HARPS Polarimeter Option

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Chapter 1

Proposal summary

Circular polarimetry at high spectral resolution measures stellar magnetic geometry and net longitudinal field strength, providing clues about stellar dynamos, coronal heating, angular momentum evolution, etc. Linear polarimetry measures scattering by circumstellar material, providing clues about protoplanetary disks, asymmetric mass loss, etc. Astrophysically important polarimetric signals are almost always much less than 1%. Achieving 0.01% precision requires careful instrumental design and observational techniques.

Based on previous experience, we have designed and are currently building a polarimeter that is specifically designed to feed the ultra-precise HARPS spectrograph. We are independently funding all design and construction costs, but request engineering support from ESO to integrate polarimeter into the HARPS interface and to commission the instrument. Before beginning this project, we obtained approval from ESO and Prof. Michel Mayor, who relies on the long-term stability of HARPS for an important planet search program.

Chapter 2

Science drivers

Magnetic fields are ubiquitous in astrophysics. Indirect signatures can be obvious (e.g., stellar flares), but direct measurements require precise instrumentation and careful data analysis. Nonetheless, magnetic field measurements are required to understand many physical systems.

In the broadest terms, polarization measurements diagnose either magnetic configuration or scattering geometry. In rotating or evolving systems, temporal changes in polarization provide key constraints on system characteristics (e.g., rotation period, inclination, dynamo cycle period).

We organize the following science discussion by object type: pre-main-sequence stars (T Tauri stars, Herbig Ae/Be stars, and circumstellar material), main-sequence stars (M dwarfs, solar-type stars, Ap/Bp stars, hot stars), and other systems (solar system objects, exoplanets, interstellar medium). We emphasize research interests of our team, rather than attempting to construct a comprehensive list of science applications.

For each object type listed above, we identify physical processes that need further investigation, state the role of high-resolution spectropolarimetry, describe recent results, and discuss future studies that would be possible with HARPS fed by a polarimeter.

2.1 Pre-main-sequence stars

Magnetic fields play a critical role throughout the star formation process, contributing to the pressure support of molecular cloud cores, controlling the accretion of disk material onto young stars, and launching and collimation of jets observed from young stars.

2.1.1 T Tauri stars

T Tauri stars are low-mass, pre-main-sequence stars that are segregated into two categories: classical T Tauri stars (CTTS) that accrete material from a circumstellar disk and naked T Tauri stars (NTTS) that no longer have inner disk material to accrete. Transition objects between these two star formation stages have received attention recently because the process that clears the inner disk may be related to planet formation. Infrared Zeeman broadening measurements show that T Tauri stars have kG strength magnetic fields over the entire stellar surface (Basri, Marcy, & Valenti 1992; Guenther et al. 1999; Johns–Krull et al. 1999, 2004; Johns–Krull 2007).

Magnetospheric accretion models (e.g., Camenzind 1990; Königl 1991; Collier Cameron & Campbell 1993; Shu et al. 1994; Long, Romanova, & Lovelace 2005) explain how idealized young stars can rotate slowly (e.g., Edwards et al. 1994), despite accreting material with high specific angular momentum. Magnetic fields open an inner gap in the accretion disk, channel disk material onto the stellar surface, drive outflows, and establish an angular momentum balance between the star and the inner edge of the disk (see Figure 2.1 and the review by Bouvier et al. 2006).

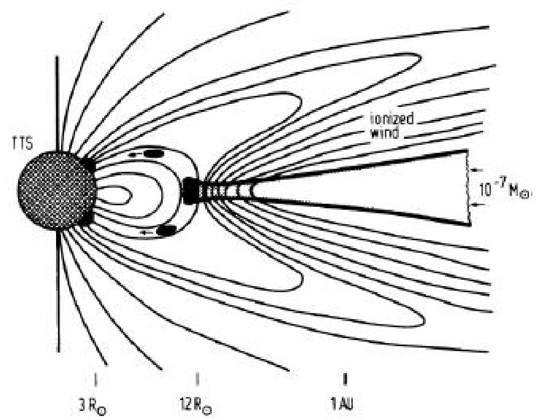

Figure 2.1: The magnetic field of a classical T Tauri star truncates the inner disk near the corotation radius, forcing accreting disk material toward the poles of the star (from Camenzind (1990).

