

Starspots: a key to the stellar dynamo

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Abstract

Magnetic activity similar to that of the Sun is observed on a variety of cool stars with external convection envelopes. Stellar rotation coupled with convective motions generate strong magnetic fields in the stellar interior and produce a multitude of magnetic phenomena including starspots in the photosphere, chromospheric plages, coronal loops, UV, X-ray and radio emission and flares. Here I review the phenomenon of starspots on different types of cool stars, observational tools and diagnostic techniques for studying starspots as well as starspot properties including their temperatures, areas, magnetic field strengths, lifetimes, active latitudes and longitudes, etc. Evolution of starspots on various time scales allows us to investigate stellar differential rotation, activity cycles and global magnetic fields. Together these constitute the basis for our understanding of stellar and solar dynamos and provide valuable constraints for theoretical models.

Contents

1	Introduction	3
2	The phenomenon of stellar activity	4
2.1	Red dwarfs and BY Dra phenomenon	4
2.2	Solar-type stars	4
2.3	T Tauri stars	5
2.4	RS CVn stars	5
2.5	FK Com stars	6
2.6	W UMa stars	6
2.7	Algols	7
2.8	Degenerated stars	7
3	Observational tools for studying starspots	7
3.1	Photometry	7
3.2	Spectroscopy	8
3.3	Polarimetry	9
3.4	Interferometry	9
3.5	Microlensing	11
4	Diagnostic techniques for studying starspots	11
4.1	Light-curve modelling	11
4.2	Doppler Imaging	13
4.3	Zeeman-Doppler Imaging	15
4.4	Molecular bands modelling	17
4.5	Line depth ratios	19
4.6	Asteroseismology	19
5	Starspot properties	19
5.1	Temperature and filling factor	19
5.2	Magnetic field	21
5.3	Lifetimes	23
5.4	Active longitudes	24
5.5	Differential rotation	26
5.6	Latitudes and butterfly diagrams	27
6	Starspot evolution and stellar activity cycles	28
6.1	Overall activity variations	28
6.2	Flip-flop cycles	30
6.3	Orbital period modulation	32
7	Theoretical models	32
7.1	Dynamo models	32
7.2	Flux-tube models	33
8	Summary	34

1 Introduction

The multitude of activity phenomena on the Sun are related to magnetic fields which are generated by cyclonic turbulence in the outer convection 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. Thus, 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 convection zones.

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 various types of stars.

It was suggested by Skumanich (1972) that rotation plays a crucial role in the generation of stellar activity. This became evident later from the strong correlation of magnetic activity indicators with stellar 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 H α emission (Middelkoop, 1981; Mekkaden, 1985), ultraviolet line fluxes (Vilhu, 1984; Simon and Fekel, 1987) and radio emission (Drake *et al.*, 1989). It was found that cool stars with more rapid rotation 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, BY Dra-type, W UMa-type and Algol-like systems). Rapidly rotating single giants of FK Com-type which are probably formed from coalesced binaries complete the selection of magnetically active stars. An overview of magnetic phenomena on such stars is given in Section 2.

Significant progress in observational tools and diagnostic techniques for studying starspots over the last two decades has advanced our understanding of the nature of stellar activity. Long-term traditional photometric observations reveal active region evolution and stellar activity cycles. High-resolution spectroscopy allows for studies of the structure of active regions and stellar differential rotation with the help of the Doppler imaging technique (Vogt *et al.*, 1987; Rice *et al.*, 1989; Piskunov *et al.*, 1990; Collier Cameron, 1992; Jankov and Foing, 1992; Berdyugina, 1998; Rice and Strassmeier, 2000). Observations of molecular lines provide a unique opportunity for insight into spatially unresolved starspots (Berdyugina, 2002) and unambiguous measurements of starspot temperature (O’Neal *et al.*, 1996). Spectropolarimetry reveals the distribution of magnetic fields on the stellar surface thanks to the Zeeman-Doppler imaging technique (Donati *et al.*, 1997). Novel applications of (spectro-)interferometry, microlensing, asteroseismology, etc., broaden the arsenal of tools and techniques for studying starspots. These are reviewed in Sections 3 and 4.

Since the discovery of rotationally modulated brightness variations due to starspots, a large amount of data has been collected for different types of stars. Brightness and colour variations allow for determining temperature of starspots and their relative area. Doppler images reveal spot distribution which is different from that observed on the Sun. Polarimetric measurements of starspots help to investigate the nature of the underlying magnetic fields. Starspot properties, including their temperature, sizes, magnetic field strengths, lifetimes and distribution over latitudes

and longitudes are reviewed in Section 5.

Time-series observations over decades reveal stellar cycles similar to the 11-year sunspot cycle. On the other hand, persistent active longitudes and a new type of stellar cycle related to them (flip-flop cycle) have been first discovered on cool stars and later on the Sun (Berdyugina and Tuominen, 1998; Berdyugina and Usoskin, 2003). In binaries, orbital period variations suggest long-term changes of the magnetic field distribution in stellar interiors (Hall, 1991b; Rodonò *et al.*, 1995; Lanza *et al.*, 1998a). Such observations provide valuable constraints for stellar and solar dynamo models. An overview of stellar activity cycles and their implications for dynamo theory is given in Sections 6 and 7.

Previous short reviews on starspots and their role in understanding the stellar dynamo were given by Hall (1991a), Lanza and Rodonò (1999a), Berdyugina (2004) and Strassmeier (2005). Also, starspots were thoroughly discussed at the international workshop “Surface Inhomogeneities on Late-Type Stars” (1990, Armagh), IAU Symposium 175 “Stellar Surface Structures” (1995, Vienna) and the First Potsdam Thinkshop “Sunspots and starspots” (2002, Potsdam). The present review covers main tendencies in starspot research for the last two decades.

2 The phenomenon of stellar activity

2.1 Red dwarfs and BY Dra phenomenon

Red dwarfs are main-sequence stars with the mass range from $0.08 M_{\odot}$ to $0.5 M_{\odot}$. The lower mass limit is the critical mass for hydrogen burning in the central cores of stars with solar abundances, while the upper limit corresponds to the spectral class M0. The radii of the red dwarfs span from $0.2 R_{\odot}$ to about $0.6 R_{\odot}$ while their effective temperatures are in the range of 2500 K–4000 K. Thus, red dwarf stars are cooler, smaller and less massive than the Sun. Correspondingly their luminosities range from 0.1% to about 8% of the solar luminosity. They constitute at least 80% of the stellar population in the Galaxy.

Remarkable magnetic activity expressed in extremely strong optical flares was first recorded on UV Cet type stars, while periodic brightness variations were observed in binary systems of red dwarfs as distortions of light curves outside eclipses. Kron (1952) suggested that it is large spots on the stellar surface that cause these distortions. Subsequent observations by Chugainov (1966, 1971) confirmed this hypothesis. Chugainov also showed that spots are much cooler than the undisturbed photosphere and can cover up to 10% of the stellar surface. This appeared to be extraordinary compared to the Sun. The star with such spottedness, BY Dra, became a prototype of a group of stars exhibiting similar behaviour. Also, this type of variability is often called as BY Dra phenomenon. It is common among binaries with G–K dwarfs as well.

A typical light curve of such a star has a near-sinusoidal shape with an amplitude about 0.1 mag. In addition to the starspot activity, these stars possess powerful chromospheres and coronae, whose activity is exhibited in strong UV, X-ray and radio emissions and flares.

2.2 Solar-type stars

Stars on the lower main sequence are known to show chromospheric activity similar to that on the Sun which is detected, e. g., in the Ca II H&K emission (Wilson, 1978). Shortly after the variability of the Sun in the visual continuum (total irradiance) was established during the Solar Maximum Mission (Willson *et al.*, 1981), evidence for continuum variability among single solar-type stars was also revealed (Radick *et al.*, 1982, 1983a,b). The solar variations, which never exceed a few tenths of a percent, are clearly associated with the disk passage of sunspots and result from a blockage of radiant flux (e. g., Fröhlich, 2002). The amplitude of the stellar variability can be as large as several percent in some cases. It appears to be analogues to the solar phenomenon and is caused

by starspots. The survey by Radick *et al.* revealed that with a precision of about 0.003 mag none of the variable stars had a spectral type earlier than F7 or later than K2, although the list of stars included A0 to K8 candidates. Thus, the starspot phenomenon in solar-type stars peaks seemingly at the effective temperature range from 6400 K to 4900 K.

Evidence linking the photometric variability of solar-type stars to the sunspot phenomenon is provided by the fact that continuum variability seems to occur in anti-phase with variations in H α and Ca II H&K emission variations (Dorren and Guinan, 1982). The anticorrelation implies that the surface activity of such stars is confined to localised activity centres that include both emission plages and dark spots, similar to active regions observed on the Sun. Moreover, short-term stellar irradiance variations may be largely explained as rotational modulation by active regions which can persist for several rotation periods (Lockwood *et al.*, 1984).

The onset of solar-type activity at F7 stars with subsurface convection zones was firmly established by the survey of Radick *et al.*, while the reality of the limit at K2 seemed to be less certain. For instance, a higher precision of 0.001 mag achieved aboard the Hubble Space Telescope allowed for detection of periodic brightness variations of the red dwarf Proxima Cen (V645 Cen, M5Ve) with an amplitude of 0.01 mag and a period of 41.6 days, which were interpreted as rotational modulation of starspots in the stellar photosphere (Benedict *et al.*, 1993).

It was firmly established that magnetic activity in solar-type stars declines with age and that it is closely related to a loss of angular momentum throughout the main-sequence lifetime (Skumanich, 1972; Noyes *et al.*, 1984; Baliunas *et al.*, 1995; Güdel *et al.*, 1997). Thus, young stars exhibit high average levels of activity and rapid rotation, while stars as old as the Sun and older have slower rotation rates and lower activity levels.

2.3 T Tauri stars

T Tau stars were discovered and recognised as a new type of variables by Joy (1945). They are associated with interstellar clouds and distinguished by irregular light variations. Emission lines in their spectra resembling the spectrum of the solar chromosphere are superimposed on photospheric absorption spectra of G–M types of low luminosity. Strongly enhanced lithium absorption in their spectra indicates the young age of these stars. T Tau-type stars are thus considered as pre-main-sequence stars of about one solar mass at an age of a few million years, still surrounded by disks of gas and dust remaining from their formation. It was admitted that magnetic fields play an important role in the surface activity of T Tau stars similar to sunspots but strongly enhanced in strength (Petrov and Shcherbakov, 1976; Gershberg, 1982; Appenzeller and Dearborn, 1984), in the flare activity (Guenther and Ball, 1999) as well as in accretion processes and stellar wind phenomena (Hartmann, 1990; Koenigl, 1991).

A subgroup of T Tau stars with weak emission spectra and little, if any, IR excess radiation, called weak-line T Tau stars, show periodic brightness variations with amplitudes up to 0.5 mag which are caused by very large cool active regions (Bouvier and Bertout, 1989; Petrov *et al.*, 1994; Hatzes, 1995; Grankin *et al.*, 1995). Properties of T Tauri type stars were recently reviewed by Petrov (2003).

2.4 RS CVn stars

RS CVn stars represent a class of close detached binaries with the primary component being a G–K giant or subgiant and the secondary a subgiant or dwarf. They show optical variability (outside eclipses) which is characterised by an amplitude up to 0.6 magnitude in the V band and interpreted as the rotationally modulated effect of cool spots on their surfaces. Because of low luminosity of the secondary many of RS CVn systems appear as single-line binaries which is attracting for spectral

analysis. In binaries where both components can be observed the primary appears more active than the secondary.

The identification of a new class of variable stars, named after the prototype system RS CVn, was proposed by Hall (1976) who identified the following classification signatures:

- (1) photometric variability
- (2) Ca II H & K emission lines
- (3) subgiant component well within its Roche lobe
- (4) fast rotation, i.e. almost synchronised binaries with orbital periods of a few days
- (5) orbital period variation.

Since they are tidally locked close binaries, they are also fast rotators. Thus, similar to other cool active stars, RS CVn-type variables are remarkable due to strong chromospheric plages, coronal X-ray and microwave emissions as well as strong flares in the optical, UV, radio and X-ray.

Large amplitude brightness variations of RS CVn stars imply the presence of enormous starspots on their surfaces covering up to 50% of the visible disc (Sect. 5). Remarkable activity and high luminosity of these stars make them favourite targets for light curve modelling, Doppler imaging and spectral line analysis. Most of the present knowledge on starspots is based on studies of this type stars.

2.5 FK Com stars

FK Comae stars were first defined as a new group of active stars in the early 1980s (Bopp and Rucinski, 1981; Bopp, 1981; Bopp and Stencel, 1981). FK Comae stars are late-type giants with spectral types ranging from G to K and rotation periods of only a few days. This indicates very rapid rotation rates. Spectroscopic observations reveal $v \sin i$ values of these stars of ~ 50 – 150 km s^{-1} . Still, these stars do not show any significant periodic radial velocity variations and are therefore most likely single. Three most active stars of this type are FK Com, V1794 Cyg (HD199178) and YY Men. A few other stars have been suggested as candidates for this group, but they exhibit milder activity and slower rotation.

The magnetic activity of FK Comae stars is revealed by rotationally modulated photometric variations with an amplitude in the V-band of 0.1–0.3 magnitude caused by cool asymmetrically distributed spots on the stellar surface. Other characteristics of these stars include a very strong and variable chromospheric emission in the Ca II H&K lines and in the Balmer lines. The photometric and spectroscopic characteristics of FK Comae stars are very similar to those of the very active RS CVn stars (Sect. 2.4), with the exception that RS CVn stars are close binary systems in which the tidal effects produce synchronous rotation and therefore also rapid rotation.

The origin of FK Comae stars is still debated. A few evolutionary scenarios have been proposed for explaining the odd rapid rotation of the late-type single giants. The first idea on the origin of FK Comae stars was that the stars may represent the further evolution of W UMa contact binaries (Sect. 2.6) into a coalesced single star (Bopp and Rucinski, 1981; Bopp, 1981; Bopp and Stencel, 1981). Such a scenario was first considered by Webbink (1976) who calculated the evolution of a contact binary and showed that the mass ratio (secondary/primary) can decrease on an evolutionary time scale until the secondary is completely dissipated, during the primary's initial ascent of the giant branch. The kinematics and age of FK Com support this hypothesis (Guinan and Robinson, 1986). However, as argued by Fekel and Balachandran (1993), the detection of lithium in these active giants is evidence against binary coalescence. They considered a scenario in which the surface convection zone reaches the rapidly rotating core just as a star begins its first ascent of the giant branch, and dredges both high angular momentum material and freshly synthesised Li to the surface. Still, the puzzle is not solved and requires further investigation of these objects.

