Cosmic Magnetic Fields:
From Planets, to Stars and Galaxies
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Measuring cosmic magnetic fields with very large telescopes

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Abstract. We review general properties and capabilities of the instrumentation employed to diagnose cosmic magnetic fields using medium-size and large optical telescopes. During the last decade these spectropolarimeters and high-resolution spectrographs have been successfully used to detect and characterize magnetic fields in stars across the H-R diagram. A new generation of high-resolution spectropolarimeters will benefit from the large collecting area of the future E-ELT and currently operating 8-m class telescopes. We review plans to develop spectropolarimeters for these very large telescopes and outline a number of science cases where new spectropolarimetric instrumentation is expected to play a key role.

Keywords. Instrumentation: polarimeters – instrumentation: spectrographs – telescopes – stars: activity – stars: magnetic fields

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1. Introduction

For a very long time astronomical polarization measurements were some of the most promising and the most frustrating. Promising – because polarization often carries geometrical information about the observed object and because it allows tracing magnetic fields, invisible otherwise. Frustrating – because polarization signal in most cases is rather small and is easily corrupted by the instrumental effects (such as instrumental polarization, chromatism of the polarimeter, sensitivity and noise properties of the detector).

Recent progress in the quality of detectors but most importantly a major progress in understanding the instrumental polarization effects made it possible to develop the new strategies for observations, calibrations and data reduction. The net results are reproducible polarization measurements of various astronomical objects carried out to unprecedented precision.

The corresponding astronomical observations are commonly divided into measurements of circular polarization, induced by the line-of-sight component of the magnetic fields, and linear polarization also produced by scattering. Scattering creates broadband continuum polarization which requires different type of instrumentation compared to high-resolution spectropolarimeters aimed at studying polarization across spectral line profiles.

In the following we review the instruments for polarimetric measurements. We start with the most advanced existing instruments followed by the projects under development.

2. Current instrumentation

2.1. *High-resolution spectropolarimetry at medium-size telescopes*

The ESPaDOnS spectropolarimeter at the 3.6-m CFHT and its twin instrument NARVAL at the 2-m TBL telescope of the Pic du Midi observatory represent the current state of the art in high-resolution, optical spectropolarimetry. ESPaDOnS is a bench-mounted echelle spectrograph designed to record a complete optical spectrum (370–1050 nm) at the resolution of $R = 65000$ in polarimetric mode (Manset & Donati 2003). The instrument is

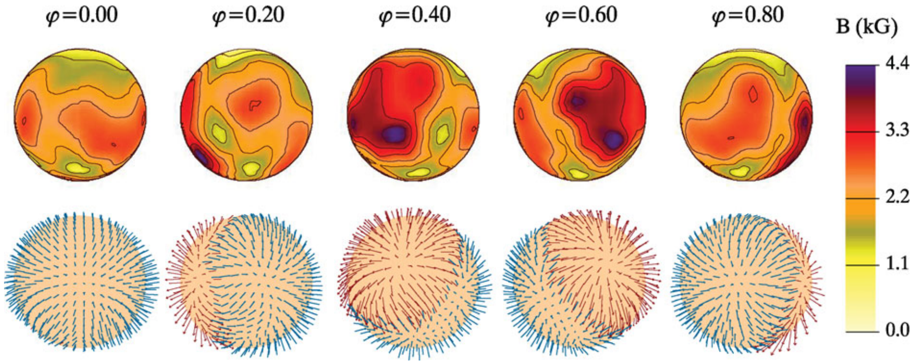

Figure 1. Magnetic field structure of the Ap star α^2 CVn reconstructed with magnetic Doppler imaging modelling of the phase-resolved observations in all four Stokes parameters (Kochukhov *et al.*, in preparation). The upper panel shows the maps of the field strength. The lower panel illustrates distribution of the field orientation.

installed in a thermally-stabilized room and is fibre-linked to a four Stokes parameter polarimeter mounted at the Cassegrain focus. An achromatic polarization analysis is made possible by the Fresnel rombs, acting as quarter-wave and half-wave plates, coupled to a Wollaston prism. The measured cross-talk from circular to linear polarization does not exceed 1% for ESPaDOnS. Analysis of circular polarization in the line profiles of weakly magnetic stars demonstrates the absence of polarization artifacts down to the level of 10^{-5}. ESPaDOnS provides $\approx$13% peak total throughput, corresponding to $S/N = 100$ in 1 h exposure of a $V = 13^{\rm m}$ star.

