

Magnetic Topologies of Cool Stars

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Abstract. Stellar magnetic fields can be investigated using several, very complementary approaches. While conventional spectroscopy is capable of estimating the average magnetic strength of potentially complex field configurations thanks to its low sensitivity to the vector properties of the field, spectropolarimetry can be used to map the medium- and large-scale structure of magnetic topologies. In particular, the latter approach allows one to retrieve information about the poloidal and toroidal components of the large-scale dynamo fields in low-mass stars, and thus to investigate the physical processes that produce them. Similarly, this technique can be used to explore how magnetic fields couple young stars to their massive accretion disc and thus to estimate how much mass and angular momentum are transferred to the newly-born low-mass star. We present here the latest results in this field obtained with spectropolarimetry, with special emphasis on the surprising discoveries obtained on very-low mass fully-convective stars and classical T Tauri stars thanks to the ESPaDOnS spectropolarimeter recently installed on the 3.6m Canada-France-Hawaii Telescope.

1. Context

Most cool stars like our Sun are known to exhibit signs of activity. These activity demonstrations can take different forms and occur on different timescales. Cool spots are seen to come and go at the surfaces of cool stars (for a recent review, see, eg, Berdyugina 2005), and their number, in the particular case of the Sun, is seen to vary regularly on a period (dubbed activity cycle) of about 11 yrs. Very-hot low-density plasma is observed around cool stars, forming the so-called corona that shows up very clearly around the Sun during total eclipses. Flares often take place on cool stars and are usually associated with massive ejections of coronal material into the interplanetary/interstellar medium. These activity demonstrations usually show up in stellar spectra through a large number of

proxies, like for instance X-ray luminosity or core emission in Ca II H and K lines. The level of activity of cool stars usually scales up with their rotation rate.

Our current understanding is that such activity demonstrations are a by-product of the complex and variable magnetic fields that cool stars generate at their surfaces and in their convective envelopes through phenomena called dynamo processes, involving cyclonic motions of ionised plasma and rotational shearing of internal layers. In the particular case of the Sun, these processes are thought to take place in a thin interface layer confined at the base of the convective zone, where rotation gradients are supposed to be largest (for recent reviews, see, eg, Fan 2004; Charbonneau 2005). Very-low-mass stars, whose interiors are fully convective and thus obviously lack such an interface layer where dynamo processes could concentrate, are thus especially interesting for studies of stellar activity; while such characteristics should make these stars unable to produce solar-like magnetic fields, they are nevertheless both very active and strongly magnetic (Delfosse et al. 1998; Johns-Krull & Valenti 1996), and the exact mechanism under which they yet succeed at producing their magnetism is still a very debated subject (see, eg, Dobler, Stix, & Brandenburg 2006; Chabrier & Küker 2006).

An even hotter issue concerns the role of magnetic fields in the formation of stars and their planetary systems. During this evolutionary phase, the star is supposed to form from a collapsing molecular cloud, turned into a flat and massive accretion disc under the effect of both gravity and rotation. Accretion in such discs is unusually strong, typically orders of magnitude stronger than what molecular viscosity can achieve. These discs are often spatially associated with powerful and highly collimated jets emerging from the disc core and aligned with the disc rotation axis. Through their spectral energy distributions and other tracers, we infer that these discs feature a central hole, suggesting that accretion from the inner disc ridge towards the central stars occurs through dense and discrete funnels. Models invoke magnetic fields as the main explanation (for recent reviews, see, eg, Pudritz et al. 2006; Bouvier et al. 2006); such fields are also expected to modify the rate at which protoplanetary clumps form and migrate within the disc. While strong magnetic fields are indeed known to be present at the surfaces of such newly-born stars (dubbed classical T Tauri stars or cTTS), very little is known on their exact topologies at the surfaces of both stars and discs. This is however precisely the kind of information we need to constrain existing models.

Magnetic fields on stars are most often estimated using the well-known Zeeman effect, that broadens the unpolarised profiles of magnetically sensitive lines and induces circular (Stokes V) and linear polarisation (Stokes Q and U) signals throughout their widths, depending in particular on the orientation of field lines with respect to the line of sight. For this very reason, high-resolution stellar spectropolarimetry, that can recover information on large- and medium-scale magnetic topologies at the surfaces of active stars, is an obvious tool to use to challenge existing theoretical models of stellar formation and dynamo processes (eg, Donati et al. 2003). ESPaDOnS, the new generation spectropolarimeter recently installed on the 3.6m Canada-France-Hawaii telescope (CFHT), and NARVAL, its twin copy just commissioned on the 2m Bernard-Lyot telescope (TBL) atop Pic du Midi, were optimised in this aim and fill a long-standing

gap in instrumental capabilities (Donati et al, in preparation). Recent surprising results obtained with ESPaDOnS in the above mentioned research fields are outlined in this paper. Future potential directions for new instruments are also suggested.