2.6 W UMa stars

W UMa stars are eclipsing binaries with periods between about 5 and 20 hours showing continuous light variations (Selam, 2004). They consist of two solar-type components surrounded by a common envelope. A large-scale energy transfer from the larger, more massive component to the smaller, less massive one results in almost equalising surface temperatures over the entire system. The components of such a contact binary rotate very rapidly in spite of their old ages ($v \sin i \sim 100\text{--}200 \text{ km s}^{-1}$) as a result of spin-orbit synchronisation due to strong tidal interactions between the stars. W UMa stars are very common, comprising some 95% of eclipsing binary variables in the solar neighbourhood or one star in every 1000–2000 in the same spectral range (Eggen, 1967).

Observations reveal that there are two subclasses of W UMa stars: A-type and W-type systems. The former have longer periods, are hotter, have larger total mass and a smaller mass-ratio and are in better contact. The effective temperatures of the primary and secondary stars in W Uma-type variables are not exactly the same. In W-type the temperature difference is larger and the secondary appears hotter, while in A-type the primary is hotter or almost the same temperature as the secondary. Mullan (1975) suggested that the primary stars in W-type systems appear cooler relative to the secondary due to cool magnetic starspots on their surfaces. Following this idea, photometric peculiarities of such systems have been often interpreted with the help of either cool or hot spots on the binary components. A study of the contact binaries with Doppler imaging technique (Sect. 4.2) reveals that both components can be covered by cool starspots, with a tendency for the primary to be more active than the secondary (Maceroni *et al.*, 1994; Hendry and Mochnacki, 2000; Barnes *et al.*, 2004).

2.7 Algols

Algols are eclipsing binaries consisting of a hot, main-sequence primary star of spectral class B to F and a cool, evolved, less massive secondary. Cool stars in Algols are usually G or K subgiants with outer convection envelopes which are in contact with their Roche lobes. Tidal interactions force most of these stars to rotate synchronously with their orbital motions, producing typical rotational velocities between about 30 and 100 km s^{-1} . The rapid rotation combined with deep convection envelopes produces a variety of magnetic activity phenomena including starspots in these stars, similar to RS CVn (Sect. 2.4), BY Dra (Sect. 2.1) and W UMa binaries (Sect. 2.6). Hall (1989) summarised observations indicating magnetic activity in Algols. In addition to strong Ca II H&K emission, X-ray and radio emission was detected from a number of Algol binaries which indicated the presence of hot coronae associated with the cool stars (White and Marshall, 1983; Stewart *et al.*, 1989; Umana *et al.*, 1989).

Brightness variations due to starspots can be observed in Algols only during primary total eclipses, when the luminous hot components are hidden. Therefore, because of synchronised rotation, only one hemisphere of the cool Algol stars can be observed and the photometric data collected are less detailed than for other spotted binaries. Photospheric continuum variations were nevertheless detected in cool components and attributed to the effect of cool starspots (Richards, 1990; Olson and Etzel, 1993; Varricatt, 2000).

2.8 Degenerated stars

If the magnetic flux is conserved during stellar evolution, white dwarfs should be expected to have magnetic fields of $10^7\text{--}10^8 \text{ G}$. Yet, isolated magnetic white dwarfs are quite rare, comprising about 5% of all white dwarfs (Wickramasinghe and Ferrario, 2000). Observed spectral variations of magnetic white dwarfs on a timescale of hours or days suggest a complex magnetic field distribution on their surfaces. In some cases, spot-like magnetic field enhancements superimposed on a weaker dipole magnetic field can be identified (Landi degl’Innocenti, 1976; Maxted *et al.*, 2000). Similar

structures are most probably present on the surfaces of neutron stars as well. There is a growing evidence, based on X-ray and radio observations, that besides the large-scale dipolar magnetic field, isolated neutron stars possess small-scale magnetic field enhancements (Geppert *et al.*, 2003). Current theory predicts that such structures can be generated from strong subsurface toroidal fields on both white dwarfs and neutron stars.

3 Observational tools for studying starspots

3.1 Photometry

Since the discovery of the first indications of starspots, photometry remains the most common technique for studying stellar activity. Thanks to efforts of individual observers, more or less regular observations of spotted stars began in 1970s. They are currently supported by a great number of Automatic Photometric Telescopes (APTs) which provide every-night routine measurements for a big sample of stars. At present, more than a dozen APTs with apertures of 20 cm to 1.2 m operate around the world (see Table 1). The accuracy of ground-based APTs is about 2–5 mmag.

Observatory/APT	Location	Aperture	Filters
Catania	Mt. Aetna, Sicily http://www.ct.astro.it/sln/apt80.html	2x80cm	UBV
Fairborn	Patagonia, Arizona http://www.fairobs.org	25-80cm	UBV
Four-College*	Patagonia, Arizona	80cm	UBVRI
Phoenix 10**	Patagonia, Arizona http://www.fandm.edu/Departments/Astronomy/Phoenix10/Phoenix10.html	25cm	UBV
SAAO	Sutherland, South Africa http://www.sao.ac.za/apt/	75cm	UBVRI
SpectraBot ⁺	Morgan-Monroe, Indiana http://www.astro.indiana.edu/spectrabot.html	1.25m	UBVRI(CCD)
STELLA II/AIP	Teide, Tenerife	80cm	UBVRI(CCD), <i>uvby</i> , H α
Strömgren APT ⁺⁺	La Silla, Chile http://www.astro.ku.dk/ijaf/0p5m.html	50cm	<i>uvby</i> , H β
Wolfgang-Amadeus [#]	Patagonia, Arizona http://www.aip.de/groups/activity/APT/	2x75cm	VRI, <i>by</i>

Table 1: Automatic Photometric Telescopes collecting data for studying starspots. Remarks: * Villanova, Cidadel, Charleston College, University of Nevada; ** Franklin & Marshal College; + University of Indiana; ++ Copenhagen Observatory; # University of Vienna.

A vast amount of photometric data have been also obtained by the ESA mission HIPPARCOS with the accuracy down to 1 mmag (van Leeuwen *et al.*, 1997). Future space missions aiming at studying stellar oscillations and detection of earth-size exoplanets will also provide immense high-precision photometry of nearby stars which can be used for studying starspots:

COROT <http://sci.esa.int/science-e/www/area/index.cfm?fareaid=39>,

Gaia <http://sci.esa.int/science-e/www/area/index.cfm?fareaid=26>,

Kepler <http://www.kepler.arc.nasa.gov/>,

MOST <http://www.utias-sfl.net/microsatellites/MOST/MOSTIndex.html>

3.2 Spectroscopy

Spectroscopy is one of the main tools of modern astrophysics. Almost all we know about the physical properties of astrophysical objects comes from the analysis of their spectra. Studying starspots requires high-resolution spectrographs ($\Delta\lambda/\lambda \geq 50\,000$) with high-sensitivity detectors which have become available for the past two decades at mid and large aperture telescopes. Among 8-10m telescopes it is worth to mention UVES at VLT, HIRES at KECK, HRS at the Hobby-Eberly Telescope (HET) and HDS at Subaru. In addition, there are about 10 high-resolution spectrographs on 4m class telescopes and even more on 2m class telescopes. Most of them are echelle cross-dispersed spectrographs allowing for a wide wavelength range in the optics. A recent overview of the currently available high-resolution spectrographs and future projects was given by Pallavicini (2002).

A study of starspots involves routine monitoring and data collection for a relatively large sample of stars. A great help comes from using robotic telescopes. The first dedicated robotic telescope T-13 was developed at the Tennessee State University and has started its operation in 2003 at the Fairborn observatory, Arizona (<http://schwab.tsuniv.edu/t13/description.html>). It is a 2m telescope with a spectrograph working at two resolutions, 34000 and 90000, and full wavelength coverage in the optical. The second spectroscopic robotic telescope STELLA I of 1.2m is being built by AIP, Hamburg Observatory and IAC. It is expected to start operation in 2005 on Tenerife and will be equipped with echelle spectrograph of maximum 50000 resolution (<http://www.aip.de/stella/index.php?home>). The two telescopes are planned to be complementary in studying starspots, as they are separated by about 95° in longitude and, thus, will allow prolonging an observing night by 6 hours.

3.3 Polarimetry

The most direct way to detect and study stellar magnetic fields is to use polarimetric techniques. Polarimetry of stars other than the Sun is however a rather challenging task and represents a relatively small field of stellar astrophysics. This, on one hand, is due to limited instrumental capabilities and, on the other hand, due to disk-integrated observations of the Stokes parameters. The latter results in significant cancellation of the signal from regions of mixed polarity fields and, thus, only large-scale magnetic fields can be detected from disk-integrated polarimetric measurements, which still requires the accuracy of the order $10^{-3} - 10^{-4}$. Such low polarimetric signals from starspots require large collecting areas of telescopes. An overview of the existing instruments and future projects was made by Semel and López Ariste (2001). A list of the available instruments is given in Table 2.

Instrument	Telescope/Observatory	Resolving power	Wavelengths, nm
SEMPOL*/UCLES	AAT/Siding Spring(3.9m)	70 000	370–870
MuSiCoS**	TBL(2m)/Pic-du-Midi	35 000	450–660
SARG SP	TNG(3.6m)/Tenerife	46 000–164 000	370–1020
ESPaDONS	CFHT(4m)/Hawaii	70 000	370–1000

Table 2: High-resolution spectropolarimeters for studying starspots. Remarks: * SEMPOL is a visitor instrument, ** MuSiCoS will soon be replaced by NARVAL (R~50,000).

The new generation large telescopes are not yet equipped with high-resolution spectropolarimetric capabilities. The only existing project is PEPSI at the double 8m LBT (Strassmeier *et al.*, 2004). Low-resolution spectropolarimetry is possible with FORS1 at VLT (Appenzeller *et al.*, 1998). A promising approach to high-precision polarimetry is provided by a ZIMPOL-type spec-

tropolarimeter, which is a transportable system being combined with a spectrograph (Stenflo, 2001).

Magnetic fields in G, K and M main sequence stars have been deduced from the broadening of line profiles (e. g., Valenti *et al.*, 1995) or even Zeeman-split spectral lines in M-type dwarf flare stars (Johns-Krull and Valenti, 1996). Using SEMPOL at AAT, Donati *et al.* (1997) reported detection of Zeeman polarisation in several kinds of active stars, including RS CVn systems, a dwarf flare star of BY Dra type, a FK Com star, and a T Tau star. Several new detections have been made with MuSiCoS (Wade, 2003).

3.4 Interferometry

Optical interferometry can be a powerful technique to image inhomogeneities on stellar surfaces. Direct observations of starspots will be the key constraints for models of stellar activity.

A stellar long-baseline interferometer consists of an array of several separate telescopes, which redirect starlight to a central location where interference fringes are formed. The angular resolution that the interferometer can achieve depends on the baseline (the telescope separation) while, for a single telescope the resolution is defined by its aperture diameter. The angular resolution is proportional to the ratio of the wavelength to the baseline of the interferometer or the diameter of the telescope. The largest existing telescope is 10 m in diameter, whereas the largest interferometer has a baseline of 600 m, giving the latter a factor of 60 increased resolving power.

If the interferometer is coupled with a spectrograph, fringes can be analysed along spectral domains. Such a spectro-interferometer allows for eliminating disturbances by the Earth atmosphere and measure differential phases between two wavelengths, i. e. carry out colour differential interferometry (Petrov, 1988). For magnetically active stars such observations can provide orientation of the stellar rotation axis with respect to the line of sight (Lagarde *et al.*, 1995), which is important for interpretation of spectroscopic and photometric observations of spotted stars. Also, differential fringe phases can be used to locate spots on the stellar surface (Wittkowski *et al.*, 2002; Jankov *et al.*, 2003; Rousselet-Perraut *et al.*, 2004), even in such difficult cases as pole-on and equator-on orientations of the star which cannot be resolved by traditional Doppler spectroscopy. In addition, the stellar differential rotation rate and the inclination angle can be disentangled (de Souza *et al.*, 2004).

A spectro-interferometer equipped with a polarimeter allows for recording the visibility function and fringe phase for different polarisation states and, thus, can provide measurements of local magnetic fields on the stellar surfaces (Rousselet-Perraut *et al.*, 2004), which is the key information for studying stellar magnetic activity.

A list of the available and planned for the near future instruments is given in Table 3.

Instrument	Location	Base, m	Resolution	Wavelengths
GI2T/REGAIN	Nice http://www.obs-nice.fr/fresnel/gi2t/en/		R=28500-35000*	400–850 nm
AMBER	VLT/Paranal http://www.obs-nice.fr/amber/	200	R=10000**	600–2500 nm
VINCI	VLT/Paranal http://www.eso.org/projects/vlti/instru/vinci/	200		8–13/17–26 μ m
MIDI	VLT/Paranal http://www.eso.org/projects/vlti/instru/midi/index.html	200		
PRIMA	VLT/Paranal http://www.eso.org/projects/vlti/instru/prima/index.prima.html	200	0.01 mas	
Keck I/II	Hawaii http://planetquest.jpl.nasa.gov/Keck/keck_index.html	85	5–24 mas	1–10 μ m

OHANA	Hawaii	800	0.5 mas 0.3 mas	K band J band
	http://www.cfht.hawaii.edu/OHANA/			
SI	Space based		0.06 & 0.12 mas	155 & 280 nm
	http://hires.gsfc.nasa.gov/~si/			
Darwin	Space based	20–200		
	http://ast.star.rl.ac.uk/darwin/			
SIM	Space based		0.004	UV
	http://planetquest.jpl.nasa.gov/SIM/sim_index.html			

Table 3: A list of existing and planned interferometers suitable for studying starspots. Remarks: * spectrometric interferometer including a polarimetric mode; ** imaging and spectroscopic instrument.

3.5 Microlensing

Gravitational imaging of stellar photospheres is a potentially useful tool for stellar astrophysics. Detecting spots in ways different from, e. g., rotationally induced modulations of the stellar brightness or spectral line profiles could bring considerable insight into their properties. For instance, microlensing can help to disentangle the temperature and spot area. Moreover, it provides an opportunity for probing starspots on the surfaces of slow rotating stars, which are unsuitable candidates for the Doppler imaging technique.

A microlensing event has been recently used for high-precision, multicolour measuring a limb darkening profile on the surface of a K3 giant and revealed a significant disagreement between the observed and predicted from atmospheric models disk brightness distribution (Fields *et al.*, 2003). The Optical Gravitational Lensing Experiment (OGLE) survey of bulge giants provided photometric evidence for stellar spots via microlensing events (Udalski *et al.*, 1995). Modelling of the spots on the stars selected from the OGLE database was undertaken by Guinan *et al.* (1997). Further theoretical investigation of possible detections of stellar spots by gravitational microlensing was carried out by Heyrovský and Sasselov (2000) and Hendry *et al.* (2002). They concluded that starspots generally produce a clear signature only for transit events. Moreover, this signature is strongly suppressed by limb darkening for spots close to the limb, although spots may still be clearly detected for favourable lens trajectories. It was found also that in order for microlensing events to be an effective starspot imaging tool, intensive temporal sampling throughout the transit is needed.