Observations carried out with ESPaDOnS and NARVAL have contributed significantly to the progress in understanding of stellar magnetism. For magnetic chemically peculiar A- and B-type stars, these instruments provided a unique opportunity to obtain high-quality spectra in all four Stokes parameters. Detection of linear polarization signatures in the profiles of individual lines was previously possible only for 2–3 strongest metal lines in a few very bright Ap stars using now decommissioned MuSiCoS spectropolarimeter (Wade, Donati, Landstreet, *et al.* 2000). Thanks to the improved sensitivity of ESPaDOnS and NARVAL, the $S/N = 500$–1000, required to study linear polarization in meaningful number of spectral lines, can be achieved for many more magnetic Ap stars. Ongoing phase-resolved observations of a sample of magnetic chemically peculiar stars (Silvester, Wade, Kochukhov, *et al.* 2008 and in this conference) will provide the data for detailed modelling of the stellar field geometries using magnetic Doppler Imaging technique (Piskunov & Kochukhov 2002). Generally, magnetic inversions require observations in all four Stokes parameters to achieve a unique reconstruction of the surface magnetic field topology (Kochukhov & Piskunov 2002). Availability of such data for several Ap stars has allowed us to produce the first assumption-free magnetic maps of early-type stars (Kochukhov, Bagnulo, Wade, *et al.* 2004). This novel, full Stokes vector approach to the problem of imaging stellar magnetic fields has demonstrated that, in addition to well-known dipolar-like, global field component seen in modulation of the circular polarization spectra and traditionally modelled with a low-order multipolar approximation, Ap stars possess unexpected, small-scale magnetic structures (Fig. 1). The latter contribute significantly to the morphology of the Stokes QU profiles but cannot be detected otherwise.

High-resolution spectropolarimetry has provided new insights into magnetism of massive stars. Due to large geometrical sizes of early-B and O stars, even fairly weak fields in these objects yield astrophysically important magnetic fluxes. Magnetic fields in massive

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stars control the mass loss (Babel & Montmerle 1997), creating complex and dynamic magnetospheric structures (e.g., Townsend, Owocki & Ud-Doula 2007). Magnetism is an important ingredient of the evolutionary models of massive stars (Maeder & Meynet 2000) and is possibly linked to the presence of magnetic fields in supernovae and neutron stars. Until now only a handful of magnetic O-type stars were identified and thoroughly studied (Donati, Babel, Harries, *et al.* 2002; Donati, Howarth, Bouret, *et al.* 2006). Their numbers are steadily increasing with the discovery of weak fields in other hot stars (Petit, Wade, Drissen, *et al.* 2008 and in this conference). The MiMeS Large Program (Grunhut *et al.*, this conference), recently started at CFHT, will perform a comprehensive magnetic survey using ESPaDOnS for all O-type stars in the solar neighbourhood.

For late-type stars, ESPaDOnS and NARVAL are employed for the magnetic field detection and Doppler imaging analysis of the strong fields in faint active low-mass and young stars and of very weak fields in bright solar-type stars. This work is based upon circular polarization measurements and is focused on the interpretation of the mean line polarization signature derived with the help of multi-line Least-Squares Deconvolution technique (Donati, Semel, Carter, *et al.* 1997). This powerful line co-addition method provides a factor of 10–40 gain in S/N by combining information from thousands spectral lines at the price of adopting a greatly simplified description of the intensity and polarization spectra, valid in the limit of low field strength and weak lines.

A combination of the multi-line approach with the increased sensitivity and wavelength coverage of the new high-resolution spectropolarimeters has allowed to detect global fields weaker than 10 G in solar-like stars (Petit, Ditrans, Solanki, *et al.* 2008 and in this conference). Reconstruction of the large-scale magnetic geometries shows that both the total magnetic flux and the relative contribution of toroidal field component in the surface field strongly depends on the stellar rotation rate and mass. The global fields were also reconstructed for the exoplanet-host stars HD 189733 (Moutou, Donati, Savalle, *et al.* 2007) and τ Boo (Catala, Donati, Shkolnik, *et al.* 2007). The field polarity reversals seen in the latter star may be a signature of activity cycle driven by the star-planet magnetic interaction (Donati, Moutou, Fares, *et al.* 2008).

For T Tauri stars, the ESPaDOnS spectropolarimeter provided observations that made possible reconstruction of the large-scale magnetic field topology (Donati, Jardine, Gregory, *et al.* 2008) and subsequent investigation of the role of magnetic fields in accretion process and star-disk coupling using more realistic field topologies than the commonly assumed dipolar fields (Gregory, Matt, Donati, *et al.* 2008). These models of stellar magnetic field could provide a realistic boundary condition for detailed MHD simulations of the magnetospheric accretion on T Tauri stars (Long, Romanova & Lovelace 2008).

Significant progress was also achieved for low-mass active stars. Despite the well-known evidence for the presence of strong magnetic fields in M dwarfs (e.g., Johns-Krull & Valenti 1996), the global geometry of fields in these stars remained unknown until recently. The study by Morin, Donati, Petit, *et al.* (2008) suggested that active mid-M dwarfs host relatively strong, mainly poloidal, axisymmetric, global fields which are stable on the time scale of many rotation periods. At the same time, these stars show no differential rotation. This underlines significant difference of the field generation processes operating in the fully-convective envelopes of M dwarfs compared to the solar tachocline dynamo. The large strength and simple organization of the large-scale fields in active M stars suggests that it should be possible to detect and interpret linear polarization in their spectral lines.

