The Physics of Sun and Star Spots
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The zoo of starspots

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Abstract. Starspots are being observed with many different techniques but not always with coherent results. In particular not if model-dependent data analysis must be employed, e.g. through two-dimensional spot modelling of one-dimensional photometric light curves. I review the zoo of currently available physical spot parameters, i.e. their size, temperature and variability time scales, and also compare results from different techniques. Most of the current values come from Doppler imaging and multi-color photometry. I also list a few cases where starspot detections turned out to be very different to the solar analog.

Keywords. Magnetic fields, stars: spots, stars: magnetic fields, stars: rotation, methods: photometric, methods: spectroscopic

1. Introduction and context

Solar chromospheric emission-line flux is directly related to the underlying photospheric magnetic field (a description of this connection is given, e.g., in the book by Schrijver & Zwaan 2000). The majority of the photospheric magnetic field itself is thought to be linked again to the internal dynamo by myriads of magnetic field lines, possibly organized as flux tubes and, of course, as spots. For the majority of stars we can still make only qualitative statements for a connection between their surface magnetic tracers and the dynamo process, e.g., through detecting their activity cycles. This is partly because the evidence is based on disk-integrated measurements, most notably for Ca II S-index variability, X-ray luminosity or broad-band UV enhancement. Some surprises were encountered, e.g. that there is an activity “saturation” in the X-ray flux when the magnetic filling factor of the atmospheric volume comes close to 100%.

The most detailed stellar surface data come from optical (photospheric) Doppler imaging, a technique that currently can not be extended to the chromosphere, not to speak about the corona. But even for photospheric mapping, we are still biased towards stars rotating several times to tens of times faster than the Sun, where we may expect a qualitatively different link of the surface to the interior as compared to the Sun. Moreover, also the Sun bears still surprises. *Hinode* has told us recently that there is an ubiquitous horizontal photospheric magnetic field of super-equipartition kG strength even at high solar latitudes (e.g. Ishikawa & Tsuneta 2009). Whether this is truly evidence for a turbulent sub-photospheric dynamo or just describes an advected field through granular motion from deeper layers is not clear yet. If such fields are assumed to exist also on other solar-type stars, stellar observations of unresolved surfaces are then left with the ambiguity whether a particular magnetic tracer, e.g. Ca II H&K emission, is more related to the radial or the horizontal field, or both, as expected. Clearly, we need to spatially resolve the full magnetic-field vector also on other stars and directly observe the field geometry in order to compare with the Sun. The only technique to do so on other star is Zeeman-Doppler-Imaging (ZDI) (see the papers by Berdyugina, Carroll *et al.* and Kochukhov *et al.* in this proceedings).

Besides that we need spatially resolved stellar disk data, we need time resolution on very long scales to provide more solid evidence for the existence of a systematically changing pattern of the magnetic tracers, like the solar butterfly diagram. This endeavor is still in an infant state and involves the consecutive solution of three major obstacles for stellar observational techniques. Firstly, we need to spatially resolve and sample the surface of stars that are otherwise ideal point sources. Secondly, we need to distill the geometry of the magnetic surface field in three dimensions and, thirdly, we need to timely sample this over various time scales, from the spot lifetime to the period of an activity cycle. The latter may not appear to be an acceptable proposal for a telescope time allocation committee.

For the time being, one shall first review the collection of Doppler images and bring them into an appropriate physical order. This shall enable a meaningful comparison, despite of the different surface parameters of these maps, the different evolutionary state of the targets and their, e.g., vastly different angular velocities. This was partly already done in the recent review by Strassmeier (2009) and is not repeated here. In the course of the present zoological work, I stumbled over "starspot" observations that showed observations that were phenomenologically similar but very different in origin and physics, and sometimes completely unrelated to "Sunspots".

2. Some starspot numbers

2.1. *Stars with spots in our galaxy*

An educated guess of the expected number of spotted stars in the galaxy yields approximately 200 billion stars. This is basically the number of stars on the right side of the granulation boundary of the H-R diagram. So far, ≈500 spotted stars were observed with any kind of method. Of these, ≈80 were Doppler imaged, of which approximately half are close binaries and half are single stars. The latter are a mixture from nearly all stellar evolutionary stages. This makes clear that we are talking small-number statistics and that many more stars of various evolutionary state and physical parameters must be mapped before we can tie in the Sun (as a star).

