The Application of FORS1 Spectropolarimetry to the Investigation of Cool Solar-like Stars

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The low resolution spectropolarimetric observations obtained with FORS1 at the VLT have often been used for investigating magnetic fields in hot stars. Here we describe the first investigation of the magnetic field over the stellar rotation in a cool late-type star, FK Com, based on FORS1 spectropolarimetry. We measure the mean longitudinal magnetic field from nine circularly polarised spectra, and study its behaviour over the stellar rotation. The magnetic field measurements are compared to a simultaneous stellar surface temperature map obtained with Doppler imaging techniques. These observations reveal two cool spots on the surface, and indicate that the main cool region coincides with the maximum value of the mean longitudinal magnetic field. Additionally, only 0.25 in phase apart from the main spot, the secondary spot is located at a similar phase to the field minimum. The observations can be interpreted as two spots having different magnetic field polarities, implying that the starspot configuration on FK Com is similar to that observed in the Sun.

The solar surface shows a varying number of sunspots. Currently, during the longest and deepest solar activity minimum of the space age, these cooler patches of the solar surface are very rarely seen, whereas a few years ago, during the solar activity maximum, many spots were constantly visible. A century ago the magnetic origin of sunspots was discovered by Hale (1908), explaining why sunspots were dark. In a sunspot the magnetic field acts as a valve, hindering the normal heat transportation from the solar interior and forms an area with temperatures of approximately 2000 K less than that of the unspotted solar surface.

With current telescopes and instruments it is not possible to obtain direct, spatially resolved images of a stellar surface, except in the few special cases of nearby supergiants. In general, indirect methods have to be used for recording the surface structures on stars, and in most stars the magnetic activity is so low that it is impossible to obtain any spatial information on the starspots using present technology.

Doppler imaging (e.g., Vogt et al., 1987) is a method that can be used for the detailed mapping of stellar surface structures. If the stellar surface has a non-uniform temperature distribution, the radiation from different parts of the stellar surface will depend on the local temperature. This produces a distortion in the spectral line, and this distortion moves across the line profile as the star rotates. In Doppler imaging, high resolution, high signal-to-noise spectroscopic observations at different rotational phases are used to measure these distortions. The measurements from different rotational phases are combined to produce a map of the stellar surface temperature (such as shown in Figure 1).

The Doppler imaging studies have taught us that starspots on active stars are different from sunspots (for a review, see Strassmeier, 2009). Firstly, the starspots that can be resolved using Doppler imaging are much larger than sunspots, and are often even larger than the Sun. Also, sunspots occur close to the solar equator, usually within 35° of it, whereas the starspots can be located at much higher latitudes, even at the rotational poles. Figure 1 shows Doppler images of two magnetically active K giant primaries of RS CVn-type binaries, ζ Andromedae and IM Pegasus. The spectra used in the Doppler imaging have been obtained using the high resolution Ultraviolet and Visual Echelle Spectrograph (UVES) at the Kueyen Unit Telescope of the VLT. ζ And shows hints of a spot at the rotational pole and a belt of spots close to the equator. On IM Peg the activity concentrates at the middle latitudes. UVES spectra and Doppler imaging techniques have also been used for spatially resolving hot spots caused by accretion shocks on the rapidly rotating T Tauri-type star MN Lupi (Figure 2).

FK Com: an enigmatic prototype

FK Comae-type stars were first defined as a new group of stars in the early 1980s (Bopp & Stencel, 1981). They are magnet-