The application of the multi-line LSD method to the problem of magnetic field detection and modelling in late-type stars succeeds in extracting useful information from the entire stellar spectrum. However, it also introduces certain complications and poorly understood systematic biases when LSD profiles are interpreted using Zeeman Doppler Imaging codes. More robust and detailed information about magnetic fields and their relation to the temperature inhomogeneities can be obtained by modelling individual atomic and molecular lines and exploiting their differential sensitivity to temperature and magnetic field at different atmospheric layers (Kochukhov *et al.*; Carroll *et al.*; Berdyugina *et al.*, this conference). The current instrumentation at the 3–4-m class telescopes is suitable to accomplish the task of reaching a high S/N necessary for the direct detection of circular polarization signatures in the spectra of most active late-type stars (Petit 2006; Berdyugina, Petit, Fluri, *et al.* 2006). Thus, some effort should be directed towards acquiring and interpreting such data in order to complement, verify and, possibly, re-calibrate the LSD-based results.

2.2. *Low-resolution spectropolarimetry at VLT*

Among the instruments at the 8–10-m class telescopes equipped with polarization analysing optics only FORS1 (Focal reducer Optical Range Spectrograph) at the ESO VLT is widely used to test the presence of magnetic fields in different types of stars. FORS1 is a multi-mode spectrograph, capable of performing low-resolution ($R \leqslant 2000$) optical spectropolarimetry in the wavelength range from the Balmer jump to Hα. Bagnulo, Szeifert, Wade, *et al.* (2002) developed a technique to measure the mean longitudinal magnetic fields with FORS1. At the low spectral resolution provided by this instrument only the broad hydrogen Balmer line wings can be resolved. Consequently, Bagnulo *et al.* (2002) proposed to employ a magnetic diagnostic technique similar to the photopolarimetric method of Borra & Landstreet (1980). Using a weak-field approximation, which is an adequate assumption for the hydrogen line formation in all types of non-degenerate magnetic stars, one can obtain longitudinal magnetic field from a correlation between the Stokes V signal and the derivative of Stokes I. Extending this regression analysis to the spectral regions containing unresolved metal line blends yields formally a more precise measure of the longitudinal field, but may introduce some systematic errors (Bagnulo *et al.* 2002).

Magnetic field measurements with FORS1 rely on obtaining $S/N \geqslant 1000$ in the hydrogen line wings. In practice, one has to collect photons for ≈ 1 h with the 8-m VLT to achieve a 50 G field measurement accuracy for a $V = 10^{\mathrm{m}}$ star. Due to the large intrinsic width of the hydrogen lines, the method is not particularly sensitive to stellar rotation and, thus, can be applied to essentially all classes of early-type stars.

The FORS1 instrument was used to search for links between magnetic fields and stellar evolution in open cluster A- and B-type stars (Bagnulo, Landstreet, Mason, *et al.* 2006). Several young Ap stars with remarkably strong longitudinal fields were discovered in this survey (Bagnulo, Landstreet, Lo Curto, *et al.* 2003; Bagnulo, Hensberge, Landstreet, *et al.* 2004). Based on FORS1 observations, global, kG-strength fields were also detected in DA white dwarfs (Aznar Cuadrado, Jordan, Napiwotzki, *et al.* 2004), hot subdwarfs (O'Toole, Jordan, Friedrich, *et al.* 2005), and in central stars of planetary nebulae (Jordan, Werner & O'Toole 2005). Systematic FORS1 observations of large samples of A and B chemically peculiar stars allowed to increase substantially the number of stars with known magnetic field properties and investigate possible variation of the field intensity with stellar age (Hubrig, Szeifert, Schöller, *et al.* 2004a; Kochukhov & Bagnulo 2006; Hubrig, North, Schöller, *et al.* 2006a).

FORS1 at VLT was also used to measure weak magnetic fields in O-type stars (Hubrig, Schöller, Schnerr, *et al.* 2008 and in this conference), hot pulsating stars (Hubrig, Briquet, Schöller, *et al.* 2006b), and Herbig Ae/Be stars (Hubrig, Schöller & Yudin 2004b). It should be noted, however, that more precise high-resolution spectropolarimetric analyses by Wade, Drouin, Bagnulo, *et al.* (2005), Wade, Abecassis, Auriere, *et al.* (2006) and Silvester, *et al.* (this meeting) cast doubt on some of these claimed FORS1 detections of fields weaker than 1–2 hundred gauss.