2. Measuring and modelling magnetic fields with spectropolarimetry

Until 1980, all experiments at measuring magnetic fields in cool active stars other than the Sun failed. Most of them were using instruments directly inherited from solar physics, measuring line shifts between spectra respectively measured in circular left and right polarisation states and giving access to the average magnetic field component along the line of sight (dubbed longitudinal field). However, for complex magnetic topologies such as that of the Sun and those anticipated on cool stars, the net longitudinal magnetic field is fairly small, with contributions of opposite polarities mutually cancelling out. This a posteriori explains why these initial attempts failed.

From 1980, investigations of the differential broadening of unpolarised spectral lines with different magnetic sensitivities demonstrated unambiguously that magnetic fields are indeed present at the surfaces of cool stars (for a recent review, see Johns-Krull 2007). This success was obtained thanks to the fact that broadening signatures from regions of opposite polarities do not mutually cancel in the integrated spectrum as polarisation signatures do. The very reason behind the success of this technique is however also what causes its intrinsic limitations. Being almost insensitive to the local magnetic topology, this technique yields no more than an estimate of the relative surface area covered with magnetic fields, along with an average magnetic intensity (sometimes a rough distribution of magnetic intensities) within these magnetic regions.

Since 1990, various studies demonstrated that polarisation signatures in spectral lines of cool stars, although often very weak, are actually detectable provided that full Zeeman signatures (rather than longitudinal fields values only) are recorded, and that specific and optimised instrument, observing procedure and reduction software are used (Donati et al. 1997). While this latter technique remains insensitive to the small magnetic scales present at the surface of cool stars, it can however yield key information such as how much fractional magnetic energy is stored within large and medium spatial scales, and how the field decomposes into its axisymmetric and non-axisymmetric modes, or into its poloidal and toroidal components. In this respect, it provides us with a genuinely new and very powerful tool for studying dynamo processes of active stars other than the Sun.

For such studies, we use high-resolution spectropolarimeters. They consist of an achromatic polarimeter mounted at the Cassegrain focus of a telescope, fiber feeding a bench-mounted high-resolution échelle spectrograph on which both orthogonal components of the selected polarisation state can be simultaneously recorded as interleaved échelle spectra on the CCD detector. It also includes all usual calibration, viewing and guiding facilities that are necessary for conventional spectroscopy. The new generation of such instruments, ESPaDOnS and NARVAL, were especially optimised to feature a very achromatic polarimetric analysis (using Fresnel rhombs as retarders), a very high efficiency

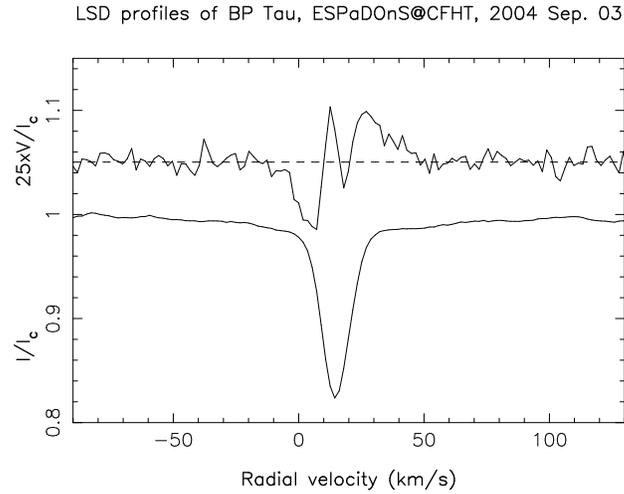


Figure 1. LSD circular polarisation Zeeman signature from the photospheric lines of BP Tau, as derived from ESPaDOnS data

(of order 10 to 15% including telescope and detector), a wide spectral coverage (370 to 1,000 nm in a single exposure) and high spectral resolution (65,000 in polarimetric mode). A complete instrumental description is given in Donati et al (in preparation).