Spectroscopic and photometric variability of T Tauri stars are often interpreted in terms of magnetically controlled accretion (e.g., Bertout et al. 1996; Alencar, Johns–Krull, & Basri 2001), in some cases with the magnetic axis inclined to the rotation axis (e.g., Kenyon et al. 1994; Johns & Basri 1995; Romanova et al. 2004; Bouvier et al. 2007). However, high-resolution spectropolarimetry is needed to demonstrate directly this relationship.

The intrinsic stellar magnetic field, perturbed by interactions with the disk, determines the geometry of accretion on the star. Spectropolarimetry of ordinary photospheric absorption lines constrains the geometry of the global stellar magnetic field, while spectropolarimetry of accretion diagnostics (e.g., He I 5876 Å) probes the magnetic topology in accretion columns (Johns–Krull et al. 1999; Yang, Johns-Krull, & Valenti 2007). Synoptic monitoring reveals variations that are consistent with rotation of an inclined magnetosphere, yielding the inclination of the rotation axis and the obliquity of the magnetic axis (see Figure 2.2 from Valenti & Johns-Krull 2004).

High-accuracy, high-resolution, spectropolarimetric observations of more T Tauri stars will address many issues. Synoptic observations of NTTS will yield surface field maps that constrain higher-order multipoles (see Figure 2.3) and bound internal dynamo models. Comparing with similar data for CTTS will test whether disk interactions affect magnetic geometry at the stellar surface. Extrapolating surface multipoles to the inner edge of the disk will constrain the various magnetic coupling formulations assumed by different models. Synoptic monitoring of CTTS will yield rotation periods, inclinations, and magnetic obliquities for many T Tauri stars, providing a firm foundation for interpreting the vast archive of spectroscopic and photometric monitoring data. The HARPS polarimeter will enable all these investigations.

2.1.2 Herbig Ae/Be stars

Herbig Ae/Be stars are intermediate-mass analogs of T Tauri stars with convectively stable envelopes that do not support dynamo action. Nonetheless, a few Herbig Ae/Be stars have globally organized kG strength magnetic fields reminiscent of main-sequence Ap/Bp stars (Wade et al. 2005).

If magnetic Herbig Ae/Be stars are the precursors of Ap/Bp stars, then spectropolarimetric observations may provide clues about the origin of magnetic fields in intermediate mass stars. By analogy to classical T Tauri stars, stellar magnetic fields may couple with the disk at a few stellar radii, forcing magnetic Herbig Ae/Be stars (and eventually Ap/Bp) stars to rotate more slowly than their nonmagnetic counterparts.

High-accuracy, high-resolution, spectropolarimetric observations of more Herbig Ae/Be stars can test these ideas. A survey would determine the fraction of Herbig Ae/Be stars that are magnetic. Synoptic monitoring of magnetic Herbig Ae/Be stars will yield rotation periods and magnetic geometries, which are important constraints on possible collapse or dynamo processes.

2.1.3 Circumstellar material

Magnetorotational instability facilitates the radial transport of angular momentum in circumstellar disks, resulting in accretion onto the central star and spreading of the disk. Magnetic fields are also responsible for driving outflows from the disk surface and/or from the inner edge of the disk. Optical spectra of FU Ori stars are dominated by disk emission, making it feasible to measure magnetic fields in the inner disk.

Donati et al. (2005) detect a significant azimuthal field in the disk around FU Ori, which they attribute to shear of the vertical field by Keplerian rotation. They detect no significant field variation over a 1 month period, but the initial epoch is quite noisy. High-accuracy, high-resolution, spectropolarimetric observations of the few known FU Ori stars would test the initial discovery and better constrain temporal evolution of disk fields.

Observations of *linear* polarization have been used to test whether circumstellar disks in binaries are aligned. Light from one component scatters off the disk around the other component, inducing linear polarization. Monin, Ménard, & Peretto (2006) find that disks are aligned in most binaries. High-precision, high-resolution spectropolarimetry may be able to constrain disk composition by detecting polarization differences in and out of spectral lines.