4 Diagnostic techniques for studying starspots

4.1 Light-curve modelling

Since the discovery of stellar photometric variations due to cool spots, generally two approaches are used to model such variations and to deduce starspot properties. One is based on a trial-and-error direct light-curves modelling (LCM) when assuming a number of circular (or of other pre-defined shape) spots causing the variations. Numerical techniques employing this approach have been developed by Budding (1977), Vogt (1981), Rodonò *et al.* (1986), Dorren (1987), Strassmeier (1988) and Kiurkchieva (1990). A technique taking into account time evolution of starspots has been proposed by Strassmeier and Bopp (1992). It allowed for detecting spot appearance and disappearance on time scales from a few to a hundred days. A zonal model with (near-)equatorial inhomogeneous bands of spots was considered by Eaton and Hall (1979) and Alekseev and Gershberg (1996).

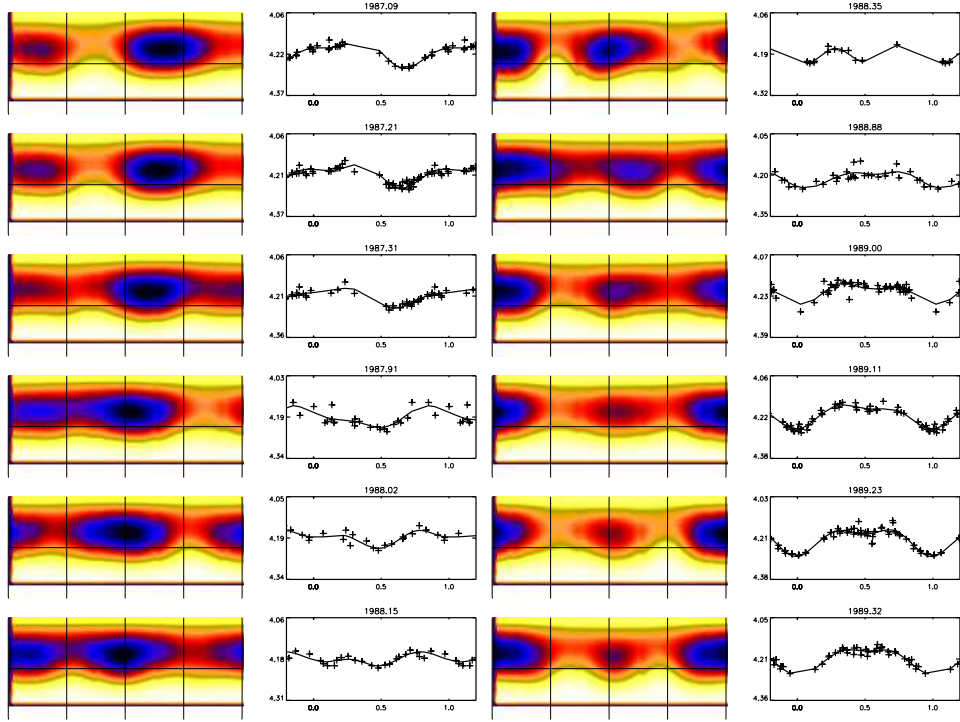


Figure 1: *Light curve inversion results for the RS CVn star σ Gem (Berdyugina & Henry, in preparation). In the images, spot filling factor is larger in darker regions. Observed and calculated V-band light curves are shown by crosses and lines, respectively. The images also illustrate a flip-flop event occurred in 1988: the active region near the phase 0.5 has diminished for about one year, while the region near the phase 0.0 has increased in size (see discussion of the flip-flop phenomenon in Section 6.2).*

A disadvantage of the above mentioned models is that they have many free parameters and the shape of spots or of spot distribution is to be assumed. Moreover, the solution is not unique. To avoid many assumptions, an alternative approach performing light-curve inversion (LCI) into an image of the stellar surface has been developed. An inversion technique is usually applied to the photometric light curves in the two temperature approximation. The model assumes that, because of low spatial resolution, the intensity of each pixel on the surface, I_i , contains contributions from both temperature components, the hot photosphere, I_p , and cool spots, I_s , weighted by the fraction of the surface covered with spots, f_i (spot filling factor):

$$I_i = f_i I_s + (1 - f_i) I_p, \quad (1)$$

with $0 \leq f_i \leq 1$. The instantly observed stellar flux is the integral of the intensity contributions from the surface elements seen at a given rotational phase. The inversion of the light curve results in a distribution of the spot filling factor over the stellar surface, i. e. stellar image. Figure 1 shows examples of light curves and maps of the spot filling factor obtained from them for the RS CVn type star σ Gem. Since a light curve represents a one-dimensional time series, the resulting stellar image contains information on the spot distribution only in one direction, in longitudes, while spot extents and locations in latitudes remain uncertain. As a result, maximum spot concentration always appears at the central latitude of the stellar disk whose value depends on the assumed inclination of the rotational axis. Because of the projection effect and limb darkening, images show more well defined structures than the light curves and, therefore, are very useful for determining longitudes of spot concentrations. Numerical techniques based on such an approach have been elaborated by Messina *et al.* (1999) and Berdyugina *et al.* (2002).

More detailed information on the spot pattern from light curves can be obtained in the case of eclipsing binaries by the eclipse mapping technique. This method employs the opportunity to scan the stellar disk in finer detail by the eclipsing companion. The inversion techniques based on the Maximum Entropy and Tikhonov regularisation methods (see Sect. 4.2) were developed by Rodonò *et al.* (1995), Collier Cameron (1997) and Lanza *et al.* (1998a).

Inversion or modelling of light-curves is clearly less informative than techniques which are based on spectroscopic observations. Continuous and frequent photometric data allow though for conclusions on longitudinal spot patterns and their long-term evolution (Sect. 6).

4.2 Doppler Imaging

During the last two decades the Doppler imaging technique has been extensively employed for studying starspots on active stars. The main idea of the technique is to use high-resolution spectral line profiles of rapidly rotating stars for mapping the stellar surface. This idea was first formulated by Deutsch (1958), while the first inversion technique with minimisation was developed by Goncharskii *et al.* (1977). It was first used for mapping chemical peculiarities on the surface of Ap stars. Modelling of photometric variations of late-type active stars has revealed that cool starspots are often quite large, covering up to 20% of the stellar surface. Such starspots should have resulted in noticeable line profile variations which were first observed in spectra of the RS CVn-type star HR1099 and from which the first Doppler image of a spotted star was obtained by Vogt and Penrod (1983).

The Doppler imaging technique aims to restore starspot distribution information which is contained in time varying line profiles of rotating stars. If the star rotates rapidly enough, so that the rotation broadening of a line profile is significantly larger than the local line profile at a single point on the stellar surface, then a cool spot on the stellar surface will result in a “bump” in the profile (Fig. 2). This “bump” moves across the profile, as the star rotates, with the velocity amplitude depending on the spot latitude. Inversion of a time series of the stellar line profiles results in a map, or image, of the stellar surface.

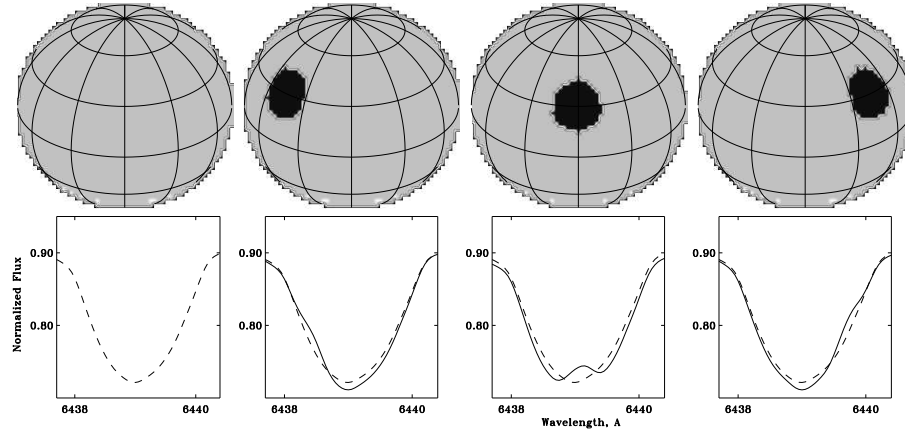


Figure 2: *Spectral line profiles for a model fast rotating star with no spots (dashed line) and with a spot moving across the disk as the star rotates (solid line). See also animation at <http://www.astro.phys.ethz.ch/staff/berdyugina/private/StellarActivity/StellarAct.html>*

An assumption on the nature of starspots is the main part of the model calculations. Cool spots will modify the flux integrated over stellar disk. Therefore, the intensity of radiation $I(T(s), \lambda, \mu)$ emitted by the stellar surface from the point s in the direction μ at the wavelength λ is defined by the local temperature $T(s)$ which is assumed to be the effective temperature of the model atmosphere used for the calculation of the local line profile at the point s . Integration over the stellar disk, given rotational phase ϕ and set of wavelengths, results in the residual flux $r_\lambda(\phi)$ which contains information on the temperature distribution on the stellar surface $T(s)$ and, therefore, is to be compared with the observed residual flux $r_\lambda^{\text{obs}}(\phi)$. Thus, the integration determines the direct transformation for a subsequent inversion. A comparison of the residual fluxes determines the discrepancy function $D(T)$. By minimising $D(T)$, one can obtain a unique solution with minimum variance. Such a solution is not however feasible due to noise in data. Smoothing the noise results in a multitude of different stable solutions. Searching for the unique and stable solution is a so-called ill-posed inverse problem, and there are different approaches and methods developed for solving it.

A common way of choosing the unique solution with a given level of goodness of the fit is to invoke some additional constraints $R(T)$, which usually determine special properties of the solution. Therefore, the original ill-posed minimisation problem is replaced by another, which has a unique solution:

$$\Phi(T) = D(T) + \Lambda \cdot R(T), \quad (2)$$

where Λ is a Lagrange multiplier and $R(T)$ is a regularisation functional, which makes the solution unique. The value of Λ should be selected so that if $T(s)$ minimises $\Phi(T)$ then the rms deviation of the fit of the profiles is of the order of the noise in the observations.

Methods developed with such assumptions differ by the definition of $R(T)$. The Tikhonov regularisation method (TRM) applied by Goncharskii *et al.* (1977) and Piskunov *et al.* (1990) claims the solution to be with the least gradient of the parameters, and $R(T) = \text{grad}T$. The Maximum Entropy method (MEM) applied by Vogt and Penrod (1983) searches for the solution with the largest entropy, and $R(T) = T \log T$. Generally, the two methods assume that the observed phenomena possess properties $R(T)$, which cannot be known *a priori*. For instance, in case of surface imaging both above assumptions cannot be proved by the observations. In fact, for choosing a unique solution, one indeed needs some additional information, and if it is not available,

it is substituted by some plausible assumptions, which lead to an apparently acceptable solution but with an unknown bias. One should note, however, that in case of data of high quality and quantity the role of the regularisation is reduced, and the solution is approaching to the maximum likelihood solution, which in this case could be also considered as an acceptable result.

An alternative Occamian approach (OA) to inverse problems was developed by Terebizh (1995) and applied to the Doppler imaging problem by Berdyugina (1998). In the Occamian approach the choice of a solution is based on the analysis of information contained in observations and the transformation model. Building the Fisher information matrix F with eigenvectors V one defines a new reference frame with coordinates Y which are linear combinations of the unknown parameters T :

$$Y = V^T T, \quad T = VY. \quad (3)$$

The new coordinates Y comprise principal components of the solution. Small eigenvalues of F indicate principal components with relatively large errors of the solution, so that the error ellipsoid is extremely elongated in these directions. Moreover, in case of a lack of data some of the eigenvalues become zero, and the corresponding parameters are linearly dependent. Therefore, only a part of the principal components $Y^{(p)}$ completely exhausts the available information on T . In such a case the $Y^{(p)}$ are estimated instead of T , while other principal components with not enough information are assumed to be zero. Then, the transformation

$$\tilde{T} = V\tilde{Y}^{(p)} \quad (4)$$

leads to the desired unique and stable solution \tilde{T} . Thus, the solution in the Occamian approach is the one which statistically satisfactorily fits the observed data with a minimum set of $\tilde{Y}^{(p)}$. Such a solution is unique because of the choice of p and stable because of removing those principal components which contain no significant information but noise. It is not constrained with any artificial assumptions. Another advantage of the Occamian approach is that the inverse Fisher information matrix gives estimates of the variances of the solution.

A number of numerical codes for Doppler imaging of cool stars based on the Maximum Entropy method have been developed by Vogt *et al.* (1987), Rice *et al.* (1989), Collier Cameron (1992, 1995), Jankov and Foing (1992) and Rice and Strassmeier (2000). Piskunov *et al.* (1990) used the Tikhonov regularisation method and Berdyugina (1998) the Occamian approach. A technique based on the CLEAN-like approach was suggested by Kürster (1993) and one based on the interferometry by Jankov *et al.* (2001). Effects of different numerical methods was investigated by Piskunov *et al.* (1990) (MEM and TR), Kürster (1993) (CLEAN and MEM) and Korhonen *et al.* (1999) (TR and OA). As mentioned above, the difference is diminished when the data used are of high quality.

Important inputs for Doppler imaging which affect significantly the result are stellar atmosphere models, atomic and molecular line lists and stellar parameters. Errors in calculations of local line profiles have a strong effect on the inversion. They easily cause artificial features in maps, like polar caps and belts of cool and hot spots (Unruh and Collier Cameron, 1995). The same features are easily obtained in case of a wrong value of the stellar rotational velocity and a wrong estimate of the effective temperature of the star (Berdyugina, 1998). Spot latitudes strongly depend on the inclination angle of the rotational axis to the line of sight. Various tests showed that capabilities of the technique are limited in the equatorial region where spots are recovered with reduced area and contrast. Sub-equatorial spots cannot be restored, especially at lower inclinations. A recent overview of the strengths and weaknesses of the Doppler imaging technique was given by Rice (2002).