Given that typical Zeeman signatures from cool active stars are rather small (Donati et al. 1997), detecting them usually requires the extraction of the relevant information from as many lines as possible throughout the entire spectrum, using cross-correlation type tools such as Least-Squares Deconvolution (LSD, Donati et al. 1997). Up to 8,000 lines can be used in the domain of ESPaDOnS, yielding average Zeeman signatures with an equivalent signal to noise ratio boosted by several tens compared to that of a single average spectral line (see Fig. 1).

Measuring Zeeman signatures of cool active stars and monitoring their modulation as the star rotates gives access, to some extent, to the parent magnetic topology at the surface of the stars, in the very same way medical imaging techniques recover 3D images of the inside structure of human bodies by looking at them from all sides. Such tomographic techniques, dubbed Doppler and Zeeman-Doppler imaging, use the fact that surface features located at different longitudes and latitudes, and hosting field lines of different orientations produce different time-dependent distortions in temporal series of spectral lines (Donati & Brown 1997). While such techniques are most efficient for stars rotating rapidly, they can also successfully be used on slow rotators (eg, Donati et al. 2006b) and are particularly good at recovering both poloidal and toroidal components of the surface magnetic field. Assuming a potential field, the poloidal field component can also be used to estimate, through vector field extrapolation techniques, the large-scale coronal structure of the stellar magnetosphere (Jardine et al. 2002).

3. Very-low-mass fully-convective stars

As mentioned already, very-low-mass main-sequence stars (with a spectral type later than M3, ie a mass lower than about $0.35 M_{\odot}$, Chabrier & Baraffe 1997) are particularly interesting for studies of dynamo processes in active stars. Being fully convective, these stars obviously lack the thin interface layer at the base of the convective zone where solar-like dynamo processes presumably concentrate. Yet, they are both very active and strongly magnetic. Current dynamo theories predict that they should trigger a genuine type of non-solar dynamo processes in which cyclonic convection and turbulence are by far the main actors, as opposed to the Sun where differential rotation is a major contributor. The most recent investigations conclude that such stars should be able to produce large-scale magnetic fields; however, while some claim that they should rotate as solid bodies and host purely non-axisymmetric large-scale field configurations (eg, Küker & Rüdiger 2005; Chabrier & Küker 2006), others diagnose that they should still generate significant differential rotation and thus produce a net (though weak) axisymmetric field component (eg, Dobler, Stix, & Brandenburg 2006).

Observations of largely convective stars indicate that surface differential rotation is indeed vanishing with increasing convective depths (Barnes et al. 2005), with fully convective stars rotating as solid bodies (Donati et al. 2006a). At first sight, this result seems to confirm nicely the theoretical predictions of Küker & Rüdiger (2005) and to invalidate those of Dobler, Stix, & Brandenburg (2006). However, spectropolarimetric observations of large-scale magnetic topologies in fully-convective stars led to a fairly different conclusion. By looking with ES-PaDOnS at the rapidly rotating M4.5 dwarf V374 Peg (whose rotation period is just under half a day, ie about 60 times shorter than that of the Sun) for almost three complete rotation periods over nine rotation cycles, Donati et al. (2006a) derived that the star hosts a strong poloidal field whose energy mostly concentrates in low-degree axisymmetric modes (see Fig. 2), in gross contradiction with all existing predictions. Also worth noting is the drastic difference between the field configuration of V374 Peg with those of partly convective stars, which always feature a significant (and often dominant) toroidal component (Donati et al. 2003; Petit et al. 2005). The main conclusion of these first observations is that fully-convective stars indeed seem to be able to trigger different kinds of dynamo processes than those of partly convective stars. There is however still some way to go before we fully understand the theoretical machinery of dynamo processes in stellar convective zones, and it may well be that the solar dynamo itself is more complex than what we think it is.

Following this initial result, a more extensive spectropolarimetric observing program of fully-convective dwarfs was initiated, in the aim of achieving a small magnetic survey of about 25 stars selected to sample as evenly as possible rotation rates and spectral types. Up to now, observations have been collected for about half a dozen stars, with spectral types spanning M3 to M7 and periods ranging from half a day up to about 5 d. Although still very incomplete, this survey already suggests that among fully convective stars, strong axisymmetric large-scale field topologies are found exclusively on rapid rotators while non-axisymmetric magnetic structures only show up on moderate rotators, the slowest rotators showing no large-scale fields at all (Morin et al., in preparation). This result, once confirmed on a more comprehensive data set, could stress how

