sigma$ interval for the best parameters obtained by Berdyugina & Henry (2007). The two solutions are statistically equivalent. Adopted from Berdyugina & Henry (2007).

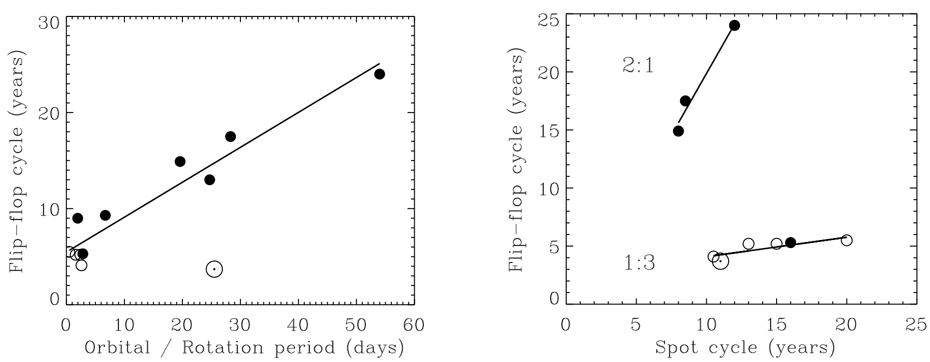

Fig. 3. Flip-flop cycles on cool active stars: binaries (filled circles), single young stars (open circles), and the Sun (big circle with dot). On the left, correlation of the flip-flop cycles versus the orbital (binaries) or rotational (single stars) periods. On the right, the relation with the sunspot-like cycles are shown. Two groups with the cycle ratios of 1:3 and 2:1 are clearly seen.

on the young solar analog EK Dra (Järvinen et al. 2007). Such behaviour indicates a possible precession of the global stellar magnetic field with respect to the stellar rotational axis.

More than a dozen of active stars exhibiting flip-flop cycles enable a statistical analysis of their properties. There is a noticeable trend for stars with longer rotational periods to have longer flip-flop cycles (Fig. 3, left panel). The trend is prominent for RS CVn binaries as they have a wide range of rotation periods which are synchronized with their orbital motion. In connection to the spot activity cycle (analogous to the 11-yr sunspot cycle), there are clearly two groups of stars with cycle ratios 2:1 and 1:3 (Fig. 3, right panel). This implies different dominant dynamo mechanisms operating in these stars. The presence of binaries in both groups excludes possible effects of binarity on this ratio. However, it appears that the two groups greatly differ by the differential rotation rate, which might provide a clue to the nature of their dynamos.

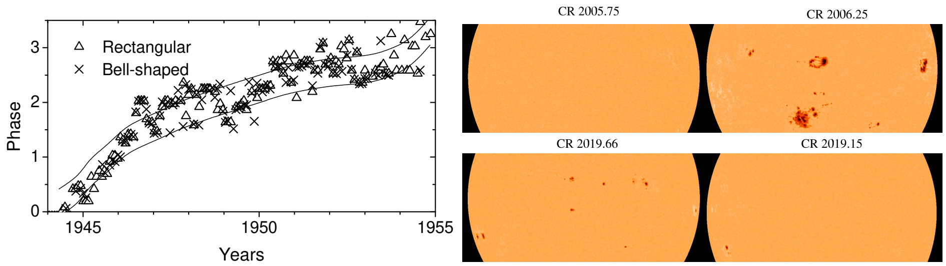

Fig. 4. Active longitudes and the flip-flop phenomenon on the Sun. On the left, rotational phases (in the Carrington system) of the biggest sunspot-cluster in the North are shown for cycle 18 (Berdyugina & Usoskin 2003; Usoskin et al. 2007). The phases obtained with two different methods are denoted by different symbols. On the right, illustration of a flip-flop in cycle 23: two opposite sides of the Sun (SOHO/MDI, only equatorial region) are shown for two Carrington rotations (CR) one year apart. The maximum activity switched from the phase ~0.25 to the phase ~0.66.

3. Preferred longitudes in solar activity

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 the solar dynamo theory. Sunspots are known to appear preferably 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 & Usoskin 2003; Usoskin et al. 2005, 2007) 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 is a long-lived quasi-rigid structure which is not fixed in any reference frame because of the differential rotation. They continuously migrate with respect to a chosen reference frame with a variable rate (Fig. 1). The migration of the active longitudes in the Carrington system is caused by changes of the mean latitude of the sunspot formation and the differential rotation. Since 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. Neglecting the migration results in complete smearing of the active longitude pattern on time scales of more than one solar cycle, in a similar way it occurs for stars. This explains the diversity and contradictions of the previously published results. Therefore, the active longitudes are best seen in the dynamic reference frame introduced by Usoskin et al. (2005); Berdyugina et al. (2006).

The relative activity level of the solar active longitudes varies in time, namely sunspots are preferably concentrated in one of the other active longitude, which is thus dominant at a given time (Berdyugina & Usoskin 2003). Moreover, the location of the dominant longitudes alternates quasi-periodically, in about 1.8–1.9 years on average. Although the dominance of one longitude may last from 1.5 to 3 years, the switch of the dominant activity from one longitude to the other is relatively rapid and may happen within a month. Thus the phenomenon is very similar to the flip-flop effect observed on active cool stars. On average 6 switches of the activity occur during the 11-yr sunspot cycle and, thus, the 3.7-yr flip-flop cycle is about 1/3 of this. 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 time scale. 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).

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 ~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 on the Sun.

4. Conclusions

Comparing the observed properties of preferred longitudes on the Sun with those detected on more active stars, we can conclude that their activity patterns appear to be similar. Thus, fine details of the stellar dynamo can be deduced by studying the Sun, while its global parameters on the evolutionary time scale are provided by a sample of active stars.

Acknowledgements. This work is supported by the EURYI (European Young Investigator) Award provided by the European Science foundation (see www.esf.org/euryi).

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