Doppler imaging of a single star with the inclination angle of the rotational axis to the line of sight close to 90° (equator-on) experiences difficulties in recovering spots on either side of the stellar equator because of the symmetry of Doppler shifts in line profiles with respect to the

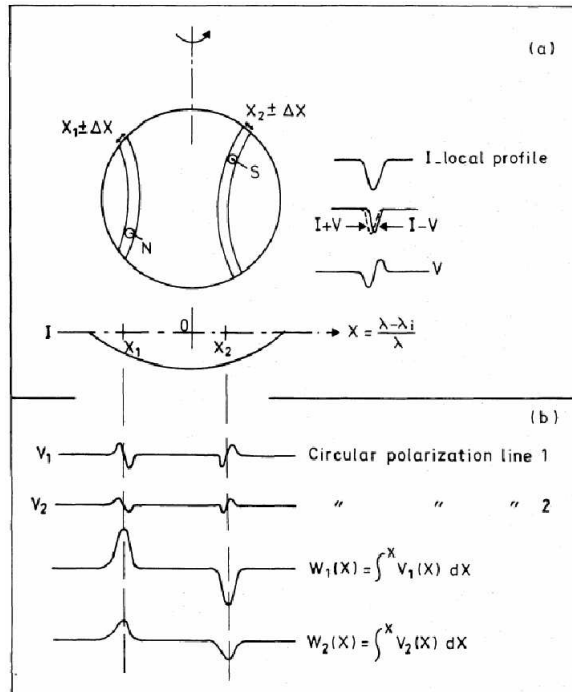


Figure 3: Observed circular polarisation in the spectrum (panel b) is a sum of opposite polarity Stokes V profiles due to spots located at different Doppler shifts (panel a). From Semel (1989). See also explanatory animations by P. Petit at <http://webast.ast.obs-mip.fr/people/petit/zdi.html>

equator. In a binary system such an inclination angle of the binary orbit would lead to eclipses of the components. For an eclipsing binary, the equatorial symmetry problem is reduced, and the quality of the mapping can be improved (Vincent *et al.*, 1993).

For the last two decades more than 60 cool stars have been studied with the surface imaging technique (see for an overview Strassmeier, 2002). Out of them 29 are single stars and 36 are components in close binaries. A dozen of stars have been monitored for several years. The total number of Doppler images is 245 as of June 2002 (<http://www.aip.de/groups/activity/DI/summary/>). The results obtained with the Doppler imaging techniques are discussed in Sect. 5. Examples of stellar Doppler images are shown in Figs. 6 and 15.

4.3 Zeeman-Doppler Imaging

As an extension of the temperature and abundance mapping of the stellar surface, a magnetic Zeeman-Doppler imaging (ZDI) method was introduced by Semel (1989) and further developed by Donati *et al.* (1989), Semel *et al.* (1993), Brown *et al.* (1991) and Donati and Brown (1997). The technique is based on the analysis of high-resolution spectropolarimetric data and allows for disentangling magnetic field distribution on the stellar surface due to different Doppler shifts of Zeeman-split local line profiles in the spectrum of a rotating star (Fig. 3). In the absence of rotation, the net circular polarisation signal in spectral lines would be zero due to mutual cancellations of contributions of regions of opposite field polarity.

Zeeman signatures in atomic lines due to starspots are expected to be extremely small, with typical relative amplitudes of 0.1%. Detecting them requires measurements of polarisation with

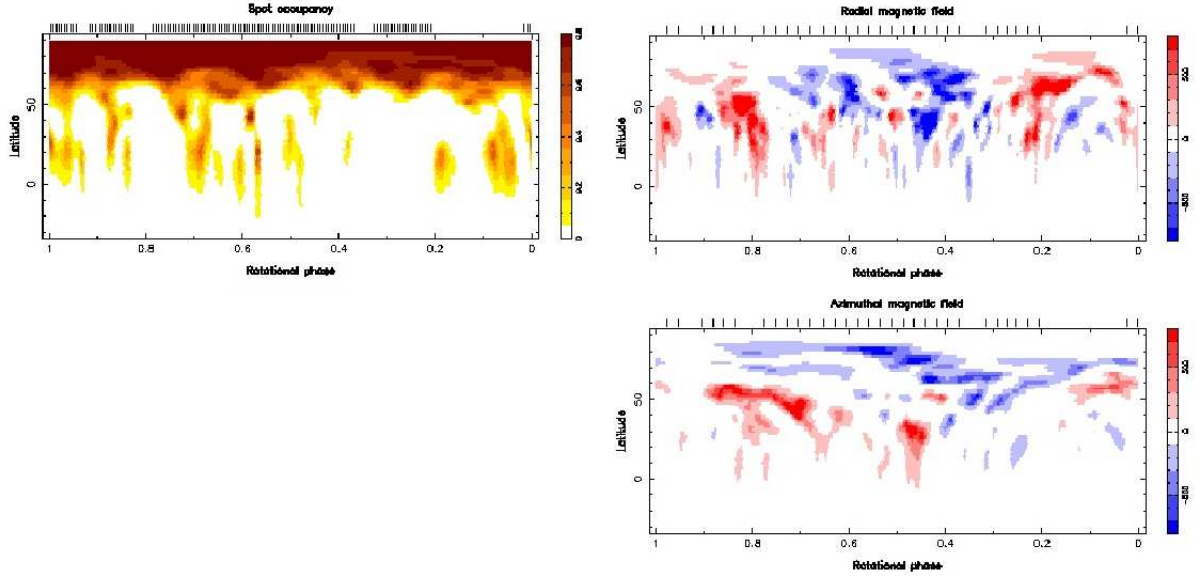


Figure 4: Zeeman-Doppler images of the young active K0 dwarf AB Dor. From Donati and Collier Cameron (1997).

noise level in Stokes V lower than 10^{-4} , while the current instrumentation allows for the best relative noise level of 10^{-3} . Semel (1989) and Semel and Li (1996) proposed a multi-line approach for increasing the signal-to-noise (S/N) ratio of the measured polarisation, which has resulted in first detection of the circular polarisation signal in a cool star (Donati *et al.*, 1997). A combination of Stokes V profiles using a multi-line technique called Least Squares Deconvolution (LSD) is based on the weak field approximation, i. e. one assumes that the magnetic splitting of spectral lines is smaller than their local Doppler broadening. In this case the Stokes V signal is proportional to the derivative of the intensity profile $I(v)$:

$$V_i(v) \propto g_i \lambda_i I_i'(v), \quad (5)$$

where g_i is the effective Landé factor and λ_i is the wavelength of the i th spectral line. It is assumed further that the local line profiles are self-similar and scale in depth and width with the central depth d_i and wavelength, i. e.

$$I_i'(v) = d_i Z(v). \quad (6)$$

The LSD Stokes V profile can be obtained as a sum over many individual lines:

$$V(v) = \sum_i g_i \lambda_i d_i Z(v). \quad (7)$$

Blends and splitting patterns should be treated explicitly for each line. The gain factor in the S/N ratio can be as large as 30 when using more than 2000 line profiles. The LSD technique allowed for detection of magnetic fields on various types of cool stars, from pre-main-sequence stars to evolved giants (Donati *et al.*, 1997). It was also used for temperature mapping using Stokes I observations of faint stars with short rotational periods for which high signal-to-noise spectra cannot be obtained through longer exposure times.

Applying an inversion technique, similar to those used for Doppler imaging (Sect. 4.2), to all four Stokes parameters one can recover the distribution of the temperature and magnetic field vector

over the stellar surface. Two numerical codes based on the Maximum Entropy method (Brown *et al.*, 1991) and the Tikhonov regularisation (Piskunov and Kochukhov, 2002) have presently been developed. In practice, however, measuring the full Stokes vector for cool stars is difficult, because magnetic signatures in Stokes Q and U are considerably smaller than in Stokes V . Obtained Zeeman-Doppler images of cool stars are based on measurements of only Stokes I and V are certainly not unique and provide limited information for the interpretation. In order to limit the solution (Piskunov and Kochukhov, 2002) suggested a special type of regularisation based on spherical harmonic expansion. In this case the solution is forced to take the form of such an expansion which is acceptable only for stars with clearly dominating multipole structures, like e.g. Ap stars.

In the inversion procedure three components of the magnetic field vector are generally represented by radial, azimuthal and meridional fields. To some extent they contribute to the line of sight component observed in Stokes V at different rotational phases and different Doppler shifts. For instance, the radial field will dominate the Stokes V near the centre of the stellar disk, while the azimuthal field will be most noticeable in the circular polarisation near the stellar limb. This allows to recover some parts of the magnetic field components from Stokes V observations. An example of such restoration is shown in Fig. 4. When interpreting the results of Zeeman-Doppler images obtained only from Stokes I and V , one has to take into account that the magnetic field distribution is underdetermined for each component and that there might be a cross-talk between different components.

4.4 Molecular bands modelling

Molecular lines provide evidence of cool spots on the surfaces of active stars. If the effective temperature of the stellar photosphere is high enough, molecular lines can only be formed in cool starspots. The first detection of molecular bands from starspots was reported by Vogt (1979) for a star whose spectral type K2 was not compatible with the presence of TiO and VO bands. From the relative strengths and overall appearance of the molecular features, an equivalent spectral type of the spot spectrum was estimated as late as M6. A phase-dependent variation in the strength of the TiO band was detected by Huenemoerder *et al.* (1989), with TiO being strongest at the photometric minimum. This confirmed that the photometric modulation is indeed caused by cool spots. Moreover, a comparison of photometric variations with TiO band strengths provided reliable estimates of unspotted stellar magnitudes (Berdyugina *et al.*, 1998a, 1999b).

A technique for determining spot filling factors and temperatures from molecular band modelling (MBM) was suggested by Huenemoerder and Ramsey (1987) and further developed by Neff *et al.* (1995) and O’Neal *et al.* (1996). They modelled the observed spectrum by combining spectra of suitable standard stars of different effective temperatures weighted by spot filling factor and continuum surface flux ratio. For instance, observations in two TiO bands of different temperature sensitivity, at 7055Å and 8860Å, were combined to estimate the area and the temperature of spots.

Since TiO lines are only formed in starspots on the surfaces of G-K giants and subgiants, polarisation observations in these lines can provide measurements of magnetic fields directly in spatially unresolved spots. As shown in Fig. 5, the TiO lines at 7055Å are rather strongly magnetically sensitive, having effective Landé factors up to 1 (Berdyugina and Solanki, 2002; Berdyugina *et al.*, 2003). The wavelength separation between rotational lines in the band is small and lines of low rotational numbers (larger splitting) almost coincide with those of high numbers (smaller splitting) in the band head. Nonetheless, a clear Stokes V signal should be measured from starspots (Berdyugina (2002)).

An excess of the absorption in the infrared OH lines at 1.5 μm due to starspots has been detected by O’Neal and Neff (1997) and O’Neal *et al.* (2001). Since OH lines can be observed at higher temperature than TiO, starting from 5000 K and below, they can be used for studying starspots

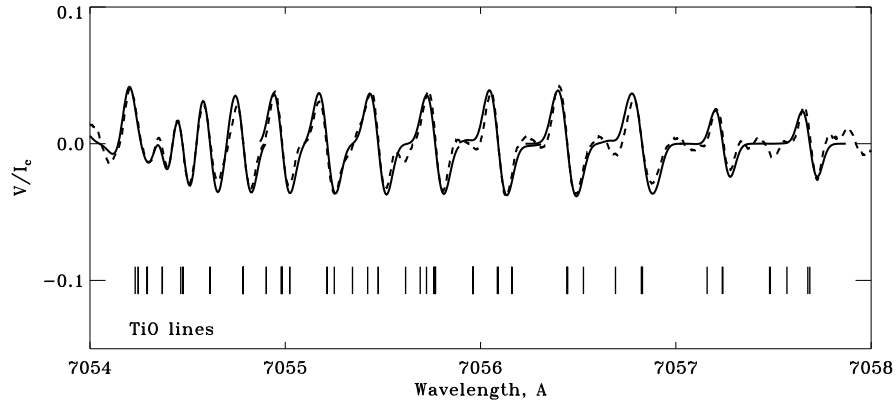


Figure 5: *Calculated (solid line) and observed (dashed line) Stokes V profile for the TiO $\gamma(0,0)R_3$ band head in a sunspot. The field strength is 3 kG and the filling factor is 0.75 for an angle between the magnetic vector and the line of sight of 0° . Vertical dashes indicate positions of lines included in the spectral synthesis. From Berdyugina (2002).*

on hotter stars. Otherwise, they are contaminated by the photospheric contribution, which should be carefully taken into account. On the other hand, OH lines provide a greater temperature range over which starspots can be detected through molecular absorption features.

4.5 Line depth ratios

Spots on slowly rotating stars can be studied by photometric and spectroscopic molecular line techniques. To discriminate between spot temperature and spot area, these techniques use at least two independent measurements, brightness and colour in photometry and different molecular bands in spectroscopy. The Line Depth Ratio (LDR) technique offers an opportunity to resolve temperature variations with unprecedented accuracy of less than 10 K (Gray, 1996). A technique for studying starspots with LDR was developed by Catalano *et al.* (2002). It is based on the analysis of depth ratios of a pair of lines, one insensitive and one very sensitive to temperature. Due to presence of a dark spot that produces a decrease of say 10% in the continuum, the depth of both lines would be equally affected and reduced by 10%, while their depth ratio would remain unchanged. Due to the lower temperature of the spot, however, the temperature sensitive line will change its intrinsic depth and, thus, the depth ratio of the two lines will change as well. The amount of depth ratio variation depends on the temperature variation and the fraction of surface covered by spots. Catalano *et al.* (2002) proposed 10 pairs of lines in the 6100–6200 Å wavelength range and calibrated them against effective temperatures of main sequence stars and giants. Their results for active stars are discussed in Sect. 5.1. Frasca *et al.* (2005) combined the LDR technique with the analysis of simultaneous light curves. This technique enables disentangling the spot temperature and area.

4.6 Asteroseismology

Magnetic activity influences the internal stellar structure. In the case of the Sun, this is observed as shifts of eigenfrequencies of global modes of solar oscillations (Woodard and Noyes, 1985). Mode frequencies increase with magnetic activity: for the 11-yr cycle, low-degree mode frequencies are shifted by the order of 10^{-4} . The study of high-degree modes has revealed that frequency shifts are

caused by structural perturbations near the solar surface which are localised in latitude (Libbrecht and Woodard, 1990). Thus, measurements of frequency shifts on solar-type stars is a potential tool for studying starspot latitudes. Lanza and Rodonò (2002) studied the possibility for asteroseismic tests of the internal structure of magnetically active close binaries. Gizon (2002) investigated prospects for detecting stellar activity through asteroseismology. He concluded that observations of solar-like oscillations contain measurable information about the latitudinal distribution of stellar activity under the following conditions: the stellar rotation is high enough to resolve frequencies of different azimuthal numbers, stellar activity is strong enough to produce significant spotted area, and the inclination angle of the stellar rotation axis is larger than 40° . Still, observations should be long and continuous, which can be provided by the future space missions COROT (<http://iaa13u.iaa.csic.es/corot/mainE.html>) and Kepler (<http://www.kepler.arc.nasa.gov/>).