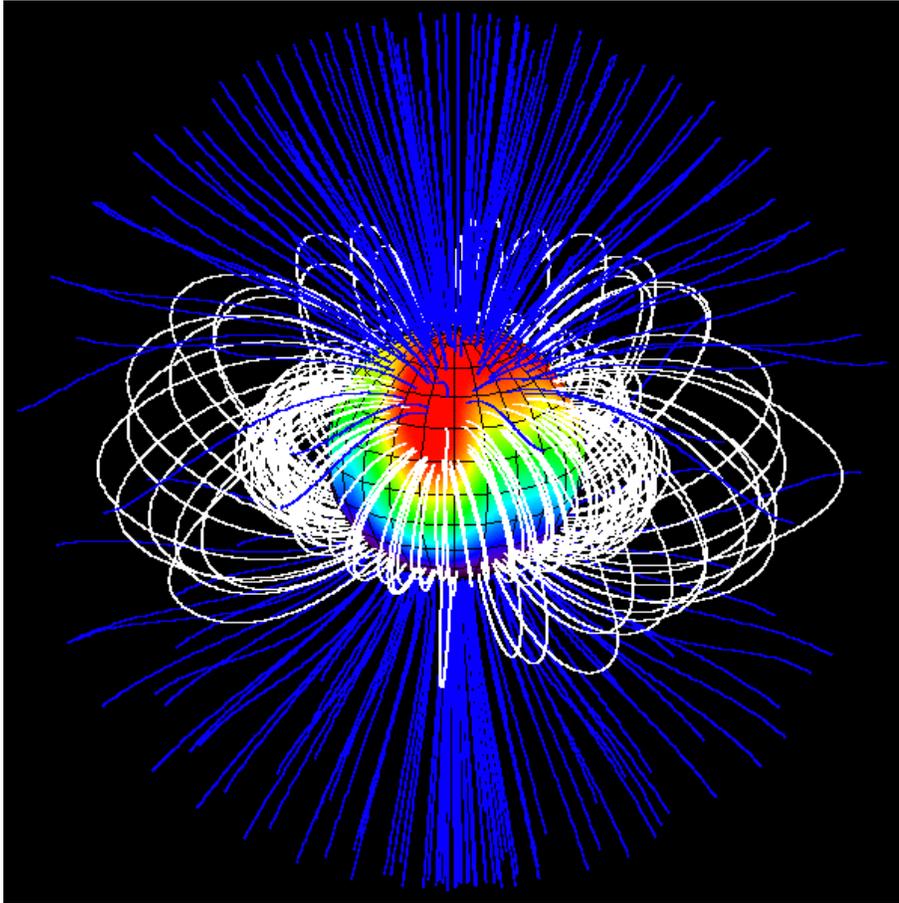


Figure 2. Magnetosphere of V374 Peg, as derived from ESPaDOnS spectropolarimetric data

critically rotation influences dynamo processes and hint at new ideas for producing a more successful theoretical description of how dynamo works in stellar convective zones.

4. Classical T-Tauri stars and their accretion discs

As briefly alluded to above, magnetic fields play a key role in the early stages of stellar evolution when the newly born star is still surrounded by a massive accretion disc (the cTTS phase). In most cases, the spectral energy distribution of such objects is dominated by light from the star in the visible, while the accretion disc outshines the star in the infrared; in rare cases though, the accretion disc is found to undergo drastic outbursts (called FU Ori episodes) during which the rate of accretion scales up by several orders of magnitude, causing the disc to outshine the star at all wavelengths. In protostellar discs, magnetic fields are expected to boost the accretion rate within the disc itself (through MHD instabilities), to expell some of the disc material along the jet-like structures

often observed around young stars, and to clear out by magnetic disruption the central regions of the disc and funnel the inner disc material to the stellar surface (when the accretion rate is not too strong).

Obviously, magnetic fields are expected to have a strong impact on the angular momentum evolution of young stars. Theorists proposed that the magnetic coupling between the stars and their inner discs was strong enough to force the star to corotate at the Keplerian velocity of the inner disc (eg, Königl 1991), thus potentially explaining why rotation rates of cTTS are significantly lower than those of discless protostars. Yet, estimates of magnetic intensities at the surface of cTTS derived from Zeeman broadening of unpolarised lines is largely uncorrelated with what those models predict to ensure star-disc coupling (Johns-Krull 2007). It essentially shows that the physical details of this magnetic link between the star and disc are still rather enigmatic to us, and need to be unravelled if we want to understand angular momentum evolution during stellar formation stages.