2.2. *Spot sizes*

The spot sizes from the list of Doppler images collected recently in Strassmeier (2009) range between 0.1% - 11% of the total stellar surface. The record holders are the K0III component in the RS CVn binary XX Tri (Strassmeier 1999) with its huge high latitude to polar spot of size 10,000 times larger than the largest sunspot group ever observed, and the ultra rapidly-rotating K3 dwarf BO Mic with spots of size as small as 0.15% (Barnes 2005, Wolter *et al.* 2005). Such small spots are only resolved if the number of resolution elements across the stellar disk is sufficiently large, i.e. small spots are only detectable on very rapidly rotating stars. Most of the spotted stars that were Doppler imaged so far rotate with an average $v \sin i$ of ≈30 $\mathrm{km\,s^{-1}}$ and have an average spot size of "a few per cent". Clearly, Doppler imaging can recover just the large-scale spot distribution and is biased from the cross-talk with the unresolved spot component for the cases when fine surface detail is seen in the maps.

A special case are the W UMa systems which are very close binaries in a common outer envelope, usually convective. Their surfaces are distorted along the apsidal line by the respective gravitational pull and oblate due to their fast rotation. For example for

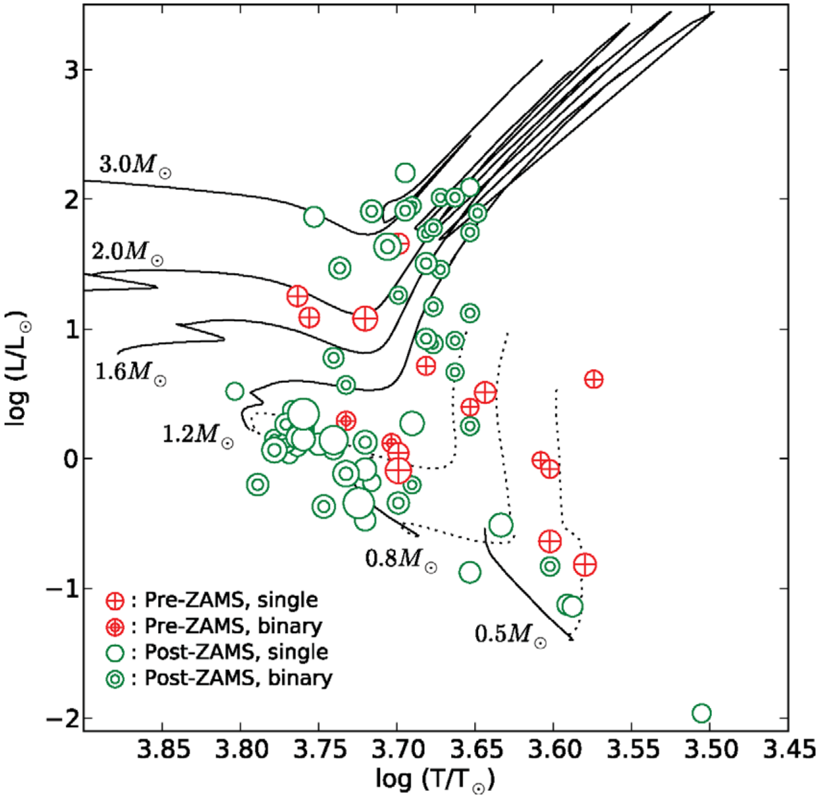

Figure 1. Cool stars with Doppler images in the H-R diagram. Tracks are shown for post-ZAMS evolution (solid lines) and for pre-ZAMS evolution (dotted lines) for masses between 0.5 and 3.0 $M_\odot$. The symbols are specified in the panel. The size of the symbol indicates the equatorial rotational velocity. The smallest size in the plot represents $v_{\rm equ}$ = 13 km s^{-1}, the largest size $v_{\rm equ}$ = 245 km s^{-1}.

VW Cep (Hendry & Mochnacki 2000), spots covered 66% of the surface of the primary and 55% of the secondary mostly at the rotational poles, much more than what has been detected for non-contact binary stars and over-active single stars. It remains to be determined whether all their spots are also magnetic.