Stellar differential rotation for solar-type stars can be measured through asteroseismology as well (Gizon and Solanki, 2004). Rotationally split frequencies of global oscillation provide information about rotation at different latitudes depending on the azimuthal order, m , of the mode of pulsation. Since the $m=\pm 1$ and $m=\pm 2$ components of quadrupole oscillations can be observed simultaneously in asteroseismology, rotational frequency splittings can be inverted to provide an estimate of the difference in stellar angular velocity between the equator and 45° latitude. The precision of the method depends on the value of the mean rotation and on the inclination angle between the rotation axis and the line of sight.

5 Starspot properties

5.1 Temperature and filling factor

Observed amplitudes of the optical brightness modulation imply that a large fraction of the stellar photosphere is covered by cool starspots. The largest ever observed light-curve amplitude $\Delta V=0.65$ mag of a spotted star was reported for the weak-line T Tauri type star V410 Tau (Strassmeier *et al.*, 1997). Two RS CVn-type stars HD12545 and II Peg have been observed at the largest $\Delta V=0.63$ mag by Strassmeier (1999) and Tas and Evren (2000), respectively. Such big amplitudes in brightness variations are accompanied by large in-phase variations of a colour, suggesting the presence of cool spotted areas covering up to 20% of the entire stellar surface or about 40% of the stellar disk (Fig. 6).

Our current knowledge on starspot temperatures is based on measurements obtained from simultaneous modelling of brightness and colour variations, Doppler imaging results, modelling of molecular bands and atomic line-depth ratios, the latter being the most accurate method. A representative sample of starspot temperatures for active dwarfs, giants and subgiants is collected in Table 5 and plotted in Fig. 7. As seen from the plot, there is a clear tendency for spots to be more contrasting with respect to the photosphere in hotter stars: the temperature difference between spots and the photosphere decreases from about 2000 K in G0 stars to 200 K in M4 stars. There seems to be no difference in this property between active dwarfs and giants, at least for G–K stars, that implies the nature of starspots to be the same in all active stars. Also a weak-line T Tauri star V410 Tau seems to fit the sequence well. The only exception found is a young solar analogue EK Dra whose starspot temperature, estimated from light-curve modelling and Doppler imaging, significantly deviates from the relation. However, the value obtained from molecular band modelling fits the sequence quite well (O’Neal *et al.*, 2004).

High filling factors, up to 50% of the stellar disk, have been determined by O’Neal *et al.* (1996, 1998) from modelling molecular bands observed in the spectra of spotted stars (Sect. 4.4). For instance, for the very active RS CVn-type star II Peg they derived a spot temperature of about 3500 K and a filling factor varying between 43% and 55%. These results were however rather sensitive to the accepted value of the photosphere temperature. Such large spot filling factors were

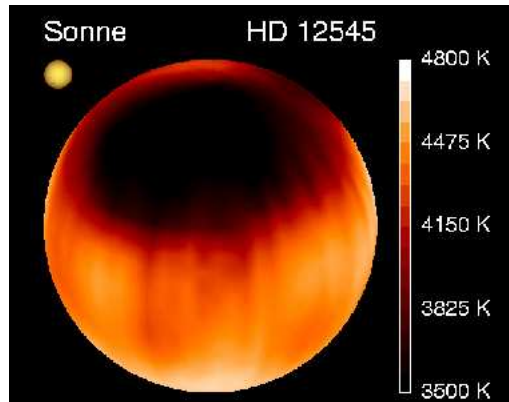


Figure 6: *Doppler image of the RS CVn type star HD12545 at the time of its largest amplitude of brightness variations. From Strassmeier (1999).*

found also for other RS CVn-type stars (cf., O’Neal *et al.*, 1996). They apparently contradict to Doppler imaging results. Possible reasons for that are discussed by Berdyugina (2002) and O’Neal *et al.* (2004).

Large spot areas and spot temperature contrasts recovered on active stars suggest that photometric and spectroscopic variability of these stars is dominated by the starspot umbra. Low temperature contrast of spots and small spot filling factors in M dwarfs as well as contradictory results for EK Dra obtained by different methods can be due to a decreasing of individual spot sizes and, thus, increasing relative contribution from the spot penumbra. For instance, the spot contrast obtained from Doppler imaging and light-curve modelling for EK Dra corresponds to the temperature contrast of the sunspot penumbra. Accordingly, we should expect that active late F-type stars possess spots with dominating penumbra and, thus, show lower contrast spots. As in the case of EK Dra, observations in molecular bands are more reliable for detection of starspot umbra.

5.2 Magnetic field

Direct measurements of magnetic fields on the surfaces of cool stars are very difficult. The net circular polarisation of the Sun as a star would be hardly observable with the present observational tools, as the mean magnetic field of the Sun peaks at maximum 8 G.

The ZDI technique (Sect. 4.3) is an excellent tool for detecting surface magnetic fields. Donati *et al.* (1999) combined Stokes *V* of more than thousand lines and obtained a time sequence of mean *V* profiles which shows clear rotational modulation, as magnetic structures are carried across the visible hemisphere of the star. This technique can be only used for rapidly rotating stars, so that the rotation disentangles surface magnetic structures with opposite polarities, reducing polarisation cancellation (Fig. 3). It has been intensively used for studying three stars: young dwarfs AB Dor and LQ Hya and RS CVn star HR1099 (Donati *et al.*, 2003a, and references therein). An example of the spot and magnetic field distribution obtained with the ZDI technique is shown in (Fig. 4). The common feature of reconstructions for the three stars is that the magnetic field distribution does not coincide with the darkest spots in the temperature images. The radial field component reveals large mid-latitude regions of mixed polarity, while the azimuthal component appears as almost axisymmetric rings of opposite polarities at higher and lower latitudes. Donati *et al.* (2003a) interpreted such a field distribution as an indication of large-scale poloidal and toroidal field components on the stellar surface and the underlying dynamo processes distributed throughout

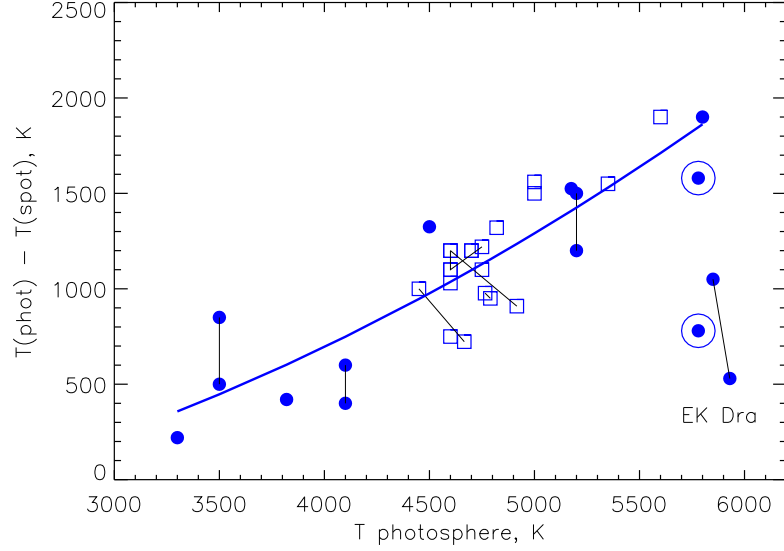


Figure 7: *Spot temperature contrast with respect to the photospheric temperature in active giants (squares) and dwarfs (circles). Thin lines connect symbols referring to the same star. The thick solid line is a second order polynomial fit to the data excluding EK Dra. Dots in circles indicate solar umbra ($\Delta T=1700$ K) and penumbra ($\Delta T=750$ K). Based on data in Table 5.*

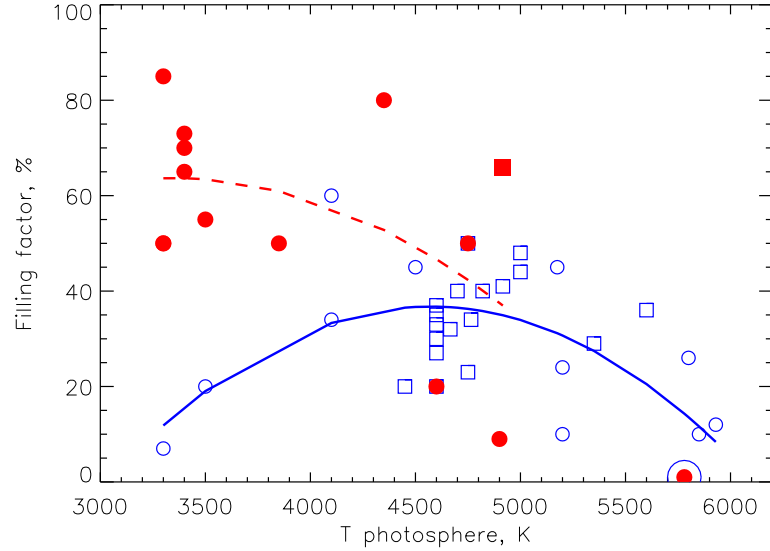


Figure 8: *Filling factors of spots (open symbols) and magnetic fields (filled symbols) on the surfaces of active dwarfs (circles) and giants (squares) versus the photosphere temperature. The thick solid line is a polynomial fit to the spot filling factors. The dashed line is a fit to the magnetic field filling factor, excluding the Sun. A big circle emphasises the sunspot umbra ($f \sim 1\%$). Based on data in Tables 5 and 6.*

the entire convection zone. It was however argued by Solanki (2002) that the rings of the azimuthal field may represent large penumbral regions with a predominantly horizontal magnetic field.

Most of our current knowledge about magnetic fields on cool stars and in starspots is however based on Zeeman broadening measurements, which reveal the distribution of magnetic field strengths with little dependence on the unknown field geometry (Robinson, 1980; Saar, 1988; Valenti and Johns-Krull, 2001). Zeeman broadening is best measured for slowly rotating stars, in contrast to ZDI. Reliable measurements require Zeeman splitting larger than or comparable to line widths in the absence of the field. Zeeman splitting is proportional to the field strength B and effective Landé factor g_{eff} :

$$\Delta\lambda \propto \lambda^2 g_{\text{eff}} B. \quad (8)$$

It is also proportional to the square of the wavelength. For this reason, successful measurements of magnetic field strengths can be carried out using red or IR lines with large g_{eff} . Also, only stars with strong magnetic fields and large field areas can be studied with this technique.

In order to derive magnetic field strength B and filling factor f , observed line profiles are fitted by the sum of synthetic spectra for magnetic and non-magnetic regions (Saar, 1992; Valenti and Johns-Krull, 2001):

$$F_\lambda = (1 - f) F_\lambda(B = 0) + f F_\lambda(B \neq 0). \quad (9)$$

Such an analysis implicitly assumes that (1) the field is concentrated into flux tubes surrounded by field free regions, (2) flux tubes are oriented radially in the photosphere, (3) magnetic regions are distributed uniformly over the surface, (4) magnetic regions are characterised by a single field strength, and (5) the temperature structure is the same for magnetic and non-magnetic atmosphere (Valenti and Johns-Krull, 2001). In this approach, the field strength being determined from the splitting is usually well constrained, but the filling factor depends on the unknown temperature structure of magnetic regions. In the case when the used spectral line becomes stronger in starspots, the filling factor can be overestimated, and vice versa. Rüedi *et al.* (1997) concluded that magnetic field strength and filling factor cannot be determined separately for moderately active stars with optical spectra of spectral resolution less than 100,000 and $S/N \leq 250$.

Magnetic field measurements for active dwarfs and giants are collected in Table 6 and are plotted in Figs. 9 and 10 versus the photosphere temperature and filling factor, respectively. These plots indicate a tendency for cooler dwarfs to have stronger magnetic fields and larger areas covered by them. It is interesting that there is a clear contradiction between spot filling factors measured from light curves and magnetic field filling factors measured from spectral lines (Fig. 8). This contradiction suggests that the two filling factors refer to different activity signatures, such as spot umbra and penumbra, or even faculae. The latter, being brighter and possessing relatively strong magnetic fields, would indeed be better seen in atomic lines. This is also supported by results obtained with the ZDI technique, which reveals stronger magnetic fields for intermediate brightness regions (e.g., Donati and Collier Cameron, 1997). Thus, it appears that umbral magnetic fields have not been measured as yet.

In order to detect magnetic fields in the starspot umbra it is necessary to employ spectral lines that are very weak outside spots. Zeeman sensitive molecular lines are the lines of choice for this purpose (Berdyugina, 2002; Fig. 5)

5.3 Lifetimes

Lifetimes of starspots can be determined from long-term observations which are, for instance, provided by continuous photometric data. Hall and Henry (1994) analysed several dozen spotted stars and concluded that lifetimes of relatively small spots are proportional to their sizes, which is consistent with sunspot properties. Lifetimes of relatively large spots are possibly limited by a shear of surface differential rotation. On the other hand, large spots causing prominent light curve

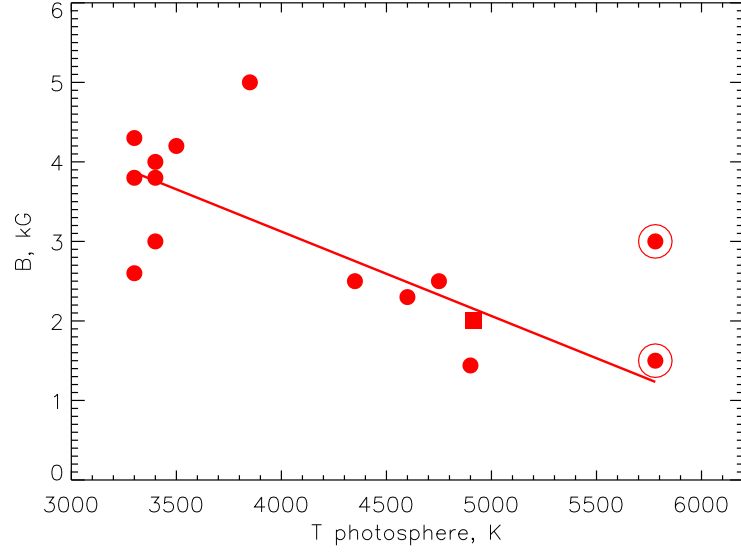


Figure 9: *Magnetic field measurements for active dwarfs (circles) and giants (squares) versus the photosphere temperature. Big circles indicate the sunspot umbra ($B=3\text{ kG}$) and penumbra ($B=1.5\text{ kG}$). The thick solid line is a linear fit to the data, excluding the sunspot umbra. Based on data in Table 6.*

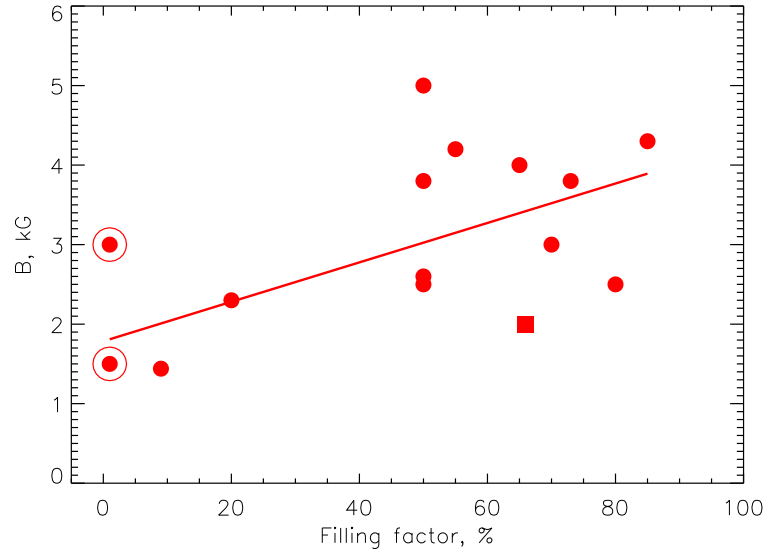


Figure 10: *Magnetic field measurements for active dwarfs (circles) and giants (squares) versus the filling factor. Big circles indicate the sunspot umbra ($B=3\text{ kG}$) and penumbra ($B=1.5\text{ kG}$). The thick solid line is a linear fit to the data, excluding the sunspot umbra. Based on data in Table 6.*

minima apparently can survive for many years, despite differential rotation, and form centres of activity, or active longitudes (Sect. 5.4). Doppler images suggest however that these regions often consist of several smaller spots. Lifetimes of those spots are yet to be analysed.