2.2 Main-sequence stars

Cool stars are one of the few astrophysical systems where active generation of magnetic fields can be studied. Observations of surface magnetic field geometry (via high-resolution spectropolarimetry) and strength (via Zeeman broadening) provide surface boundary conditions on dynamo models. These same observations constrain models of chromospheric and coronal heating.

Warm and hot stars have convectively stable envelopes, and hence no dynamo. Nonetheless, a small fraction of these stars have strong, globally organized magnetic fields. The origin of these fields is a long standing mystery.

Observable properties at the stellar surface include net magnetic flux longitudinal magnetic field (for slowly rotating stars), magnetic topology (for rapidly rotating stars), field strength distribution (via Zeeman broadening), rotation period, and differential rotation.

2.2.1 Late-type Stars

Many late-type show signatures of magnetic activity analogous to those observed on the Sun, and are considered to be generated by dynamo processes that result from the interplay of convection and differential rotation. In the case of the Sun, the dynamo that amplifies the magnetic field, is considered to be located at the base of the convection zone. As the depth of the convective zone decreases towards earlier stars and disappears at early F spectral type, a change in the observed magnetic activity and dynamo processes are likely to take place as we move from later to earlier spectral types.

Spectropolarimetric observations, when used with tomographic techniques, such as Zeeman-Doppler imaging, allow the reconstruction of the magnetic field geometry into its poloidal and toroidal components providing a great insight into the dynamo mechanisms of cool stars other than the Sun. An example of the magnetic field topology that can be reconstructed using Zeeman-Doppler imaging is shown in Figure 2.4. Observations of largely convective stars indicate that surface differential rotation decreases with increasing convective zone depths (Barnes et al. 2005) with the highest levels of differential rotation measured for the G0V spectral types (Jeffers and Donati 2008) down to the fully convective stars rotating as solid bodies (Donati et al. 2006). However, in contrast to theoretical predictions, this solidly rotating M-dwarf V374 Peg, surprisingly shows evidence of large-scale poloidal magnetic fields. Additionally, the magnetic field geometry of V374 Peg is in contrast to other partially convective late-type stars which are usually dominated by a toroidal component. Motivated by these results, newer models (e.g., Dobler et al. 2006) are starting to produce large-scale fields at the surface of fully-convective stars.

Evidence for a non solar-like dynamo operating stars with shallower convective zones has been shown for the K0V dwarfs AB Dor and LQ Hya, where differential rotation measurements using brightness and magnetic features are found to differ. Donati et al. (2003) conclude that this is evidence of a non-solar dynamo that is distributed throughout the star's convective zone. Jeffers et al. (2007) have also measured the temporal evolution of differential rotation on AB Dor.

High-accuracy, high-resolution spectropolarimetric observations of fully convective M dwarfs and earlier type stars with shallower convective zones will provide essential observational input to test this new generation of dynamo generation models.

2.2.2 Ap/Bp stars

The magnetic fields of intermediate-mass chemically peculiar stars (the Ap and Bp stars) have quite different characteristics (and probably a different origin) than those of late-type stars (e.g. Mestel 2003). In early-type stars, the large-scale surface magnetic field is static on timescales of at least many decades, and appears to be "frozen" into a rigidly rotating atmosphere. The magnetic field is globally organized, permeating the entire stellar surface, with a relatively high field strength (typically of a few hundreds up to a few tens of thousands of Gauss). The presence of a magnetic field strongly influences energy and mass transport within the atmosphere, and results in the presence of strong chemical abundance non-uniformities in photospheric layers (e.g. Turcotte 2003). Due to its global nature, the magnetic field of Ap stars can be much more easily detected and studied than that of late-type stars; in fact, these are the only stars for which assumption-free recovery of the full vector map of the magnetic field is currently possible (Piskunov & Kochukhov 2002). Moreover, spectra of magnetic Ap stars can reveal a host of poorly-understood photospheric physical processes, including convection, diffusion, and weak stellar winds.