On the smallest size scales, transit mapping of surface spots from the occultation by an orbiting exoplanet revealed two astounding spots of size just 0.025% for HD189733 from HST photometry (Pont *et al.* 2007). This is still larger than but similar to the size of a very large sunspot group. More data are now coming online from the Kepler spacecraft (e.g. Basri *et al.* 2010, Brown *et al.*, this proceedings) as well as from CoRoT (e.g. Silva-Valio *et al.* 2010).

2.3. *Spot temperatures*

The observational problem here is the cross talk between spot temperature and spot size and the ambiguity to separate these two quantities during the modelling approach. This problem is most evident for photometric spot modelling and does not exists in Doppler imaging. Photometric data are so prone to this ambiguity that the modelling results are fully model dependent. This was realized very early on by, e.g. Poe & Eaton (1979), and led to the common practice to use at least two well-defined photometric bandpasses to minimize the cross talk, usually one bandpass optimized for the unspotted photosphere and the other optimized for the spotted photosphere, e.g., Johnson V and I, respectively. All of the space-based exoplanet-transit photometry is done in "white light" and can not be used for classical spot modelling (or should not be used) unless one is very well aware that it just allows the reconstruction of spot longitudes, i.e. zonal rotational periods (e.g. Lanza *et al.* 2009, Fröhlich *et al.* 2009).

The spot temperature is much better constrained in Doppler imaging (DI; see the discussion in Strassmeier 2009 a.o. why this is so). Not all DI codes invert the spectral line profiles into a temperature map and thus our statistics are less convincing. However, from temperature-DI it appears that the cooler the star the smaller is the temperature difference between the spot and the unspotted photosphere. Berdyugina (2005) lists an average of 200 K temperature difference for M dwarfs and up to 2000 K for the F-stars.

From broad-band multi-color photometry alone, various authors obtained spot temperatures for a number of stars of a mixture of stellar parameters. The values range between 300–1700 K (see also Oláh *et al.*, this proceedings). The literature on this is just too extensive in order to comment here on individual results and I may refer to our "Thinkshop" proceedings on *Sunspots & Starspots* (Strassmeier *et al.* 2002) for further references. Multi-color photometry combined with modern light-curve inversion techniques (e.g. Savanov & Strassmeier 2008, Berdyugina 2005) is still a powerful tool to get good estimates of spot temperatures for a large number of stars.

A differential technique, based on two nearby spectral lines of different temperature sensitivity, was explored by David Gray and collaborators (e.g. Gray & Johanson 1991). From such line-ratios, plus the accompanying continuum variation from photometry, Catalano *et al.* (2002) and Frasca *et al.* (2008) obtained spot temperatures in the range of 700–1000 K.

Vogt (1979) was the first to realize the potential of molecular spectral lines as a temperature indicator for spots. Certain molecular absorption band heads can only be formed at temperatures significantly below the typical photospheric temperature of a cool star and thus a simple detection of its rotationally modulated strength can constrain the spot temperature. Employing the TiO band heads at 705 nm and 886 nm, O'Neal *et al.* (2004) obtained relative spot temperatures for five stars in the range 1000–2000 K. The 2000 K for the G1.5 dwarf EK Eri is the largest temperature difference obtained so far, even among all the techniques mentioned before. Previous spot-temperature determinations of this star ranged between 500–1200 K. Just recently, Rice *et al.* (2010) obtained separate Doppler images of the WTTS V410 Tauri from atomic lines as well as from the TiO 705.5-nm lines and found an average temperature difference between these images of 150 K in the sense that the TiO-based temperatures appeared to be generally cooler. Part of this difference likely stems from the difficulties to find the correct continuum at the TiO-band wavelengths but the basic conclusion is that atomic-line Doppler imaging may underestimate the true spot temperatures (on a 100 K level for a $T_{\rm eff} \approx$ 4500-K star).

2.4. *Spot time scales*

Among the most important time scales associated with sunspots and starspots are their lifetimes and decay times. No single starspot or starspot group has been observed and followed from its formation to its death so far. Not to speak about a proper time sampling. Even for sunspots such observations are rare, hard to disentangle from intra-group evolution, and biased towards the visibility due to the one-month rotational period of the Sun. The new *SDO* data movies, now shown at various conferences, bear a great potential to settle also this question (tbd).