5.4 Active longitudes

Decades of continuous photometric monitoring of RS CVn stars revealed that large spots maintained their identities for years which was interpreted as a signature of one or two active longitudes similar to the distribution of solar energetic flares (Zelik *et al.*, 1988; Olah *et al.*, 1988; Henry *et al.*, 1995; Jetsu, 1996). Whether such a structure has a preferred orientation with respect to the line of centres in a binary and how long it survives was a long debate (Hall, 1996). Berdyugina and Tuominen (1998) showed that active longitudes on RS CVns are permanent but can continuously migrate in the orbital reference frame and generally have no preferred orientation. The active longitudes are separated by 180° on average and differ in their activity level. Periodic switching of the dominant activity from one active longitude to the other results in a so-called flip-flop cycle (Berdyugina and Tuominen, 1998) which is described in more detail in Sect. 6.2. A further analysis of photometric data confirmed the existence of active longitudes on RS CVn stars (Lanza *et al.*, 1998a; Rodonò *et al.*, 2000).

Two active longitudes seem to be a conspicuous pattern of the stellar activity. In addition to RS CVn stars they have been found in the spot distribution on FK Com-type stars (Jetsu *et al.*, 1993, 1999; Korhonen *et al.*, 2002) and very active young solar analogues (Berdyugina *et al.*, 2002; Järvinen *et al.*, 2005a; Berdyugina and Järvinen, 2005). Two examples for the RS CVn star σ Gem and young dwarf AB Dor are shown in Fig. 11.

The migration of active longitudes occurs with respect to the chosen reference frame. In binaries, this is usually the orbital ephemeris, while in single stars it represents an average epoch obtained over several years. If the migration is linear, a phase difference accumulates 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 stars (Berdyugina and Tuominen, 1998). A non-linear migration suggests the presence of differential rotation and changes in mean spot latitudes as, e.g., on the Sun. Such a behaviour is typical for single stars, young solar type dwarfs and FK Com-type giants (Fig. 11).

The analogy with solar active longitudes is further supported by the longitudinal distribution of sunspots (Berdyugina and Usoskin, 2003). 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 (Fig. 11). 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 migration pattern of the active longitudes bears therefore the information on both differential rotation and mean spot latitudes. This can be used for inferring stellar differential rotation and butterfly diagrams.

5.5 Differential rotation

Differential rotation of stars plays an important role in the generation of magnetic fields in the convection zone. In the Sun, it is involved in transformation of a weak large-scale poloidal field

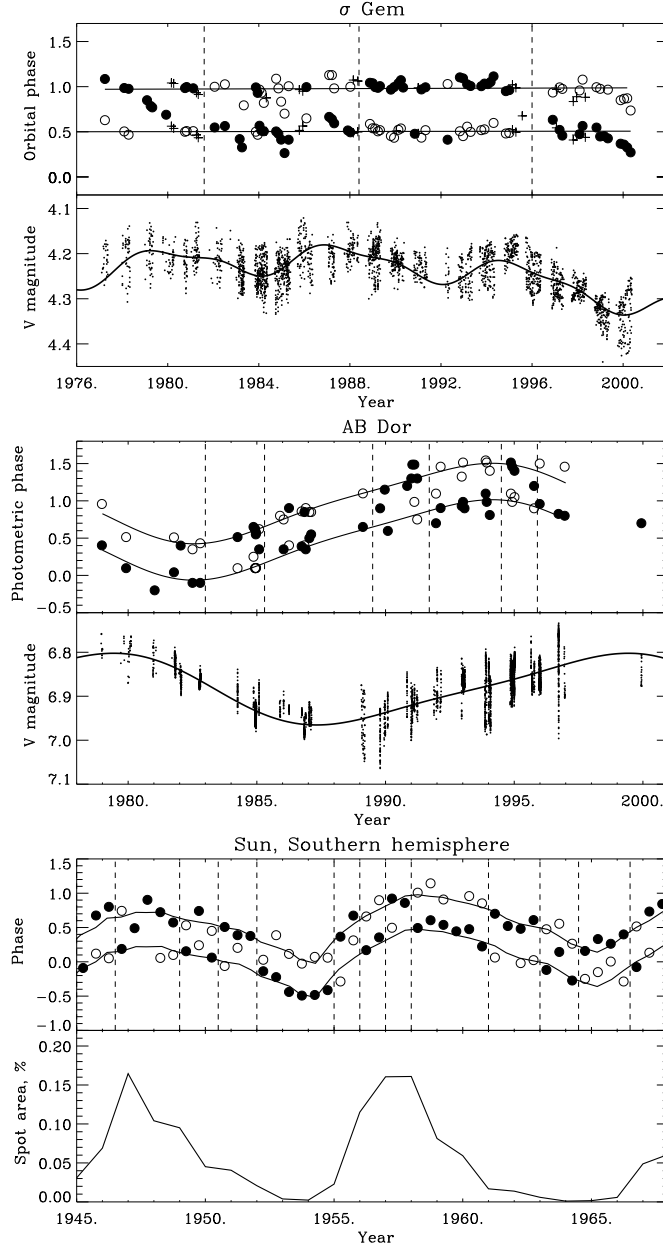


Figure 11: Active longitudes, flip-flops and sunspot-like cycles on the RS CVn star σ Gem (Berdyugina and Henry, 2005), young solar analogue AB Dor (Järvinen et al., 2005a), and the Sun (Berdyugina and Usoskin, 2003). In the three plots upper panels show phases of spot concentrations (filled and open circles denote primary and secondary regions, respectively). The migration paths of active longitudes are emphasised by solid lines. Flip-flops are marked by vertical dashed lines. They occur when the primary region jumps to the opposite active 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 for both σ Gem and AB Dor, in contrast to the Sun (e. g., Amado et al., 2001).

into a stronger toroidal component. By analogy, stellar activity is most probably also connected to differential rotation.

On the Sun the differential rotation is observed in relative motion of sunspots and can be expressed in the form

$$\Omega = \Omega_0 - \Delta\Omega \sin^2 \psi, \quad (10)$$

where ψ denotes heliographic latitude, Ω_0 is the rotation rate at the equator and $\Delta\Omega$ is the difference in rotation rate between the pole and the equator. A strength of the differential rotation can be quantified by the rotational shear $\Delta\Omega$ or its reciprocal $2\pi/\Delta\Omega$, which is the time the equatorial regions need to lap the pole, i.e. the lap time. It can also be characterised by the ratio of the rotational shear to the equatorial velocity:

$$\alpha = \frac{\Delta\Omega}{\Omega_0}. \quad (11)$$

For instance, on the Sun with $\Delta\Omega=0.055$ rad/day, the lap time is 115 days, and $\alpha=0.2$.

On stars these characteristics can be estimated from observations with various methods, for instance: Fourier analysis of light curves (Lanza *et al.*, 1993), cross-correlation of successive stellar Doppler images (Donati and Collier Cameron 1997), direct spot tracking (Collier Cameron *et al.*, 2002), Fourier transform of rotationally broadened line profiles (Reiners and Schmitt, 2002), parameter fit in Zeeman-Doppler imaging (Petit *et al.*, 2002), through asteroseismology (Gizon and Solanki, 2004) and from spectro-interferometric observations (de Souza *et al.*, 2004). For slowly rotating stars of the solar type, analysis of disk-integrated Ca II K line core emission appears to be a promising method (Donahue *et al.*, 1996; Hempelmann and Donahue, 1997).

Long-term photometric monitoring of starspot modulation reveals changes in the seasonal rotation period which indicate the presence of differential rotation on stellar surfaces and of changes in spot latitudes (Hall, 1991a; Henry *et al.*, 1995; Messina and Guinan, 2003). Confronting the range of seasonal variations and the mean rotation period yields a possible correlation between them in the sense that slower rotators show larger period variations. A majority of stars show however a significantly smaller rotational shear than that observed on the Sun. Similar behaviour is found in periods obtained from variations of chromospheric Ca II H&K emission-line fluxes. Over timescales of many years, the rotation period was found to show a sine-like variation which can be attributed to a solar-type activity cycle (Donahue *et al.*, 1996). Note however that the seasonal period variations yield only lower limits of the rotational shear as they represent rotational rates spread over the range of latitudes where active regions erupt during the stellar cycle.

Using the Fourier transform method Reiners and Schmitt (2003a,b) derived differential rotation of a sample of rapidly rotating F0–G0 dwarfs and found that it is more common in slower rotators, in agreement with the previous findings. Moreover, the differential rotation in more active stars seems to diminish to values which cannot be measured with the Fourier transform technique.

In such cases cross-correlation of successive stellar Doppler images is a helpful alternative. It was first performed by Donati and Collier Cameron (1997) for the active young dwarf AB Dor and revealed the solar type differential rotation with the equator rotating faster than the polar region (Fig. 12). The parameter fit using DI or ZDI developed by Donati *et al.* (2000) and Petit *et al.* (2002) is the next step in using inversion techniques. It was applied to a small sample of active G2–M2 dwarfs, all showing a solar type differential rotation (Petit *et al.*, 2004; Barnes *et al.*, 2005). This sample revealed a clear dependence of the rotational shear on spectral class, indicating the differential rotation to be negligible in M dwarfs and very strong in G dwarfs. The Sun however deviates from the correlation. In contrast to the results for early F and G dwarfs, no significant dependence of $\Delta\Omega$ on rotation rate was found. An interesting finding though is that the differential rotation is different when estimated from cool spots or magnetic regions and that it undergoes temporal fluctuations on time-scales of one to a few years (Donati *et al.*, 2003b). Note, however,

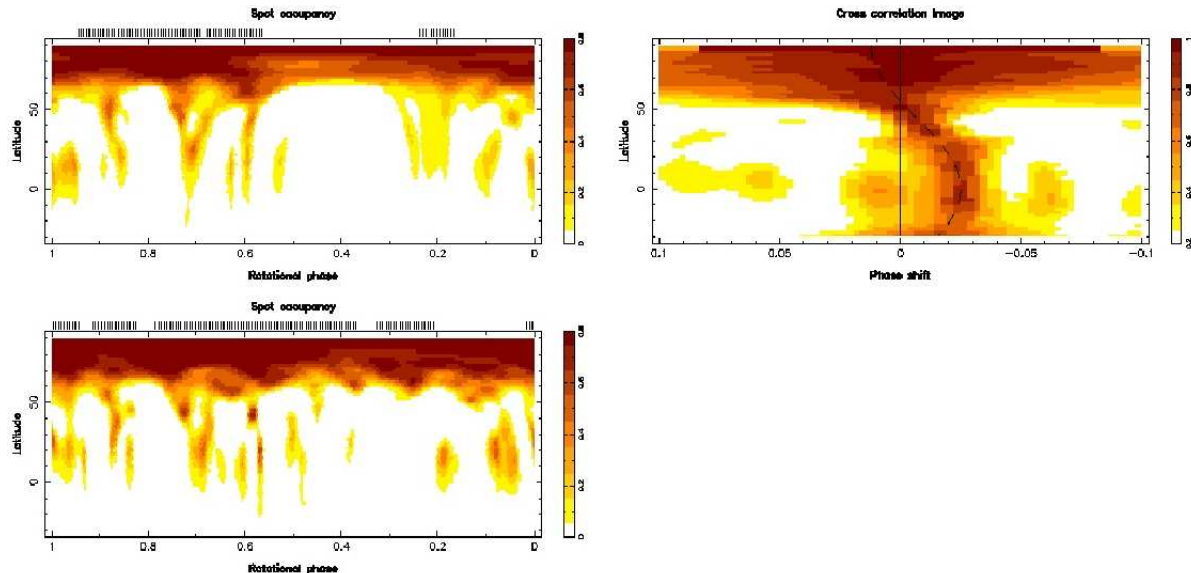


Figure 12: Two Doppler images of the young active K0 dwarf AB Dor (top and middle panels) and a cross-correlation image showing that near-equatorial spots rotate faster than high-latitude regions. From Donati and Collier Cameron (1997). See also animation by J.-F. Donati at <http://webast.ast.obs-mip.fr/people/donati/diffrot2.html>

that the lack of spatial resolution and spot growth and decay as well as their systematic proper motions can significantly affect the derived values of the differential rotation. Also, it appears that uncertainties in the inclination of the stellar rotational axis result in systematic errors in the deduced differential rotation law.

5.6 Latitudes and butterfly diagrams

Spot latitudes can be directly recovered from Doppler images. Interesting and still controversial features in stellar Doppler images are large polar spots, cool active regions over the stellar poles. Out of 65 stars, whose surfaces were mapped with the Doppler imaging technique, 36 showed prominent polar spots, independently on the rotational rate or effective temperature (Strassmeier, 2002). Earlier studies however suggested that latitudinal distribution of spot activity may depend on the rotational period, since faster rotators apparently show a tendency for polar spots, while slower rotators more often have high-latitude spots not covering the pole (Hatzes, 1998). Such a feature appears to be a convenient compensation for a uniformly distributed spot area which cannot be recovered from rotational modulation of spectral lines and of light curves. On the other hand, flat-bottomed spectral line profiles in rapid rotators may indicate a lack of the continuum flux at the polar region, and this kind of profiles appears to be common for stars with a lower inclination of the rotational axis, implying changes of spot visibility near the poles (Hatzes *et al.*, 1996).