New advances in the quality and quantity of the available observational data, as well as the sophistication of computational hardware and software, have recently permitted a major step forward in our ability to model magnetic fields of Ap stars. Using time series measurements of rotationally-modulated Zeeman circular and linear polarization resolved within stellar line profiles (observations in all four Stokes parameters obtained using the MuSiCoS spectropolarimeter at Pic du Midi Observatory, and reported by Wade et al. 2000) and the new Magnetic Doppler Imaging technique (MDI, described by Piskunov & Kochukhov 2002 and Kochukhov & Piskunov 2002), we have succeeded in constructing the very first assumption-free, high resolution maps of the surface vector magnetic field of an Ap star (for the Ap star 53 Cam, Kochukhov et al. 2004, see Fig. 2.5). These unique maps reveal that the magnetic topology of 53 Cam departs significantly from the commonly-assumed low-order multipolar geometry. They have allowed us to study the presence of atmospheric electrical current systems (which, in the case of the Sun, accompany rapid rearrangements of local magnetic field structures). Finally, these maps have allowed the ability to compare the local magnetic intensity and geometry to the local abundance of chemical elements within the atmosphere (reconstructed self-consistently with the magnetic field maps), and to thereby begin addressing models of mass transport invoking the magnetic field.

Although of unique value, the data currently available for magnetic mapping of Ap stars are fundamentally limited. The low signal-to-noise ratio (less than 5:1 for essentially all linear polarization profiles) and resolving power (only 35000 for MuSiCoS) lead to significant ambiguity in the field reconstruction. In practice, observational material can be used to study only 2–3 lines in a few brightest Ap stars. Consequently, only an extremely limited range of stellar properties (rotation, mass, temperature, magnetic field, etc.) which may influence the phenomena of interest can be studied.

A HARPS polarimeter will significantly widen the scope of detailed magnetic field modelling of magnetic CP stars. A large wavelength coverage and a very high resolution of HARPS are ideal for the studies of polarization inside profiles of individual spectral lines. The Stokes Q and U signatures could be detected securely in a large number of spectral features, greatly improving the robustness of Magnetic Doppler Imaging and allowing us to probe vertical gradients of magnetic field. With HARPS, magnetic mapping can be extended to many more fainter targets. This step is crucial for understanding general characteristics of the magnetism in intermediate-mass stars, for comparing empirical magnetic maps with advanced magnetohydrodynamical simulations (e.g. Braithwaite & Spruit 2004) and systematically exploring field geometries as a function of age and formation environment.

2.2.3 Massive stars

Massive stars are those with initial masses on the main sequence above about 8 solar masses, leading to core-collapse (or pair-instability) supernovae. Due to the supposed relic nature of their magnetic fields and very short evolutionary time scales, these stars potentially provide us with a powerful capability: to study how fields evolve throughout the various stages of stellar evolution, and to explore how they influence, and are influenced by, the structural changes that occur during the pre-main sequence, main sequence, and post-main sequence evolutionary phases. Ultimately, this allows us to investigate how fields affect, both directly and indirectly, the process of stellar evolution.

In this context, hot, massive OB stars represent unique targets for the study of stellar magnetism. Their strong, radiatively-driven winds couple to magnetic fields, generating complex and dynamic magnetospheric structures (e.g. Babel & Montmerle 1997, Donati et al. 2002). Recent models and simulations (e.g. ud-Doula et al. 2006; Townsend et al. 2007) show that magnetic confinement of stellar winds can explain wind variability and X-ray emission as observed in large numbers of OB stars (e.g. Kaper & Fullerton 1998, Stelzer et al. 2005). The interaction of the wind with the magnetic field modifies mass loss, and may enhance the shedding of angular momentum via magnetic braking (e.g. Weber & Davis 1967). As the evolution of massive stars is particularly sensitive to rotation and mass loss (e.g. Maeder & Meynet 2000), the presence of even a relatively weak magnetic field can profoundly influence the evolution of massive stars and their feedback effects, such as mechanical energy deposition in the ISM and supernova explosions.