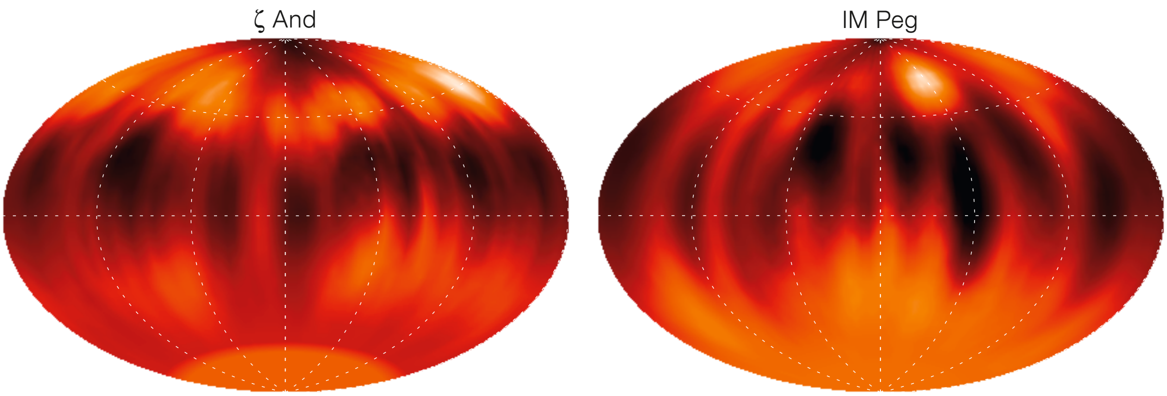


Figure 1. Examples of surface temperature maps of two K giants, ζ And and IM Peg, obtained from UVES spectra. The darker colour denotes lower temperature.

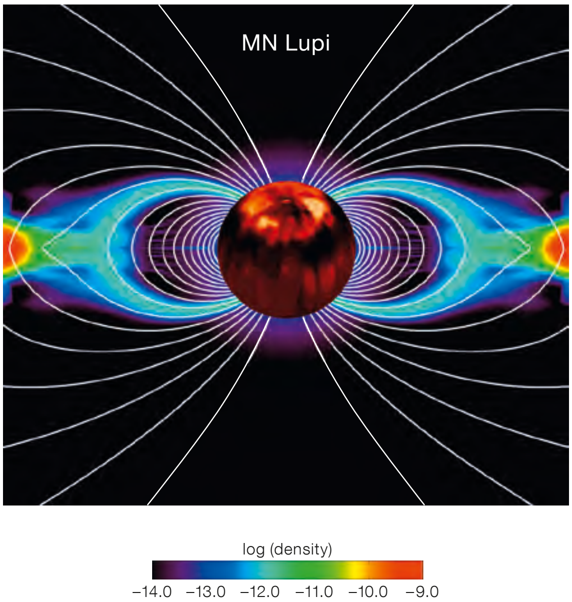


Figure 2. Doppler imaging results of MN Lupi together with numerical simulation results for the magnetic field and the density of the accretion disc. The bright high latitude spots seen in the Doppler image are not traditional starspots, but are thought to be the impact locations of the accreting material funnelled by the magnetic fields onto the star (from Strassmeier et al., 2005).

ically very active late-type giants with rotation periods of only a few days. Spectroscopic observations of these stars do not reveal any sign of the presence of a companion. The photometric and spectroscopic characteristics of FK Comae-type stars are very similar to those of the active RS CVn-type stars, e.g., ζ And and IM Peg described above. But the RS CVn-type stars are close binary systems in which tidal effects produce synchronous rotation, and therefore also rapid rotation, whereas FK Comae-type stars are thought to be single.

Among the late-type single giants, $v\sin i$ values larger than about 10 km/s are extremely rare. Thus, the anomalously rapid rotation of FK Comae-type stars demands an explanation. Three main theories have been put forward for their nature: post-main-sequence stars, whose rapid rotation is provided by core angular-momentum transport; coalescing binaries that accrete material from an unseen companion; or coalesced W UMa-type binaries. The last scenario is the most likely one to explain the observed characteristics of the FK Comae-type stars. If the coalescence is really the cause of the rapid rotation in these stars, it could have interesting ramifications for the internal structure and dynamo operation of these stars, and thus also on their magnetic activity.

FK Com itself, with its $v\sin i$ value of 160 km/s, is the fastest rotator of the FK Comae-type stars, and thus also the most active among them. The spectrum of FK Com is peculiar, showing Hα and Ca II H&K emission and variable Balmer line profiles. Its visual brightness varies by 0.1–0.3 magnitudes in the V-band with a period of approximately 2.4 days. These variations are interpreted as being caused by large starspots on the surface. Several surface temperature maps of FK Com have been obtained over the years using Doppler imaging techniques. These surface temperature maps mainly show high latitude spots with spot temperatures approximately 1000 K less than that of the unspotted surface (see, e.g., Korhonen et al., 2007).

An unexplained phenomenon

Long-term photometric observations show that the spots on FK Com tend to concentrate on two active longitudes which are about 180 degrees apart (Jetsu et al., 1993). These active longitudes alternate in strength and a switch in the longitude of the main spot activity occurs every few years. Figure 3 shows examples of V-band light curves from the 1990s showing one of these so-called flip-flop events. The cycle length of the flip-flop phenomenon in FK Com has been estimated to be 6.4 years (Korhonen et al., 2002), i.e., one flip-flop occurs on average every 3.2 years. After its discovery in FK Com, the flip-flop phenomenon has also been reported in RS CVn-type binaries and young solar-type stars, and it has been suggested that it also occurs in the Sun (see, e.g., Berdyugina & Tuominen, 1998; Usoskin et al., 2005).