The reliability of polar spots has been thoroughly discussed (Strassmeier *et al.*, 1991; Schüssler and Solanki, 1992; Piskunov and Wehlau, 1994; Strassmeier and Rice, 1998). For instance, the chromospheric activity could reduce absorption in cores of strong spectral lines which can be interpreted as presence of cool polar caps. To investigate such a bias in Doppler imaging Unruh and Collier Cameron (1997) used Na D lines which are sensitive to the chromospheric tempera-

ture structure and found that the images obtained from the Na D lines show less high-latitude structure and give more reliable light-curve predictions than images derived previously from fits to several weaker photospheric lines. Also, Bruls *et al.* (1998) studied effects of the chromospheric temperature increase on spectral line profiles, including non-LTE effects. They concluded that it is unlikely that polar spots are an artefact due to unaccounted chromospheric activity. It appears that Doppler imaging using simultaneous inversions of atomic and molecular lines can limit the amount of non-modulating spot area and resolve the controversy of polar spots (Berdyugina, 2002).

In very active stars spots are distributed over a large range of latitudes, including low- and high-latitude spots, as shown by Doppler imaging and eclipse mapping models (Donati *et al.*, 1999; Strassmeier *et al.*, 1999; Berdyugina *et al.*, 1998b, 1999a; Rodonò *et al.*, 1995). A long-term Doppler imaging monitoring of the active component of HR1099 suggests that starspots form at low or intermediate latitudes and then slowly migrate towards the pole on time scales of a few years (Vogt *et al.*, 1999).

The time span of Doppler images for most studied stars is not long enough to see the latitude changes over the spot cycle, i. e. to recover stellar butterfly diagrams. Light curve modelling offers a longer time scale but spot latitudes obtained from the model are usually not unique and thus are less reliable.

A new approach for recovering stellar butterfly diagrams was suggested by Berdyugina (2005). As was emphasised in Sect. 5.4, phase migration of the active longitudes bears the information on both differential rotation and mean spot latitudes. Thus, knowing the surface differential rotation and phase migration of active longitudes one can recover mean spot latitudes during the course of sunspot-like cycles. 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.

6 Starspot evolution and stellar activity cycles

6.1 Overall activity variations

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). For a sample of stars (about 100) of spectral type G0-K5 V changes in rotation and chromospheric activity are found to occur on an evolutionary timescale. Young rapidly rotating stars exhibit high average levels of activity and rarely display a smooth, cyclic variation. Stars of intermediate age (approximately 1–2 Gyr for 1 solar mass) have moderate levels of activity and occasional smooth cycles (Fig. 13). Finally, stars as old as the Sun and older have slower rotation rates, lower activity levels and smooth cycles. Some stars showed no variations at all which was first interpreted as stars being in the stage similar to the Maunder minimum on the Sun. Later it was shown though that these stars are probably subgiants evolved off the main sequence (Wright, 2004). In addition, contemporaneous photometric and chromospheric H&K emission time series for 35 stars revealed that 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.

The detection of activity cycles in overall brightness variations due to cool spots on young solar analogues confirms the above implication. At least eight young dwarfs of the solar type and one weak-line T Tau star clearly show spot cycles (Amado *et al.*, 2001; Berdyugina *et al.*, 2002; Messina and Guinan, 2002, 2003; Stelzer *et al.*, 2003; Järvinen *et al.*, 2005a; Berdyugina and

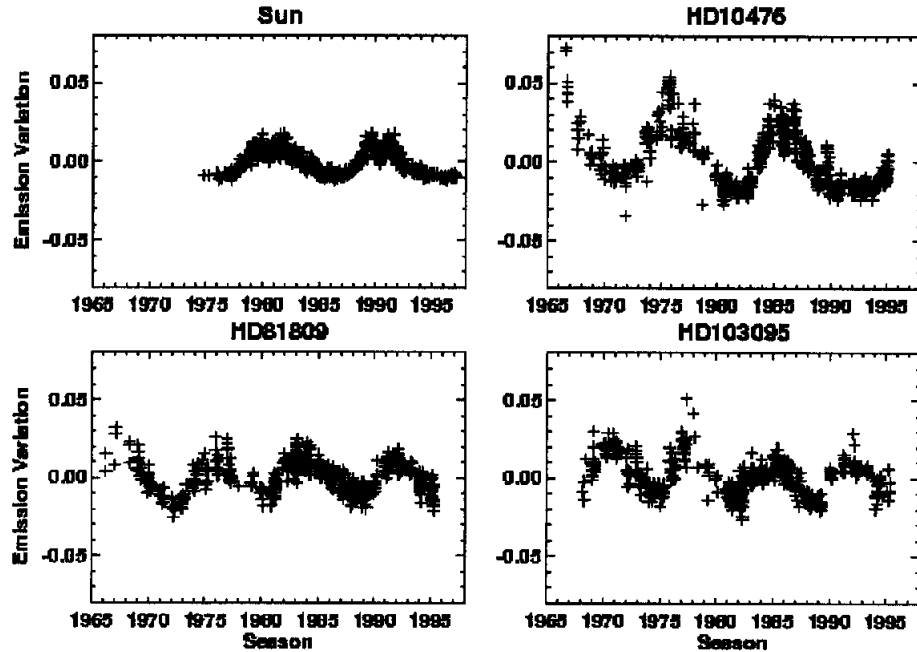


Figure 13: Chromospheric Ca II emission cycles for Sun-like stars, illustrating the regular cyclic variation that is common in such stars. The Ca II emission is plotted in Mount Wilson “S-Index” units. From Radick (2000).

Järvinen, 2005). Two examples (AB Dor and LQ Hya) are shown in Fig. 14. In contrast to the Sun, where the maximum spot area is reached at the maximum irradiance, on more active stars it occurs at minimum brightness. In addition, such stars exhibit periodic changes of spot rotation periods in phase with the spot cycle which is consistent with the presence of a differential rotation. Variations of the total spottedness are also found on other types of cool active stars, including components of binary systems (e. g., Henry *et al.*, 1995, see plot for σ Gem in Fig. 14). The stellar spot cycles are therefore reminiscent of the 11-yr sunspot cycle.

A sample of stars with different rotation rates and cycle frequencies provides an opportunity to investigate the likely evolution of the stellar dynamo, as was done by, e. g., Saar and Brandenburg (1999). For instance, it appears that there is only a weak correlation, if any, between cycle and rotational frequencies, while the cycle length probably correlates with the differential rotation shear (Messina and Guinan, 2003). However, in such an analysis it is important to distinguish between different cycle types as they can be associated with different dynamo modes, as discussed by Moss (2004) and Fluri and Berdyugina (2004).

A comparison of the activity patterns of the present Sun and young solar analogues allows us to infer possible evolution of the stellar dynamo on main sequence stars. First of all, the overall activity level is reducing while the star evolves along the main sequence and loses its angular momentum. Secondly, 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. Thirdly, young stars show conspicuous non-axisymmetric fields, which coexist on the Sun and solar-age stars with a strong axisymmetric component.

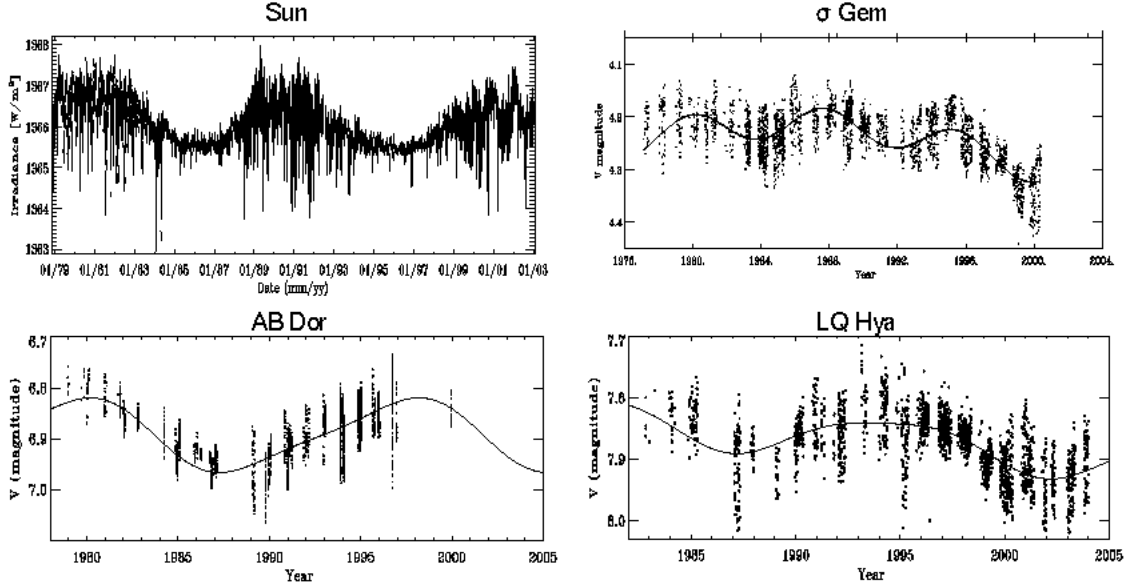


Figure 14: Spot cycles in the solar irradiance and V magnitudes of the RS CVn binary σ Gem and two young solar analogues AB Dor and LQ Hya. Note that the maximum of the spot area corresponds to the maximum irradiance on the Sun and minimum brightness on the stars.

6.2 Flip-flop cycles

Although active longitudes endure for a long time, the active regions they consist of evolve in size, indicating possible cyclic variations as observed in Doppler images (Berdyugina *et al.*, 1998b, 1999a). While one active longitude reduces its activity level, the other increases, which suggests a redistribution of the spotted area between the opposite hemispheres (Fig. 15). 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 analysed 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. Korhonen *et al.* (2002) inferred a flip-flop cycle on FK Com. In addition to RS CVn stars and FK Com, such cycles have been detected on young solar analogues (Berdyugina *et al.*, 2002; Järvinen *et al.*, 2005a; Berdyugina and Järvinen, 2005), examples of which are shown in Fig. 11. A list of stars exhibiting a flip-flop phenomenon is given in Table 4.

The frequency ratio between the spot cycle and flip-flop cycle 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 spot cycle, implying the flip-flop cycle to be twice as long as the spot cycle. In young dwarfs flip-flop cycles are 3–4 times shorter than the spot cycle.

The solar active longitudes also exhibit a flip-flop cycle. On the Sun 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 (Berdyugina and Usoskin, 2003). This is about 1/3 of the 11-yr sunspot cycle and agrees with the results obtained for young solar analogues. 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.

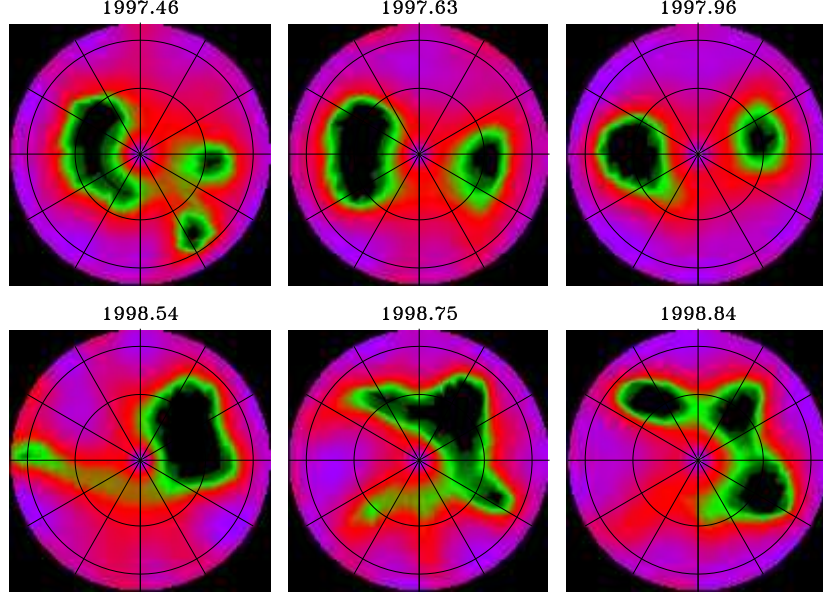


Figure 15: *Doppler images of the RS CVn star II Peg in the pole-on projection illustrating a flip-flop that occurred between the end of 1997 and mid of 1998. From Berdyugina et al. (1999a).*

Star	Sp	M/M _☉	R/R _☉	Ω/Ω _☉	P _{rot,d}	P _{spot,yr}	P _{ff,yr}	Reference
Binary stars								
II Peg	K2 IV	0.8	3.4	3.8	6.7066		9.3	[1]
IM Peg	K2 III	1.5	13.3	1.05	24.65		13	[2]
EI Eri	G5 IV	~1.5	>3.4	13.3	1.9510		9.0	[1]
σ Gem	K2 III	~2	~13		19.604		14.9	[1]
HR 7275	K2 IV	~1	>8	0.90	28.263		17.5	[1]
HR 1099	K1 IV			9.2	2.841			[3]
HD 37824	K0 III	2.0	12.6	0.5	53.12		13.5:	[9]
HD 181809	K0 III-IV	1.7	6.5	0.4	59.85		4:	[9]
Single stars								
Sun	G2 V	1.0	1.0	1.0	25.	11	3.7	[4]
LQ Hya	K2 V	~0.7	~0.8	16.3	1.601	15	5.2	[5]
AB Dor	K0 V	~0.8	~0.8	50.5	0.515	20	5.5	[6]
EK Dra	G1 V	~1	~1	10.0	2.606	10.5	4.5	[7]
FK Com	G5 III	~1.5	~10	10.8	2.400	13/30	6.4	[8]

Table 4: Stars with flip-flop cycles. References: [1] Berdyugina and Tuominen (1998), [2] Berdyugina *et al.* (2000), [3] Berdyugina and Henry (2005), [4] Berdyugina and Usoskin (2003), [5] Berdyugina *et al.* (2002), [6] Järvinen *et al.* (2005a), [7] Järvinen *et al.* (2005b), [8] Korhonen *et al.* (2002), [9] Fekel and Henry (2005).

6.3 Orbital period modulation

A modulation of the orbital period in close binaries with cool active components is a phenomenon which is suggested to be associated with magnetic activity cycles (Hall, 1989). It can be induced by changes of the angular momentum and magnetic field distribution within the convection envelope of the active component which may occur during an activity cycle (Applegate, 1992; Lanza *et al.*, 1998b). The variation of the gravitational quadrupole momentum induces changes of the gravitational acceleration of the companion star, leading to the observed modulation of the orbital period.