In this respect, spectropolarimetric observations of cTTS can bring us new clues for this problem. The discovery that spectral lines formed at the base of accretion funnels (eg the He I line at 587.6 nm) exhibit strong levels of circular polarisation (Johns-Krull et al. 1999) indicate that magnetic fields are indeed likely to control accretion from the inner disc to the stellar surface. Further observations collected across the rotation cycles of a few cTTS (Valenti & Johns-Krull 2004; Symington et al. 2005) revealed that the large-scale magnetic geometry, anchored in kG field regions, seems rather simple and stable on time scales of at least several years, suggesting the presence of strong dipoles moderately tilted with respect to the stellar rotation axis. Numerical simulations of magnetospheric accretion were carried out in this context, including various additional ingredients such as winds from the star and disc and dynamo disc fields (eg, Romanova et al. 2003, 2004; vonRekowski & Brandenburg 2004), to obtain more realistic predictions along with detailed observational diagnostics.

The apparent weakness of Zeeman signatures in photospheric lines of cTTs (eg, Johns-Krull et al. 1999) remains however mysterious in the context of strong dipole-like magnetospheric topologies. Prominent circular polarisation signals are indeed expected in most lines from strong dipole fields, while only highly tangled magnetic topologies can remain undetected through spectropolarimetry.

With the availability of ESPaDOnS, new perspectives are opened for studying magnetospheric accretion on cTTS. The K7 low-mass cTTS BP Tau was monitored for 9 consecutive nights in Feb. 2006 while the more massive G5 cTTS V2129 Oph was looked at in June 2005 for 8 successive nights. In both of them, strong Zeeman signatures from numerous emission lines formed in accretion funnel footpoints were detected and found to vary smoothly and simply with rotation rate, in complete agreement with previous results (Valenti & Johns-Krull 2004; Symington et al. 2005). In addition to this, weaker (though still very clear) Zeeman signatures were also detected in photospheric lines thanks to the higher efficiency of ESPaDOnS (eg, see Fig. 1); their complex shape however confirms that the surface field topology on both BP Tau and V2129 Oph is indeed more complex than a simple dipole.

Attempts at finding a unique magnetic model that can reconcile both sets of Zeeman signatures are being carried out at the moment, under the assumption that photospheric lines are not sensitive to the highly magnetic (and thus

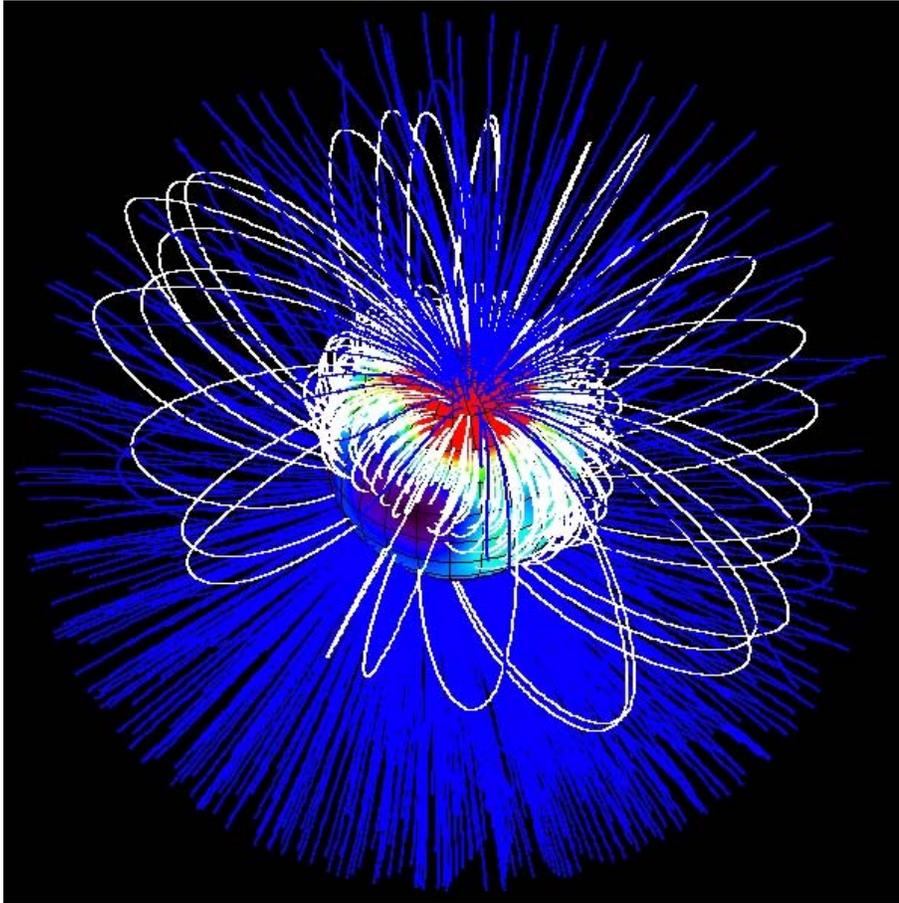


Figure 3. Magnetosphere of V2129 Oph, as derived from ESPaDOnS spectropolarimetric data (this result is still preliminary)