In addition to measurement of the mean line of sight magnetic field component in early-type main sequence stars, the FORS1 polarimeter provided data for detailed Stokes line profile analysis of several magnetic white dwarfs with fields exceeding 100 kG (Euchner, Reinsch, Jordan, *et al.* 2005; Valyavin, Wade, Bagnulo, *et al.* 2008; Jordan, this meeting).

2.3. *Diagnosing magnetic fields with high-resolution infrared spectra*

Analysis of high-resolution circular polarization observations across a wide wavelength range has been successfully used for detection of weak stellar magnetic fields. Spectropolarimetric time series, interpreted using magnetic inversion codes, provided constraints on the global field topologies for a variety of magnetic stars, from massive magnetic O stars to late-M dwarfs. However, circular polarization measurements suffer from two important limitations. On the one hand, the Stokes V spectrum provides information only on the line of sight projection of the stellar magnetic field. The mean field strength and magnetic flux cannot be inferred in a straightforward and model-independent manner for the majority of magnetic stars which host weak or moderate-strength fields. Secondly, the amplitude of the observed disk-integrated line of sight field component is very sensitive to the geometry of the magnetic field. The presence of complex field structures, such as bipolar groups frequently seen on the sun, leads to cancellation of the polarization signal and no detectable net longitudinal field.

Magnetic broadening and splitting of atomic and molecular lines in the intensity spectra can supply missing information about small-scale, complex magnetic fields. The relative strength of the π and σ components of the Zeeman split spectral lines is generally weakly sensitive to the field orientation, while the separation of the Zeeman components depends only on the field strength. In this way, interpretation of the Stokes I spectra of magnetic stars can complement and enhance polarization measurements.

The fundamental difficulty of the Stokes I analysis is the necessity of disentangling small magnetic perturbations from the intrinsic, often poorly known, line shape. Therefore, analysis of magnetic broadening in active late-type stars is often considered as not particularly robust and strongly model-dependent (Robinson 1980; Basri & Marcy 1994; Guenther, Lehmann, Emerson, *et al.* 1999). But as the Zeeman splitting increases and eventually exceeds the other line broadening mechanisms (thermal and rotational Doppler broadening), one can securely measure the mean field strength in a simple and direct way. The optical spectra of slowly rotating strongly magnetic Ap stars provide such a possibility (Mathys, Hubrig, Landstreet, *et al.* 1997; Freyhammer, Elkin, Kurtz, *et al.* 2008). For low-mass stars, especially the mid- and late-M active dwarfs, the optical and near-infrared spectra yield evidence of kG-strength fields (Johns-Krull & Valenti 1996; Reiners & Basri 2007; Reiners, this conference). However, even for M stars with the fields in the range of 3–4 kG none of the molecular or atomic diagnostic lines accessible to common optical spectrographs exhibits resolved Zeeman split pattern.

Saar & Linsky (1985) showed that observations in the infrared K-band are of enormous potential for the magnetic diagnosis of active M dwarfs and other cool stars. Due to the λ^2 wavelength dependence of the Zeeman effect, the magnetic splitting of lines at 2.2 μm is 5–10 times larger than for most Zeeman-sensitive lines below 1 μ. Moreover, in the infrared wavelengths the intensity contrast between the photosphere and a cool starspot decreases, leading to substantial increase of the contribution of cool, strongly magnetic regions to the disk-integrated stellar spectrum.

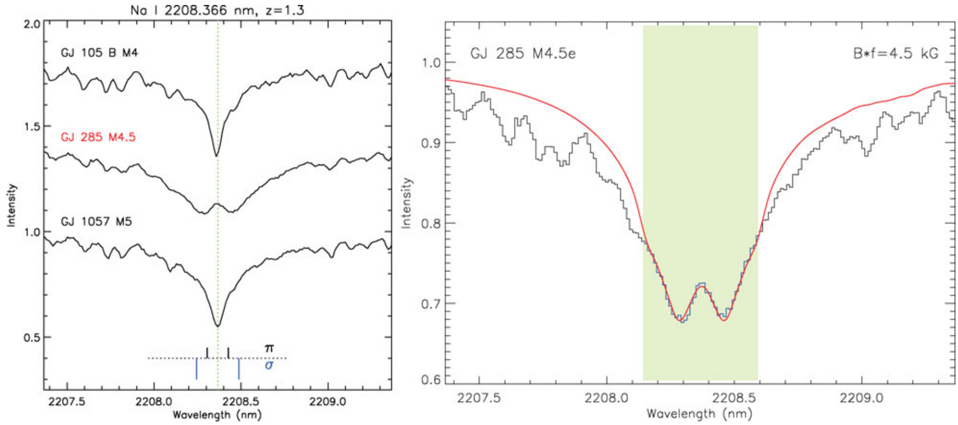

Figure 2. Direct detection and measurement of the strong small-scale magnetic field in M4.5 flare star YZ CMi (GJ 285) using infrared observations with the CRIRES instrument at the ESO 8-m VLT (Kochukhov *et al.* 2008). *Left*: comparison of the Na I 2208 nm line profile in the spectra of inactive M stars (top and bottom) and in YZ CMi (middle). Zeeman splitting is clearly detected in the spectrum of the active star. *Right*: magnetic spectrum synthesis fit to the observations of YZ CMi yields magnetic flux, $\sum B \cdot f$, of 4.5 kG.