The time scale for such a modulation is of several decades and its cyclic origin is still an assumption. The relationship between the orbital period modulation and the starspot cycle is not yet clear. In some stars the spot cycle is half as long as the orbital period modulation (Keskin *et al.*, 1994; Rodonò *et al.*, 1995; Lanza *et al.*, 1998a), in others these two cycles are approximately of the same length (Ibanoglu *et al.*, 1994; Hall, 1991b). On the other hand, the length of the cycle of the orbital period modulation seems to be correlated with the angular velocity of the star. This supports the suggestion that a distributed non-linear dynamo is at work in the convection envelopes of very active stars and that it strongly affects the differential rotation (Lanza and Rodonò, 1999b). If the cyclic origin of the orbital period modulation and its relation to the spot cycle is confirmed, this can be used as a proxy for magnetic cycles in Algols and cataclysmic variables where photometric modulation of the cool secondary is difficult to detect.

7 Theoretical models

7.1 Dynamo models

Mean field dynamo models assume a dynamo action which is extended over the entire convection envelope. In the Sun, a shell dynamo based on the $\alpha\Omega$ mechanism seems to be able to explain the main features of the 11-yr cycle. However, in the most active stars it is difficult to reproduce the observed latitudinal range of starspots with the thin-shell dynamo models. It appears that in addition to a solar-like dynamo, probably working in the overshoot zone, a distributed $\alpha^2\Omega$ dynamo is likely to be present in very active stars (Brandenburg *et al.*, 1989; Moss *et al.*, 1995). Such a distributed dynamo is able to explain, at least qualitatively, a threshold for light modulation, active longitudes and flip-flops (see below). Also, it is a good candidate for explaining the observed orbital period modulation in active close binaries (Lanza *et al.*, 1998b).

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, spot 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, e. g., a dipole-like $\mathcal{S}1$ mode (Moss *et al.*, 1991, 1995), or antisymmetric such as a quadrupole-like $\mathcal{A}1$ mode (Tuominen *et al.*, 2002). The magnetic field configuration in such modes consists of magnetic spots of opposite polarities (active longitudes) 180° apart. It appears that such modes can be excited at lower dynamo numbers than axisymmetric modes in the case when the differential rotation is not large. The extension of these models to synchronised binaries reveals that the maxima of the mean magnetic field appears to concentrate near the line joining the centres of the binary components (Moss and Tuominen, 1997).

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 alternating 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 *et al.* (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.

Differential rotation is a key parameter for stellar dynamos, and a theoretical study of its dependence on the rotation rate and spectral type is important for interpreting observations. A noticeable progress in such modelling was achieved during the recent decade (Kitchatinov and Rüdiger, 1995; Rüdiger *et al.*, 1998). In particular the following results are important. Simulations of global circulation in outer stellar convection zones for spectral classes G2 and K5, rotating at the same rate, demonstrate that differential rotation for G2 is larger compared to K5 (Kitchatinov and Rüdiger, 1999). However, as the rotation period decreases, the differential rotation first decreases as well but starts to increase for the shortest periods. It appears that rapid rotation can explain the rather strong total surface differential rotation of the observed very young solar-type stars, as it creates an equatorward meridional flow at the stellar surface which accelerates the equatorial rotation (Rüdiger and Küker, 2002). A possibility for stars to have an anti-solar differential rotation was discussed by Kitchatinov and Rüdiger (2004).

The latest developments in the solar and stellar dynamo theory are reviewed by Brandenburg and Dobler (2002) and Rüdiger and Hollerbach (2004).

7.2 Flux-tube models

High-latitude spots on very active stars can be explained by non-linear models for flux-tube instability (Schüssler and Solanki, 1992; Schüssler *et al.*, 1996). In a rapid rotator with a dynamo operating near the base of the convection zone, the effect of the Coriolis force makes flux tubes to emerge nearly parallel to the rotation axis, thus producing high-latitude activity even if the dynamo amplifies the field only at low latitudes. Such a model is capable to reproduce the sunspot behaviour as well (Caligari *et al.*, 1995). In addition to rapid rotation, the depth of the convection zone, stratification and magnetic field strength play an equally important role in the poleward deflection of rising flux-tubes. In particular, the size of the stellar core affects the magnetic curvature force and the rise time, while gravity determines the strength of the buoyancy force.

Calculations for zero-age main-sequence stars show that for increasing rotation rate the emergence pattern shifts to higher latitudes, while an equatorial zone of avoidance grows (Granzer *et al.*, 2000). The concentration to higher latitudes is stronger for stars with lower mass and deeper convection zones because of geometrical reasons and the larger rise time. It is remarkable that once the Coriolis effect has enforced a nearly axis-parallel rise of the flux tube, further increase of the

rotation rate has no effect on the emergence latitudes, indicating a saturation effect. Truly polar flux emergence was however not found for main-sequence stars. Also, low-latitude activity in rapid rotators cannot be described by such a model. For T Tauri-type stars Granzer *et al.* (2000) find a different pattern of behaviour. Because of the small size of the stellar core, the unstable flux tubes detach completely from the overshoot layer and rise through the convection zone as free-floating rings. They can emerge in a broad range of latitudes, almost from pole to equator.

A similar perturbation study of rising flux-tubes have been made for close synchronised binary stars with main-sequence components in order to examine an influence of tidal effects on the formation of observed active longitudes (Holzwarth and Schüssler, 2003a, 2003b). It was found that although the magnitude of tidal effects is rather small, they nevertheless lead to the formation of clusters of flux tube eruptions at preferred longitudes on opposite sides of the star. The longitude distribution of the clusters depends on the initial parameters of flux-tubes in the overshoot region, such as magnetic field strength and latitude. This implies that there is no preferred orientation of the active longitudes and agrees with most of the observations. The extension of the model to post main-sequence stars revealed difficulties in recovering starspot properties frequently observed on evolved binary components (Holzwarth, 2004). This points out an insufficiency of the applied flux tube model and implies that additional flux transport and possibly amplification mechanisms have to be taken into account.

Note that the flux-tube concept, when applied to heavily spotted stars, implicitly assumes that large starspots represent clusters of smaller, more sunspot-like magnetic structures, to which the thin flux-tube approximation is applicable during most of their rise through the convection zone (Schüssler, 2002). Further, such an approach gives only the information about potential emergence locations. The actual prediction of emergence patterns would require a coupling of the emergence calculations with a full dynamo model providing the flux distribution as functions of latitude, longitude and time.

8 Summary

Cool stars with external convection envelopes exhibit various magnetic phenomena similar to those observed on the Sun. Starspots are the best studied proxy of stellar magnetism and, thus, represent a key tool for understanding the stellar dynamo. A remarkable progress in observational facilities and numerical techniques for studying starspots achieved for the last two decades allows for a deep insight into the nature of starspots and underlying magnetic fields. In addition to traditional photometric and spectroscopic observations, advanced instrumentation for high-precision spectropolarimetry and (spectro-)interferometry together with foreseen space missions constitute a powerful arsenal for studying starspots and promise for ground-breaking discoveries in stellar magnetism.

Starspot properties are revealed with the help of various numerical techniques, such as light-curve modelling and inversions, Doppler and Zeeman-Doppler imaging, molecular line diagnostics, asteroseismology, etc. Parallel brightness and colour variations, i.e. the faintest state being accompanied by the reddest colour, imply that starspots are significantly cooler than the unspotted photosphere, on average by 500 K to 2000 K. Large variations in brightness, 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, in contrast to sunspots which on average appear at latitudes below 30° . Magnetic field measurements suggest that the large starspots represent active

regions consisting of smaller, mixed polarity spots.

Summarising the discussion on starspot evolution, the following main activity patterns appear to be common on cool active stars, namely components of binary systems, young single dwarfs and single rapidly rotating giants:

- total spottedness variations indicating sunspot-like cycles;
- persistent active longitudes 180° apart implying non-axisymmetric magnetic fields;
- switching of dominant activity between active longitudes: flip-flop cycles;
- migration of active longitudes;
- differential rotation and butterfly diagrams;
- orbital period variations in binaries: changes of the distribution of magnetic fields in the convection envelope.

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.

These activity patterns challenge the current stellar dynamo theory. It appears that non-linear dynamo models can qualitatively explain most of the phenomena, although many parameters of the models are not realistic as yet.

Comparing the observed properties of the magnetic field on the Sun and active stars, we can conclude that the activity patterns emphasised above for single stars 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.

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Additional tables

Star	Sp	T _{eff} ,K	ΔV	ff,%	T _{spot} ,K	ΔT,K	Method	Ref.
Giants and subgiants								
HD199178	G5 III	5350		29(d)	3800±200	1550	MBM	[1]
EI Eri	G5 IV	5600		36(d)	3700±150	1900	MBM	[1]
λ And	G8 III	4750		23(d)	3650±150	1100	MBM	[1]
HK Lac	K0 III	4790	0.14		3840±200	950±200	LCM	[3]
		4765	0.37	34(d)	3788±10	977	LDR	[4]
XX Tri	K0 III	4820	0.63	20(s)	3500	1300	DI	[5]
		4750		35(d)	3420±120	1320	MBM	[20]
HU Vir	K0 IV	5000		44(d)	3440±100	1560	MBM	[1]
UX Ari	K0 IV	5000		48(d)	3500	1500	MBM	[2]
AR Lac	K0 IV	4700	0.04		3500	1200	LCM	[6]
σ Gem	K1 III	4600		33(d)	3850±100	750	MBM	[1]
DM UMa	K1 III	4600		35(d)	3570±100	1030	MBM	[1]
		4500		42(d)	3450±120	1010	MBM	[20]
SZ Psc	K1 IV	4700			3500±400	1200±400	LCM	[7]
HR1099	K1 IV	4700		40(d)	3500	1200	MBM	[2]
		4700	0.09		3500	1200	LCM	[6]
HR7275	K2 III	4600		27(d)	3500±150	1100	MBM	[1]
II Peg	K2 IV	4600	0.42	37(h)	3400±100	1200±100	LCM	[3]
		4750	0.16	50(d)	3530±100	1220	MBM	[1]
		4750	0.23	43(d)	3530±100	1220	MBM	[1]
		4500	0.25		3300	1200	LCM	[6]
		4600	0.25	20(d)	3500	1100	DI	[8]
IM Peg	K2 III	4666	0.20	32(d)	3943±10	723	LDR	[4]
		4450		20(d)	3450	1000	DI	[9]
IN Vir	K2 IV	4600		40(d)	3350±170	1250	MBM	[20]
VY Ari	K3 IV	4916	0.41	41(d)	4007±10	909	LDR	[4]
		4600	0.28	15(s)	3400	1200±50	LCM	[10]
		4600	0.20	12(s)	3400	1200±50	LCM	[10]
		4600	0.10	15(s)	3400	1200±50	LCM	[10]
Dwarfs								
Sun	G2 V	5870			4200(um)	1670		
Sun	G2 V	5870			5000(pen)	870		
HD307938	G2 V	5800	0.06	13(s)	3900	1900	DI+LC	[11]
EK Dra	G2 V	5930		6(s)	5400	500	LCM	[12]
		5850	0.08	11(d)	4800	1050	DI	[13]
		5830		40(d)	≥3800	≤2030	MBM	[20]
AB Dor	K0 V	5200	0.05	12(s)	4000	1200	LCM	[14]
		5200	0.12	5(s)	3700	1500	LCM	[14]
LQ Hya	K2 V	5175		45(d)	3650	1525	MBM	[2]
OU Gem	K3 V	4925		35(d)			MBM	[2]
V833 Tau	K4 V	4500		45(d)	3175	1325	MBM	[2]
EQ Vir	K5e	4380		45(d)	3350±120	1030	MBM	[20]
BY Dra	M0 V	4100	0.08	34(h)	3500±450	600±450	LCM	[3]
		4100		60(d)	3700	400	LCM	[15]
		4100	0.10		3500	600	LCM	[6]
YY Gem	M0 V	3820			3400	400	LCM	[16]

AU Mic	M2e V	3500	0.10		2650	850	LCM	[6]
		3500	0.32	10(s)	3000	500	LCM	[17]
EV Lac	M4e V	3300	0.10	7(d)	3080	220	LCM	[18]
T Tauri stars								
V410 Tau	K4	4300	0.38	32(d)	2900	1400	LCM	[19]
		4300	0.55	41(d)	2900	1400	LCM	[19]

Table 5: A sample of starspot temperatures and filling factors. The filling factors are normalised to the stellar disk (d), hemisphere (h) or whole surface (s). For the stellar disk normalisation maximum observed filling factors are given. Different measurements for the same star from the same publication correspond to different seasons of observations. References: [1] O’Neal *et al.* (1998), [2] O’Neal *et al.* (2001), [3] Vogt (1981), [4] Catalano *et al.* (2002), [5] Strassmeier (1999), [6] Rodonò *et al.* (1986), [7] Eaton and Hall (1979), [8] Berdyugina *et al.* (1999a), [9] Berdyugina *et al.* (2000), [10] Strassmeier and Bopp (1992), [11] Marsden *et al.* (2005a), [12] Dorren and Guinan (1994), [13] Strassmeier and Rice (1998), [14] Amado *et al.* (2001), [15] Chugainov (1976), [16] Torres and Ribas (2002), [17] Torres and Ferraz Mello (1973), [18] Abranin *et al.* (1998), [19] Petrov *et al.* (1994), [20] O’Neal *et al.* (2004).

Star	Sp. class	B, kG	f, %	Reference
G–K dwarfs and subgiants				
HII 1100	K3V	2.50±0.09	50	Valenti and Johns-Krull (2001)
ϵ Eri	K2V	1.44±0.15	9	Valenti <i>et al.</i> (1995)
ξ Boo B	K4V	2.3	20	Saar (1992)
VY Ari	K3IV	2.0±0.3	66	Bopp <i>et al.</i> (1989)
M dwarfs				
AD Leo	M3.5Ve	3.80±0.26	73	Saar and Linsky (1985)
		4.0	65	Saar (1992)
		3.0	70	Valenti and Johns-Krull (2001)
AU Mic	M1.6Ve	4.2	55	Saar (1992)
EQ Vir	K5Ve	2.5±0.3	80	Saar <i>et al.</i> (1986)
EV Lac	M4.5Ve	3.8±0.5	50	Johns-Krull and Valenti (1996)
		4.3	85	Saar (1992)
GJ 729	M4.5Ve	2.6±0.3	50	Johns-Krull and Valenti (1996)
GJ 1049	M0V	5.0	50	Kochukhov <i>et al.</i> (2001)
T Tau stars				
BP Tau		2.46±0.12		Johns-Krull <i>et al.</i> (1999a)
		2.6±0.3		Johns-Krull <i>et al.</i> (1999b)
TW Hya		2.6	70	Valenti and Johns-Krull (2001)

Table 6: Magnetic field measurement results

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