Historically, it has been assumed that magnetic fields in OB stars are very rare, and perhaps altogether absent in stars with masses above 8 solar masses. However, recent discoveries of fields in early B-type stars on the main sequence and pre-main sequence (e.g. Donati et al. 2006; Alecian et al. 2008) and in both young and evolved O-type stars (Donati et al. 2002) show convincingly that fossil fields can and do exist in stars with masses as large as 45 solar masses. Given that the detected fields are sufficiently weak (0.3–1.5 kG) to have remained undetected by previous generations of instrumentation, and that recent observational results suggest that the fraction of magnetic stars increases toward higher masses, it may well be that magnetic fields are far more common in OB stars than has been supposed. Such a conclusion would have fundamental implications for our interpretation of the observational properties of hot, massive stars, for our models of their evolution, and for our understanding of the magnetic descendants, the neutron stars (e.g. Ferrario & Wickramasinghe 2006).

Although the existence of magnetic fields in massive stars is no longer in question, our knowledge of the basic statistical properties of massive star magnetic fields is seriously incomplete. There is a troubling deficit in our knowledge of the scope of the influence of fields on massive star evolution, and almost no empirical basis for how fields modify mass loss. The HARPS polarimeter can play a key role in obtaining critical missing information about the poorly-studied magnetic properties of these important stars, confronting current models and guiding theory. The general scientific objectives of the massive-star research possible with HARPS polarimeter will be i) to observe and model interaction between magnetic fields and massive star winds, ii) to identify and model the processes responsible for the generation of the fields in massive stars, and iii) to investigate the impact of magnetic fields on massive star evolution, and the evolution of the fields themselves. Of particular interest is exploration of the connection between magnetic fields of non-degenerate massive stars and those of neutron stars, with consequential constraints on stellar evolution, supernova astrophysics and gamma-ray bursts.

2.3 Solar system and beyond

2.3.1 Solar system

Spectropolarimetry of solar system bodies provides vital clues about the consistency of the surface and/or atmosphere of a broad range of objects. Polarimetric observations of asteroids at different scattering angles as they orbit the sun allows for a careful inversion of their mineralogical composition and surface roughness. Currently, only sparse photopolarimetric data is available (e.g. Cellino et al. 2005). High resolution spectropolarimetry of the outer gas planets and their moons is a unique diagnostic of their atmospheric constituents and stratification. Rotational Raman scattering creates polarization at the wavelengths of solar absorption features (the Ring effect), which can serve as a diagnostic of aerosols (Stam et al. 2002). Observations with the HARPS polarimeter of e.g. Titan, Europa and Ganymede would therefore significantly contribute to the exploration of these Jovian and Saturnian moons.

2.3.2 Exoplanets

HARPS has discovered nearly half the known exoplanets, including some only a few times more massive than the Earth. The success of HARPS is due in part to the excellent stability of the spectrograph, which eliminates many sources of systematic error. Spectropolarimetry with HARPS will also benefit from this stability.

Stars hosting short period planets may have active regions caused by tidal or magnetic interactions between the star and planet (Kuntz et al. 2000; Ip, Kopp, & Hu 2004). Time series spectropolarimetry of cool stars with short period planets can search for these effects. Initial observations of the K2 dwarf HD 189733 showed complex magnetic features that rotate with the star, rather than tracking the planet (Moutou et al. 2007). The F7 dwarf τ Boo has a planet with orbital period comparable to the mean stellar rotation period. Spectropolarimetric observations show no equatorial magnetic features at the longitude of the planet, but there are magnetic features at other longitudes (Donati et al. 2008).

The HARPS spectropolarimeter will monitor stars with short period planets to determine whether magnetic features rotate with the star or follow the planet, and whether activity is modulated on a rotational or orbital timescale. In the case of stars like τ Boo with synchronized rotation periods, HARPS spectropolarimetry at different epochs can test whether magnetic features always appear at certain phases with respect to the longitude of the planet.

Exoplanet characterization is the next frontier after discovery. Starlight reflected by the planet will be linearly polarized by an amount that depends on orbital phase. The degree of polarization is also a function of wavelength and depends on the structure and composition of the planetary atmosphere. Linear polarization cancels to a high degree in direct radiation from the star, but Poisson noise still makes detection of reflected light from the planet extremely challenging, even for the HARPS polarimeter. Nonetheless, it may be worth attempting such a measurement.