The promising diagnostic content of the infrared magnetic observations was utilized to detect the presence of 1–2.5 kG magnetic fields in T Tauri stars (Johns-Krull, Valenti & Koresko 1999; Johns-Krull, Valenti & Saar 2004). These observations, summarized by Johns-Krull (2007 and in this conference), were performed with the help of the CSHELL spectrometer (Greene, Tokunaga, Toomey, *et al.* 1993) at the NASA Infrared Telescope Facility. The $S/N \approx 100$ spectra of T Tauri stars were recorded for several 6 nm wavelength windows, at the resolving powers of 21 000–37 000.

Magnetic analysis of the infrared spectra can be significantly improved and extended to fainter stars with the availability of the CRIRES (CRyogenic high-resolution InfraRed Echelle Spectrograph) instrument (Kaeufl, Ballester, Biereichel, *et al.* 2004) at the ESO VLT. CRIRES works in the 0.9–5.4 μm range and has a wavelength coverage similar to CSHELL, but allows to reach $R = 10^5$ using an adaptive optics system. These high-quality infrared spectra of cool stars open access to a much more refined analysis of magnetic topologies than possible with the optical spectra.

Kochukhov, Heiter, Piskunov, *et al.* (2008) have used CRIRES to carry out a survey of a large sample of M dwarfs with the aim to increase the number of stars with known surface field strengths and to determine small-scale field characteristics for several stars with strong fields. Such observations are essential for understanding non-solar dynamo mechanism operating in these fully convective stars (Dobler, Stix & Brandenburg 2006; Browning 2008). We found that in many active M dwarfs Zeeman splitting is readily detectable in the strong Na I line at λ 2208.4 nm (Fig. 2). The mean field modulus can be directly inferred from the resolved Zeeman split line profile. A more elaborate spectrum synthesis fitting, illustrated in Fig. 2 for the M4.5e star YZ CMi, can be used to determine a distribution of field strengths over the stellar surface.

Magnetic fluxes measured with the infrared lines are significantly stronger than $\leqslant 0.5$ kG fields determined by the ZDI analysis of the circular polarization time series obtained for the same active M dwarfs (Morin *et al.* 2008). This demonstrates that for this interesting type of low-mass magnetic stars the field topologies are dominated by the complex, small-scale structures, unaccessible to circular polarimetry in the optical. On the other hand, the latter constrains the large-scale field component and allows to determine stellar rotation periods. Thus, high-resolution spectropolarimetry in the K-band could be extremely useful for combining the two types of magnetic observations. This may become possible with the implementation of the circular polarization modulator currently considered for the CRIRES instrument.

3. Future facilities

3.1. *The upgrade of HARPS to a full-Stokes spectropolarimeter*

HARPS (High Accuracy Radial velocity Planet Searcher) is one of the most successful ESO instruments dedicated to search of exoplanets and studies of stellar oscillations. The instrument is installed in environmentally and vibrationally isolated tank while the light is transmitted by optical fibers from the Cassegrain adaptor of the La Silla 3.6m telescope. This results in extremely stable PSF in time and across the focal plane. As part of the HARPS upgrade ESO plans to replace the iodine cell (which was barely used) with a 4-Stokes polarimeter (Snik, Jeffers, Keller, *et al.* 2008) installed in the Cassegrain adaptor. The possibility of polarization splitting before accumulating any significant instrumental polarization, the availability of two fibers and the extreme stability of the HARPS make it an ideal instrument for measuring full Stokes vector with a very high precision ($\sim 10^{-4}$ and better). The polarimeter is currently in the manufacturing phase with the commissioning scheduled for the middle of 2009. Polarization measurements will be provided in the ESO standard as a sequence of raw frames and pipeline-reduced data.

The HARPS polarimeter is using a novel beam-splitter – a Foster prism – which unlike the conventional Wollaston prism allows the rays to cross all air-glass boundaries at nearly normal angle. This makes the polarimeter truly achromatic. The design includes two identical beam splitters (one for linear and one for circular polarization) with rotatable super-achromatic retarder plates installed in front of them. The full Stokes vector is obtained in 6 sub-exposures where the two beams are switched between the fibers and the two beam splitters sequentially positioned on the optical axis of the telescope. This allows to exclude CCD pixel sensitivity variations from the relative polarization measurements.