Idealized sunspots appear to follow a mean decay law of the form $dA/dt = C\, r/r_{\rm max}$, with $C = 32.0\pm0.26$ a constant and r the relative spot radius (Petrovay *et al.* 1999). The area decay rate is in units of one millionth solar hemisphere per day. It is directly related to the magnetic diffusivity, η, by $dA/dt = -4\pi\eta$. Numerical values for the magnetic diffusivity are not known exactly and adopted values range from 10^{10} cm^2/s to 10^{13} cm^2/s (see Hathaway & Coudhary 2008). This value may also appear to be important for dynamo models that are tailored to predict the next solar activity cycle. A recent determination from spot variations on CoRoT-2a inferred an η of 1.2×10^{13} cm^2/s (Fröhlich *et al.* 2009), which is a first step in the right direction but likely an overestimation given the spot model assumptions in this and comparable papers.

For a summary of starspot lifetimes I refer again to Strassmeier (2009) and the references therein. More recently, we have some first preliminary results from time-series Doppler images obtained with STELLA. STELLA is a new robotic observatory in Tenerife, and dedicated to the observation of spotted stars. It consists of two 1.2-m telescopes, one fiber feeding a high-resolution echelle spectrograph and the other feeding a wide-field imaging photometer (Strassmeier *et al.* 2010). Among the targets is the famous active binary XX Triangulum (HD 12545).

3. Other fierce creatures of the zoo

A "starspot" may not always be what we believe it is supposed to be, i.e. somehow an analog of a sunspot or a sunspot group. They can be impact regions from magnetospheric accretion, obscurations from circumstellar material, or planetary transits. Even if a magnetic field can be associated the field can be of rather different origin, e.g. a fossil field (31 Com, HR3162), a mixture of surface and core dynamo fields or due to some sort of magneto-gravitational coupling of the components in a close binary.

Betelgeuse (α Ori) is a neat example. It exhibits a well observed bright spot in ultraviolet observations, in particular at Mg II h&k (see Dupree, this proceedings, for a detailed account and further references). Is has been speculated that the spot is a granulation cell, a certain non-radial pulsation mode, an outflow structure, and a chromospheric magnetic faculae. Most likely it is a combination of the latter two. Another example is ϵ Aurigae, the eclipsing binary with the longest known period (27 years). It is during mid eclipse while we are meeting, and this time, the stellar disk has been resolved by phase-coherent interferometry with the CHARA array in the H band (Kloppenborg *et al.* 2010). What is seen is an obscuration of the stellar disk due to the accretion disk around the secondary star, itself possibly a neutron star. While the eclipse is progressing, the disk is "eating away" parts of the stellar disk. If one would not know about the eclipsing phenomenon one could interpret the obscuration as due to cool starspots, in particular if one has only snapshot images.

Another fierce case is the low-mass, single, pre-main sequence star MN Lupi (Strassmeier *et al.* 2005). Doppler imaging detected not only two high-latitude hot spots (2000 K warmer than the effective temperature) but also generally a warm polar cap (1200 K warmer than photospheric), some cool spots 400-500 K below the photospheric temperature, and a generally 500-K cooler "southern" than "northern" hemisphere. The hot spots are interpreted as the heating points of accretion shocks, the shock itself is evident in emission lines like He I and Balmer H 1-13 and not seen in optically thin lines. The warm polar cap is the trailed and redistributed impact energy. The isolated cool spots are likely of local magnetic origin as we know it from the Sun, but the cool "southern" hemisphere is an obscuration due to the inner rim of the accretion disk, or whatever is left of it (the star does not have an IR excess and is classified as a weak-line T Tauri star).

4. Outlook

Among future observational tasks is time-series Doppler imaging of a representative number of stars over the entire activity cycle, if one exists. The reward should be stellar butterfly diagrams as a function of relevant global parameters like rotation rate or age, i.e. internal stellar structure. If this could be done with polarized spectra would allow, in principle, to follow the magnetic field evolution as well. It has the potential to revise our common understanding of stellar evolution, in particular for the young Sun and its infant planetary system. The magnetic field possibly played a decisive role during the star and planetary formation and its broader impact on Earth may have been underestimated (e.g. Moore & Horwitz 2007). As a small nuisance, high spectral resolution combined with polarimetry requires a fairly large telescope for good S/N, and the need for dense phase cadence in order to do Doppler imaging in the first place requires most of its time. Not the best of all conditions for an observing proposal.

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