The flip-flop phenomenon has strong implications for the dynamo theory. The behaviour of the global solar magnetic field can be explained by an axisymmetric mean-field dynamo without any longitudinal structure. In more rapidly rotating stars, the higher order non-axisymmetric modes become excited, forming two active regions that are 180° apart, i.e., equivalent to the two permanent active longitudes, as seen in many active stars. Not only is the magnetic configuration different in the axisymmetric and non-axisymmetric modes, but so are their oscillatory properties. The solar-type axisymmetric modes show clear cyclical behaviour, whereas the non-axisymmetric modes do not oscillate. To explain the flip-flop phenomenon, both properties — non-axisymmetric field configuration and oscillations — are needed. To constrain the dynamo models and to properly understand the mechanism behind the flip-flops, it is crucial to obtain measurements of the magnetic field behaviour at the two permanent active longitudes.

Spectropolarimetric investigation of FK Com

To investigate the magnetic field of FK Com, and especially the polarities of the active longitudes, we have obtained low resolution ($\lambda/\Delta\lambda = 2000$) spectropolarimetric observations using FORS1 with VLT Kueyen. The observations were obtained in April 2008 and show a distinct signal in the circular polarisation, as is seen in Figure 4. We have obtained nine separate observations at different rotational phases of FK Com. The mean longitudinal magnetic field, which is measured from the circularly polarised spectra, shows a clear variation over the stellar rotation. Figure 5 shows the magnetic field behaviour over the rotation, with the maximum value of the mean longitudinal field $\langle B_z \rangle = 272 \pm 24$ G occurring at the phase 0.08 and the field