The HARPS polarimeter is primarily aimed at detection and modelling of stellar magnetic fields measuring polarization in spectral lines, similar to ESPaDOnS.

3.2. *High-resolution spectropolarimetry with PEPSI at LBT*

The PEPSI (Potsdam Echelle Polarimetric and Spectroscopic Instrument, Strassmeier, Woche, Ilyin, *et al.* 2008; Ilyin *et al.*, this conference) instrument for the 2×8.4-m Large Binocular Telescope will represent the next major step in the high-resolution astronomical spectropolarimetry. The instrument, scheduled for first light in 2011, is a fibre-fed, dual-arm echelle spectrograph capable of reaching an unprecedented resolution of $R = 310\,000$. In polarimetric mode PEPSI will be able to perform full Stokes vector observations in the wavelength range 450–1050 nm at a spectral resolution of $R = 130\,000$. A unique feature of the polarization observations with PEPSI is the use of two independent polarimeters in each of the two Gregorian foci of LBT. The spectrograph will be fibre-linked to both polarimeters and will have spacing of the echelle orders sufficient for recording of four spectra for each order. This will allow simultaneous observation of circular and linear polarization with spectral and temporal resolution surpassing that of any existing or planned instruments.

The design of PEPSI polarimetric modules (Strassmeier, Hofmann, Woche, *et al.* 2003) is based on a combination of a Wollaston prism and a new type of super-achromatic quarter-waveplate retarder. Measurements of circular polarization will be performed by rotating the quarter-waveplate in 45° steps. No half-wave retarders are foreseen for

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observations in linear polarization. Instead the entire polarimeter package will be rotated in steps of 45° with respect to the optical axis. This will minimize the polarization cross-talks and lead to a significant improvement in the throughput compared to the Fresnel-rhomb design adopted for ESPaDOnS and NARVAL.

PEPSI at LBT is expected to achieve $S/N \approx 100$ for a $V = 14^{\rm m}$ star in 1 hour integration time. The relative polarimetric precision of $\delta P/P \sim 10^{-2}$ will be obtained for objects in the $V = 10$–$14^{\rm m}$ brightness range. This remarkable performance will allow making a significant progress in detecting magnetic fields in different types of active stars and reconstructing stellar surface field topologies. Furthermore, the range of topics which could be addressed with PEPSI extends far beyond stellar magnetism. The instrument has a potential to make an important contribution to the research on accreting binary systems, AGNs, supernovae, interstellar and intergalactic magnetic fields, etc. (see Strassmeier, Pallavicini, Rice *et al.* 2004 for an overview of PEPSI science cases).

3.3. *Spectropolarimetry at E-ELT*

Several instruments for the future E-ELT are currently going through phase A studies and some of them include spectropolarimetry as a main or optional operation mode.

CODEX – high-resolution single-object fibre-fed spectrometer with a spectral format and stability similar to that of HARPS and the throughput comparable or higher than that of the UVES (18 %). The polarimetric capability is not included in the baseline design but provision is made for such option by including two fibers feeding the light from the intermediate focus of the ELT and allowing sufficient spacing between orders in the detector. The availability of polarimetric option depends on the budget to be allocated for phase B.

EPICS – imager and spectropolarimeter for exoplanets. This instrument will have two arms – IR coronograph with extreme adaptive optics for imaging young exoplanets and a low-resolution spectropolarimeter to detect reflected light from exoplanets on short orbits. Linear polarization analysis will be used to discriminate between the stellar and the reflected light. This is a very specialized instrument with the emphasis on detection of the broad-band linear polarization.

METIS – mid-infrared imager and medium/high resolution spectrometer. This instrument is aimed at working in 3–17 μm region. The polarimetry will be supported for the imaging and the medium-resolution spectroscopy modes in the N band. The main goal of the polarimetry is to analyze extended objects where polarization is created by scattering and not magnetic fields. The accuracy of linear polarization measurements should be around 10^{-3}.

SIMPLE – is a near-infrared cross-dispersed echelle spectrometer with $R \sim 10^5$. This spectrometer will work in the 0.8–2.5 μm range and will provide the stability and the wavelength coverage similar to the optical high-resolution echelle spectrometers. The current baseline includes fibre feed from the intermediate focus of the ELT which offers a great opportunity for implementing a full Stokes polarimeter. The consortium is currently considering a totally novel type of polarimeter where the light passes a highly-chromatic retarder plate and the reduction procedures must recover spectral and polarization information.