2.4 Data analysis tools

2.4.1 Spectral extraction

We will process HARPS spectropolarimetry data using our sophisticated REDUCE package (Piskunov & Valenti 2002), which already handles standard data from HARPS and more than a dozen other echelle spectrographs. Minor modifications will be needed to extract two (or four) instances of each echelle order and to combine the results. REDUCE uses two-dimensional optimal extraction to reject outliers and achieve maximum accuracy. The package operates in batch mode and is publicly available [1].

2.4.2 When global fields are weak

Magnetic Doppler imaging creates magnetic field maps from Stokes spectra obtained at many rotational phases. In case of pre-dominant global fields (e.g. magnetic A stars) the rapid stellar rotation spectroscopically resolves surface magnetic structures, reducing polarization cancelation. When fields are mostly local one can try to combine polarization signatures of many lines.

Donati et al. (1997) combine lines using a technique known as least squares deconvolution (LSD). LSD obtains a mean Stokes V profile vs. velocity offset (v) from the least squares solution of $V(v) = g_i \lambda_i d_i Z(v)$. This follows heuristically from the weak field approximation, $V_i(v) \propto g_i \lambda_i I_i'(v)$, and an assumption that the derivative of Stokes I with respect to v is self-similar, $I_i'(v) = d_i Z(v)$.

The broad wavelength coverage, high spectral resolution and PSF stability of the HARPS spectrograph will be ideal for LSD studies. We will advance beyond the LSD approach by explicitly modeling the splitting patterns and blends for each spectral line, using our existing expertise and computer codes for magnetic radiative transfer.

[1] http://www.astro.uu.se/ piskunov/RESEARCH/REDUCE/

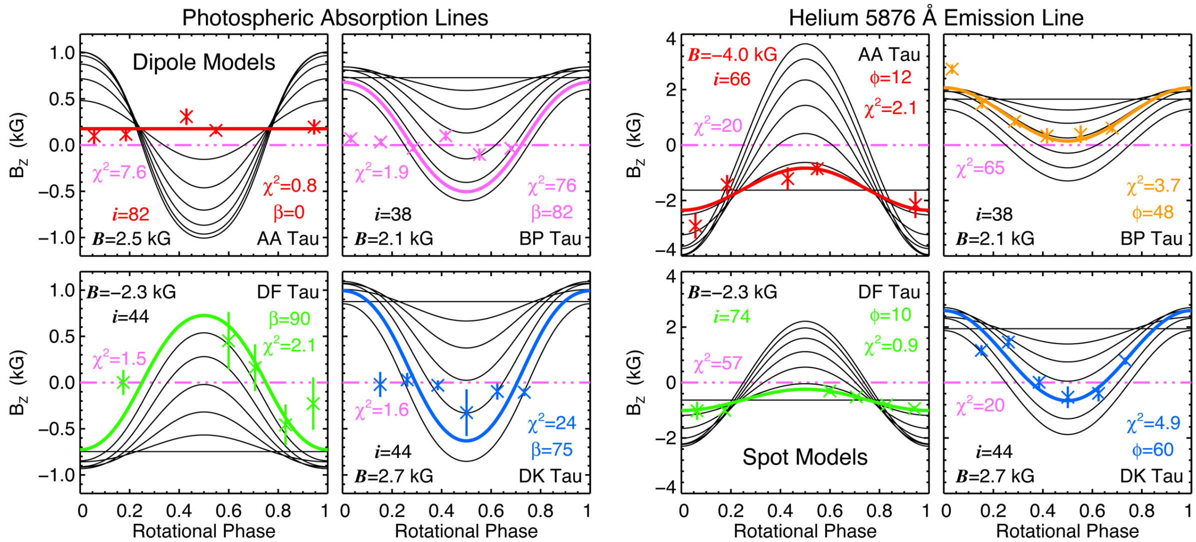

Figure 2.2: *Left Panel:* Magnetic field measurements (B_z) from photospheric absorption lines ($\times$) compared with dipole models assuming various obliquities, β. Inclined dipole models are ruled out for BP Tau and DF Tau; better data are needed for AA Tau and DF Tau. *Right Panel:* Measured B_z for the He I 5876 Å accretion diagnostic ($\times$) compared with models of magnetic spots at various latitudes, ϕ. The best spot model (heavy curves) fits remarkably well. *Spectropolarimetry with HARPS will yield measurements at least an order of magnitude more precise in half the time.*