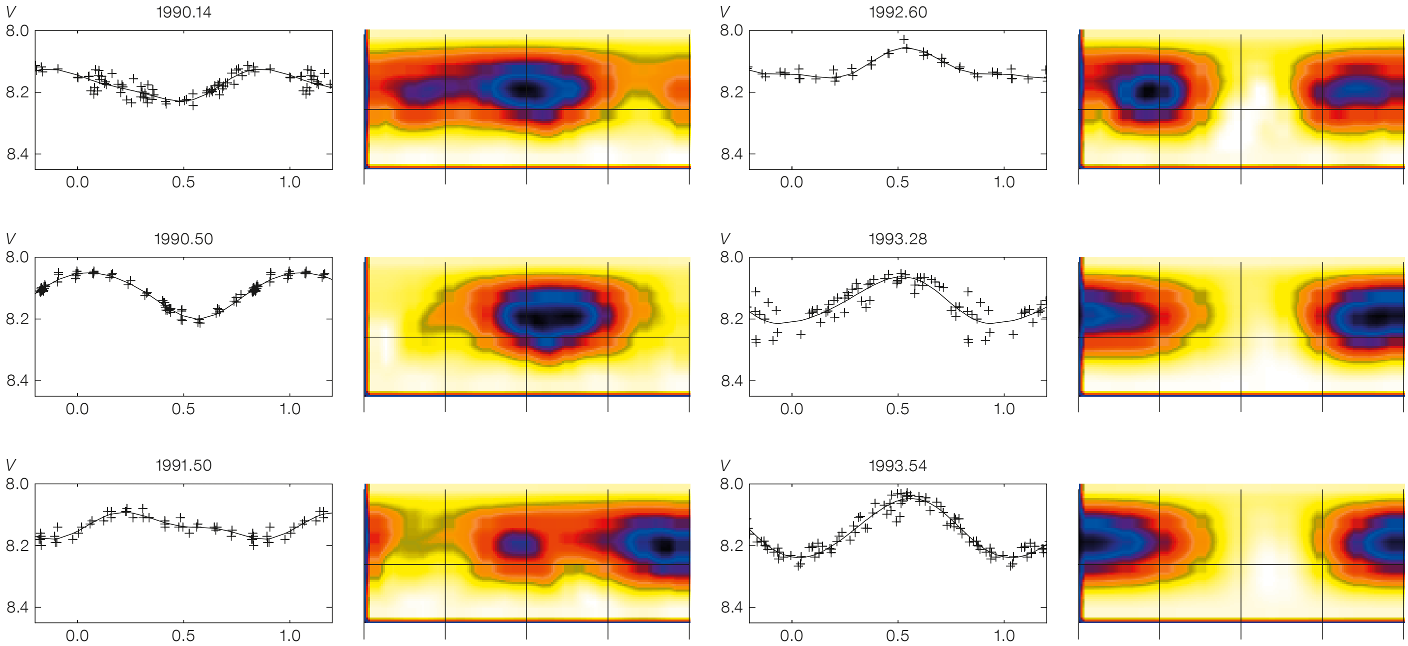


Figure 3. *V*-band light curves of FK Com and the spot filling factor maps obtained from them. The photometric observations are from 1990–1993. In the light curves the crosses are the observations and the solid line the result from the inversion. In the light-curve inversion maps the darker colour indicates a larger spot filling factor. Note that these maps are not Doppler images, and only give information on the longitudinal distribution of the spots. A flip-flop event is clearly seen in the data. In 1990 the spots concentrate around the phase 0.5 and in late 1991 change to a configuration with an active region at phase 0.0 (1.0) (from Korhonen et al., 2002).

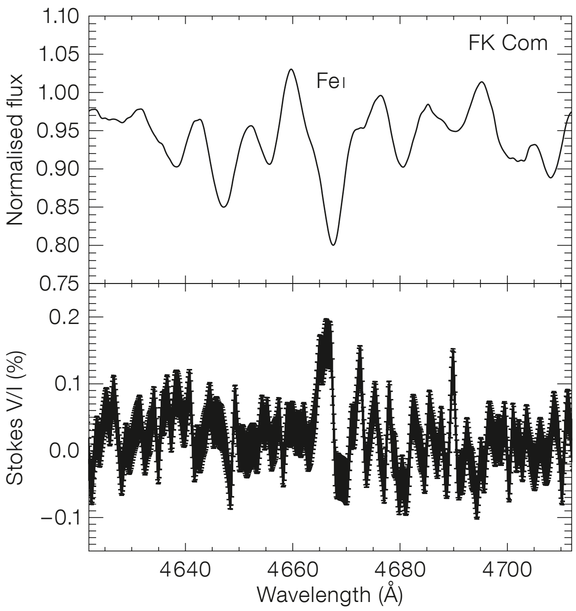
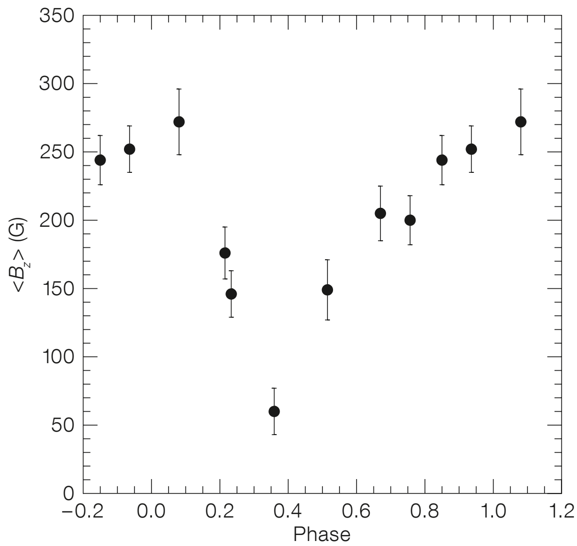


Figure 4 (left). FORS1 Stokes I (integral light) and Stokes V (circularly polarised) spectra of FK Com. In the plot the spectrum around the iron line, Fe 466.8 nm, is shown (from Korhonen et al., 2009).

Figure 5 (below). The mean longitudinal magnetic field measured from the FORS1 circularly polarised spectra plotted over the rotational phase.



minimum $\langle B_z \rangle = 60 \pm 17$ G at the phase 0.36. None of the observations show negative magnetic field polarity.

To be able to compare the field behaviour to the starspot locations, we have also carried out contemporaneous high resolution spectroscopy using the STELLA robotic telescope of the Astrophysical Institute Potsdam and the Instituto de Astrofísica de Canarias, located on Tenerife. These spectra have been used to obtain a surface temperature map of FK Com simultaneous with the magnetic field measurements from the FOcal Reducer and low dispersion Spectrograph (FORS1). Figure 6 shows the surface temperature map in which the