4. Conclusions

In Fig. 3 we summarize performance of a typical high-resolution, optical spectropolarimeter for different telescope mirror diameters. The throughput of ESPaDOnS at CFHT is taken as a reference. The noise levels necessary for meaningful four Stokes parameter observations of a typical Ap star and circular polarization measurements of a

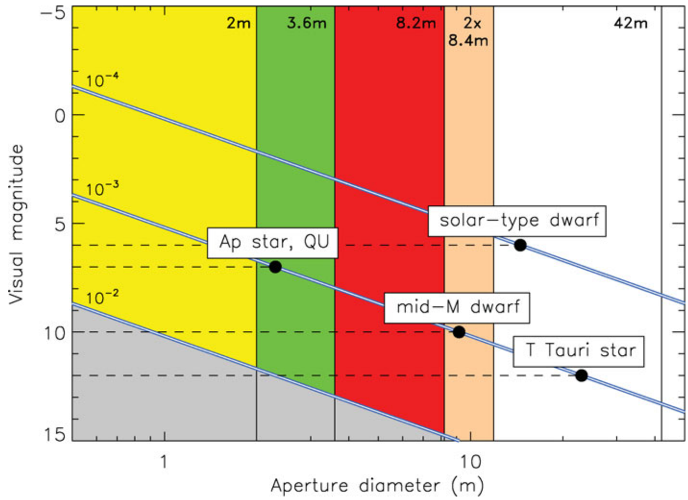

Figure 3. Performance of a generic high-resolution spectropolarimeter for different telescope diameters. Thick double lines correspond to a noise level that could be achieved in 1 h exposure time for a star of a given magnitude, assuming the total instrument throughput similar to that of ESPaDOnS at CFHT. Noise levels required for magnetic field detection and modelling are indicated for the full Stokes vector analysis of a typical Ap star and for the circular polarization observations of a typical bright solar-type dwarf, mid-M dwarf, and T Tauri star.

bright solar-type dwarf, mid-M dwarf and T Tauri star are also indicated. It is clear that only relatively bright Ap stars can be studied using direct analysis of the polarization signatures in individual spectral lines. For late-type stars the LSD multi-line methods have to be applied to decrease the noise level by a factor of 10–40 and allow magnetic field studies at 2–4-m class telescopes.

A major performance improvement that can be provided by a larger collecting area of 8–10-m class telescopes and, eventually, by the E-ELT will allow expanding high-resolution magnetic field studies along the two main directions. On the one hand, it will become possible to apply the multi-line polarization analysis to much fainter objects, such as very low-mass M and L dwarfs, late-type stars in well-studied clusters of different age, various accreting systems with magnetized components, etc. On the other hand, the bright active stars, currently studied with approximate, average-line treatment of the Stokes V spectra, can be analysed with a better accuracy and a physical completeness matching that of the solar magnetic field studies. This can be accomplished by dealing with individual atomic and molecular absorption lines and extending polarization analysis to all four Stokes parameters.

References

Aznar Cuadrado, R., Jordan, S., Napiwotzki, R., *et al.* 2004, *A&A* 423, 1081

Babel, J. & Montmerle, T. 1997, *A&A* 323, 121

Bagnulo, S., Szeifert, T., Wade, G. A., Landstreet, J. D., & Mathys, G. 2002, *A&A* 389, 191

Bagnulo, S., Landstreet, J. D., Lo Curto, G., Szeifert, T., & Wade, G. A. 2003, *A&A* 403, 645

Bagnulo, S., Hensberge, H., Landstreet, J. D., Szeifert, T., & Wade, G. A. 2004, *A&A* 416, 1149

Bagnulo, S., Landstreet, J. D., Mason, E., *et al.* 2006, *A&A* 450, 777

Basri, G. & Marcy, G. W. 1994, *ApJ* 431, 844

Berdyugina, S. V., Petit, P., Fluri, D. M., Afram, N., & Arnaud, J. 2006, in *Astronomical Society of the Pacific Conference Series*, eds. R. Casini, and B. W. Lites, *ASP Conf. Ser.* 358, 381

Borra, E. F. & Landstreet, J. D. 1980, *ApJS* 42, 421

Browning, M. K. 2008, *ApJ* 676, 1262

https://doi.org/10.1017/S1743921309031482 Published online by Cambridge University Press