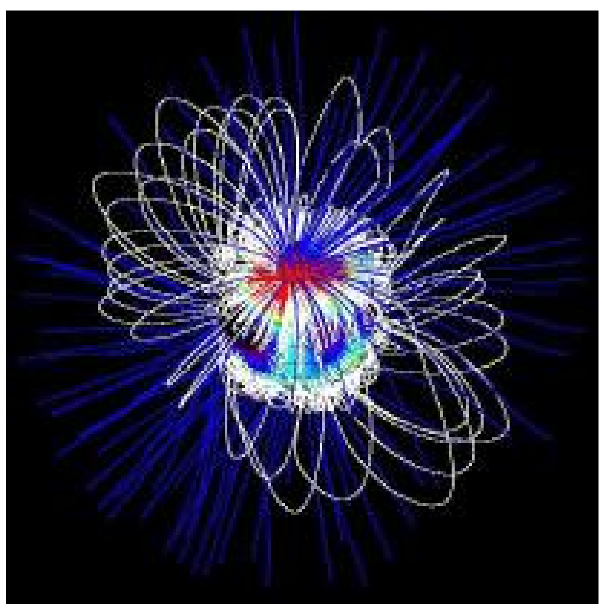

Figure 2.3: The magnetic field of a T Tauri star, reconstructed from time series observations with ESPaDOnS (Donati et al. 2007). A potential field extrapolation constrains magnetic field strength at the inner edge of the disk, providing a test of magnetospheric accretion models.