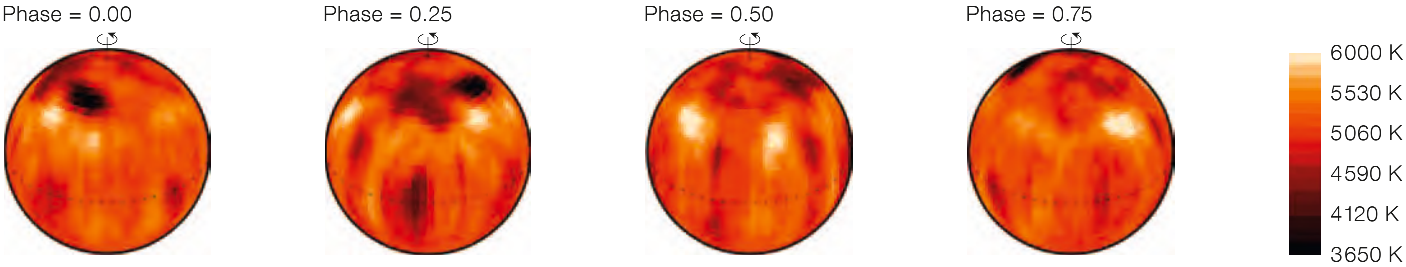


Figure 6. The surface temperature map of FK Com obtained from the STELLA data using the Doppler imaging technique. The stellar surface is shown at four different rotational phases, 0.25 in phase apart. The colour indicates the surface temperature.

coolest active region is seen at the phases 0.00–0.14 and a secondary active region at the phases 0.21–0.35. Both of the active regions occur at high latitude, but the weaker region, located at phases 0.21–0.35, also extends towards the equator.

The maximum of the longitudinal magnetic field occurs at the same rotational phase as the coolest spot seen in the surface temperature map. Also, the field minimum at the phase 0.36 coincides with the secondary active region seen on the surface at phases 0.21–0.35. It seems that the behaviour of the mean longitudinal magnetic field in FK Com is correlated with the starspots, and that the main spot on the surface, at phase 0.1, has a positive magnetic field polarity. The observed minimum, and also the very fast change from the maximum in the mean longitudinal magnetic field to the minimum, could be explained by the secondary active region having a negative magnetic field polarity. The negative field would partly cancel the positive field emerging in the dominant spot.

If the spot at the phase 0.1 does indeed have a different polarity from the one at phase 0.3, then this configuration closely resembles the one that is commonly observed in the Sun. Sunspots usually occur in pairs where the two components have different polarities. Also, in the Sun, the leading spot (the one in the pair that is first in the direction of rotation) is more compact, and the following one is more fragmented. In Doppler images the compact spot would be seen as a cooler spot and the fragmented one would have a higher average temperature, as is seen in the Doppler image of FK Com (Figure 6). In the solar case, the spots in a pair are connected by magnetic loops. The earlier X-ray observations of FK Com also hint at loops connecting two nearby spots (Drake et al., 2008), also indicating that the two spots on FK Com could have different spot polarities.

The low resolution FORS1 spectropolarimetric observations show some evidence that the two main spots on FK Com have different magnetic field polarities. However, these spots are only 0.25 in phase away from each other and have to be viewed as residing on the same active longitude. Thus, even though the FORS1 observations have provided an interesting view of the possible spot polarity configuration analogous to the solar case, they have not been able to answer the question on the active longitude polarities on FK Com. Partly this is due to the fact that during our observations the second active longitude did not show spots. One has to keep also in mind that the low spectral resolution observations do not provide a detailed insight into the magnetic surface structures. To answer the question on the spot polarities at the two permanent active longitudes properly, high resolution spectropolarimetric observations would be needed. Also, these high resolution observations should be carried out before and after a flip-flop event to study the possibility of the active longitudes changing polarity during the flip-flop, as predicted by some models (e.g., Tuominen et al., 2002).

Closing remarks

We have shown that the low resolution spectropolarimetry with FORS1 can also be used to investigate magnetic fields in cool stars, and not only for hot stars, as has previously been the case (see Hubrig et al., 2009). The recent change of polarimetric capabilities from FORS1 to FORS2, which has a more red-sensitive CCD, will be beneficial for studying the cooler, redder stars. Also, until now ESO has not had a high resolution spectrograph with polarimetric capabilities, which is needed for studying the stellar surface in greater detail. This situation will improve dramatically with the commissioning of the polarimetric mode of the HARPS high resolution spectrograph on La Silla. This facility will open a new frontier for the ESO community for studying stellar magnetic fields until the E-ELT comes online. A high precision spectropolarimeter on the E-ELT could address cosmic magnetism in many more objects than just the brightest and most prominent stars.

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