Catala, C., Donati, J.-F., Shkolnik, E., Bohlender, D., & Alecian, E. 2007, *MNRAS* 374, L42
Dobler, W., Stix, M., & Brandenburg, A. 2006, *ApJ* 638, 336
Donati, J.-F., Semel, M., & Carter, B. D., *et al.* 1997, *MNRAS* 291, 658
Donati, J.-F., Babel, J., & Harries, T. J., *et al.* 2002, *MNRAS* 333, 55
Donati, J.-F., Howarth, I. D., & Bouret, J.-C., *et al.* 2006, *MNRAS* 365, L6
Donati, J.-F., Moutou, C., & Fares, R., *et al.* 2008a, *MNRAS* 385, 1179
Donati, J.-F., Jardine, M. M., & Gregory, S. G., *et al.* 2008b, *MNRAS* 386, 1234
Guenther, E. W., Lehmann, H., Emerson, J. P., & Staude, J. 1999, *A&A* 341, 768
Greene, T. P., Tokunaga, A. T., Toomey, D. W., & Carr, J. B. 1993, *SPIE* 1993, 1946
Gregory, S. G., Matt, S. P., Donati, J.-F., & Jardine, M. 2008, *MNRAS* 389, 1839
Hubrig, S., Szeifert, T., Schöller, M., Mathys, G., & Kurtz, D. W. 2004a, *A&A* 415, 685
Hubrig, S., Schöller, M., & Yudin, R. V. 2004, *A&A* 428, L1
Hubrig, S., North, P., Schöller, M., & Mathys, G. 2006a, *AN* 327, 289
Hubrig, S., Briquet, M., Schöller, M., *et al.* 2006b, *MNRAS* 369, L61
Hubrig, S., Schöller, M., Schnerr, R. S., *et al.* 2008, *A&A* 490, 793
Euchner, F. Reinsch, K. Jordan, S., Beuermann, K., & Gänsicke, B. T. 2005, *A&A* 442, 651
Freyhammer, L. M., Elkin, V. G., Kurtz, D. W., Mathys, G., & Martinez, P. 2008, *MNRAS* 389, 441
Johns-Krull, C. M. & Valenti, J. A. 1996, *ApJ* 459, L95
Johns-Krull, C. M. Valenti, J. A., & Koresko, C. 1999, *ApJ* 516, 900
Johns-Krull, C. M. Valenti, J. A., & Saar, S. H. 2004, *ApJ* 617, 1204
Johns-Krull, C. M. 2007, *ApJ* 664, 975
Jordan, S., Werner, K., & O'Toole, S. J. 2005, *A&A* 432, 273
Kaeufl, H.-U., Ballester, P., Biereichel, P., *et al.* 2004, *SPIE* 5492, 1218
Kochukhov, O. & Piskunov, N. 2002, *A&A* 388, 868
Kochukhov, O., Bagnulo, S., Wade, G. A., *et al.* 2004, *A&A* 414, 613
Kochukhov, O. & Bagnulo, S. 2006, *A&A* 450, 763
Kochukhov, O., Heiter, U., Piskunov, N., *et al.* 2008, in *Cool Stars 15*, ed. H.C. Stempels, in press
Long, M., Romanova, M. M., & Lovelace, R. V. E. 2008, *MNRAS* 386, 1274
Maeder, A. & Meynet, G. 2000, *ARA&A* 38, 143
Manset, N. & Donati, J.-F. 2003, *SPIE*, 4843, 425
Mathys, G., Hubrig, S., Landstreet, J. D., Lanz, T., & Manfroid, J. 1997, *A&AS* 123, 353
Morin, J., Donati, J.-F., Petit, P., *et al.* 2008, *MNRAS* 390, 567
Moutou, C., Donati, J.-F., Savalle, R., *et al.* 2007, *A&A* 473, 651
O'Toole, S. J., Jordan, S., Friedrich, S., & Heber, U. 2005, *A&A* 437, 227
Petit, P. 2006, in *Astronomical Society of the Pacific Conference Series*, eds. R. Casini, and B. W. Lites, *ASP Conf. Ser.* 358, 335
Petit, V., Wade, G. A., Drissen, L., Montmerle, T., & Alecian, E. 2008, *MNRAS* 387, L23
Piskunov, N. & Kochukhov, O. 2002, *A&A* 381, 736
Reiners, A. & Basri, G. 2007, *ApJ* 656, 1121
Robinson, Jr., R. D. 1980, *ApJ*, 239, 961
Saar, S. H. & Linsky, J. L. 1985, *ApJ* 299, L47
Silvester, J., Wade, G. A., Kochukhov, O., Landstreet, J. D., & Bagnulo, S. 2008, *CoSka* 38, 341
Snik, F., Jeffers, S., Keller, Ch., *et al.* 2008, *SPIE* 7014, 22
Strassmeier, K. G., Hofmann, A., Woche, M. F., *et al.* 2003, *SPIE* 4843, 180
Strassmeier, K. G., Pallavicini, R., Rice, J. B., & Andersen, M. I. 2004, *AN* 325, 278
Strassmeier, K. G., Woche, M.., Ilyin, I., *et al.* 2008, *SPIE* 7014
Townsend, R. H. D., Owocki, S. P., & Ud-Doula, A. 2007, *MNRAS* 382, 139
Valyavin, G., Wade, G. A., Bagnulo, S., *et al.* 2008, *ApJ* 683, 466
Wade, G. A., Donati, J.-F., Landstreet, J. D., & Shorlin, S. L. S. 2000, *MNRAS* 313, 823
Wade, G. A., Drouin, D., Bagnulo, S., *et al.* 2005, *A&A* 442, L31
Wade, G. A., Auriere, M., Bagnulo, S., *et al.* 2006, *A&A* 451, 293

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