presumably very cool) surface regions located at the footpoints of accretion funnels. A preliminary solution for V2129 Oph (see Fig. 3) illustrates what the true magnetosphere of a cTTS could look like (Donati et al., in preparation); while the large-scale field indeed resembles a dipole as witnessed from the simple variational behaviour of the Zeeman signatures from accretion proxies, the surface field is more complex and features nearby field regions of opposite polarities. More realistic simulations of magnetospheric accretion are thus needed (and underway, Jardine et al. 2006; Gregory et al. 2006a,b) to obtain a better understanding of this crucial stage in stellar formation.

Protostellar accretion discs may also host magnetic fields. In fact, they are the likely vectors that convey interstellar magnetic fields within stellar cores through ambipolar diffusion and advection. Magnetic fields are probably playing a main role in boosting accretion rates through instabilities such as the now famous magneto-rotational instability (eg, Balbus & Hawley 2003) - they are also the major ingredient with which accretion discs succeed at producing pow-

erful collimated jets and expel a significant fraction of their mass and angular momentum (eg, Pudritz et al. 2006).

Magnetic fields are known to be present within molecular cores (eg, Girart, Rao, & Marrone 2006) and in the external regions of accretion discs (eg, Hutawarakorn & Cohen 2003), suggesting that interstellar magnetic fields are indeed playing a role in stellar formation. However, until very recently, no observation existed about the putative magnetic field in the inner regions of accretion discs where the jets are actually fired and the surface densities culminate. The new results obtained by ESPaDOnS on FU Ori demonstrate that strong disc core magnetic fields are indeed present, with topologies compatible with what is predicted by collimated jet formation theories (Donati et al. 2005). These observations, although still very fragmentary, also indicate that the magnetic plasma within the disc is apparently slowed down more than what models predict.

Extensive spectropolarimetric monitoring of protostellar accretion discs such as FU Ori carried over several Keplerian periods (for disc radii up to a few 0.1 AU), should allow mapping, through Doppler tomography, the full distribution of densities and magnetic fields with radius and azimuth throughout the disc core. In particular, it could tell us how successful theoretical models of magnetised molecular cloud core collapse (eg, Banerjee & Pudritz 2006) are. It could also give us a completely new opportunity to investigate the formation and migration of protoplanetary clumps within cores of accretion discs as well as the associated role of magnetic fields, and thus test the various theoretical models proposed in the literature (eg, Terquem 2003).

5. Conclusions and prospects

Our knowledge of magnetic topologies of cool active stars has greatly improved in the last two decades thanks to spectropolarimetry. The recent introduction of new generation instruments with increased sensitivity (such as ESPaDOnS at CFHT) allowed to explore new classes of objects such as young forming stars and fully convective dwarfs. As a result, we are now able to detect magnetic topologies in most cool stars provided that their rotation and activity are high enough and that they host a significant large-scale field component.

When coupled to tomographic techniques, spectropolarimetry allows not only to detect, but also to characterise the geometry of stellar magnetic topologies. For instance, we are able to decompose the field topology into its poloidal and toroidal components, thus offering great promises for studies of dynamo processes in cool stars other than the Sun. Such studies have already revealed major surprises, the latest being that fully-convective stars are apparently able to trigger strong axisymmetric large-scale field components, contrary to most theoretical expectations. Similarly, extended observations of young stars should soon allow in-depth testing of most theoretical models attempting to describe stellar formation in the presence of magnetic fields.

These results suggest that high-resolution spectropolarimetry should be actively developed in the coming years, with efficient ESPaDOnS-like instruments routinely installed on intermediate size instruments offering reasonable access for the long-term monitoring runs that such studies require. At the same time, new instruments should be designed to expand further our spectropolarimetric

capabilities and access new types of diagnostics; in this respect a high resolution near-infrared spectropolarimeter providing full spectral coverage from 0.9 to 2.4 microns appears as a very promising option for the study of magnetic fields in cool stars.

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