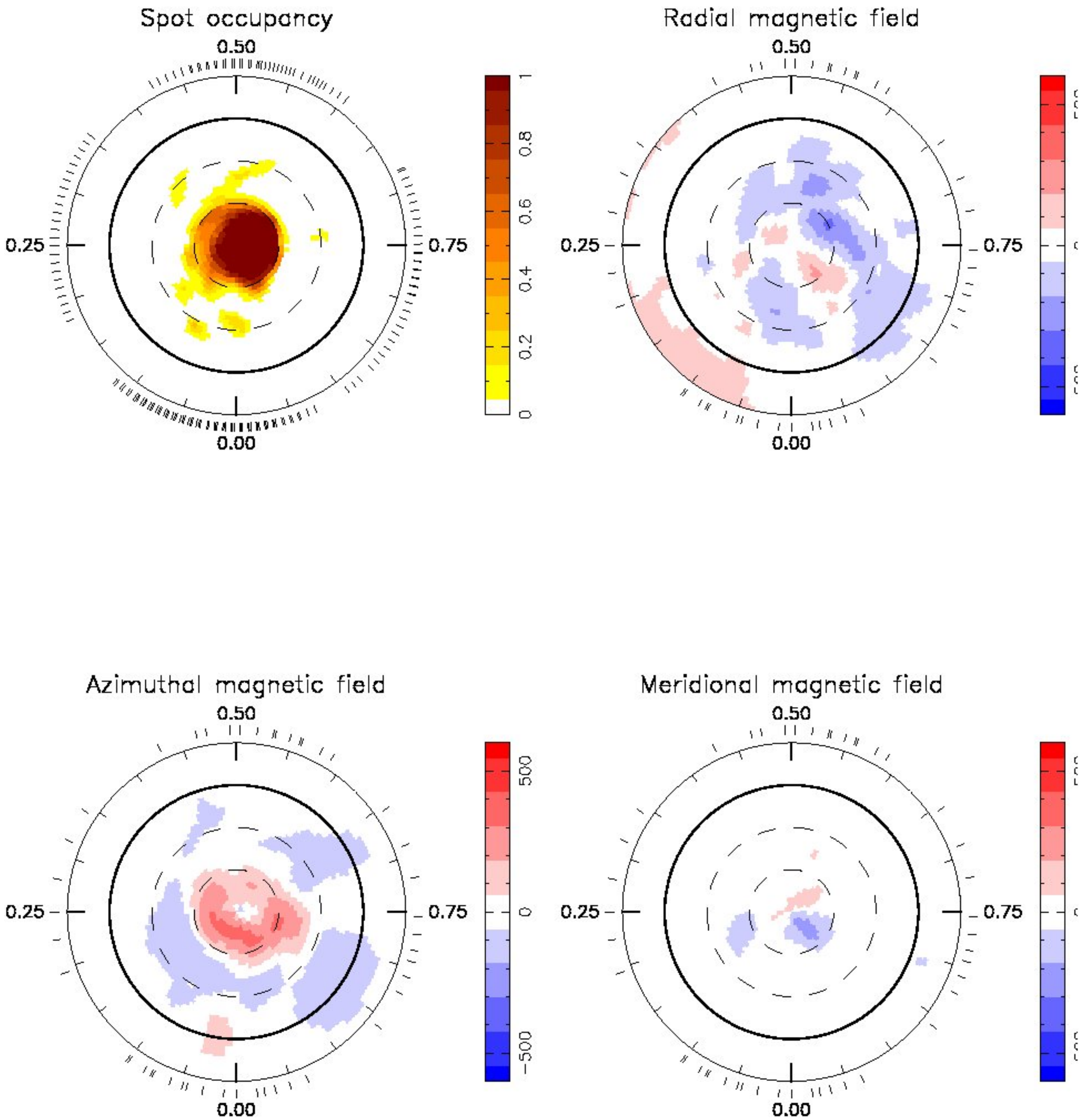

Figure 2.4: Surface brightness images and magnetic maps for HD 171488 reconstructed using Zeeman-Doppler imaging techniques (Jeffers and Donati 2008). These images are flattened polar projections that extend down to a latitude of -30° where the bold line depicts the equator. The scale of the magnetic field strengths are in Gauss, where positive field values correspond to magnetic vetors directed outwards, anti-clockwise, and poleward respectively for radial, azimuthal and meridional field components.

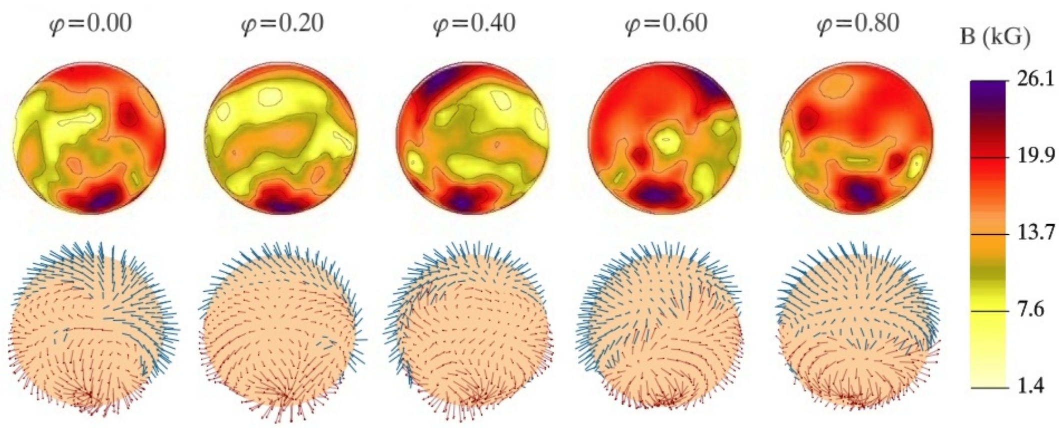

Figure 2.5: Magnetic field intensity (upper panel) and direction (lower panel) of 53 Cam, as recovered using the Magnetic Doppler Imaging technique and Stokes $IQUV$ spectropolarimetric data (Kochukhov et al. 2004). The maps reveal the presence of small-scale field structures at the surface of this intermediate-mass magnetic Ap star.

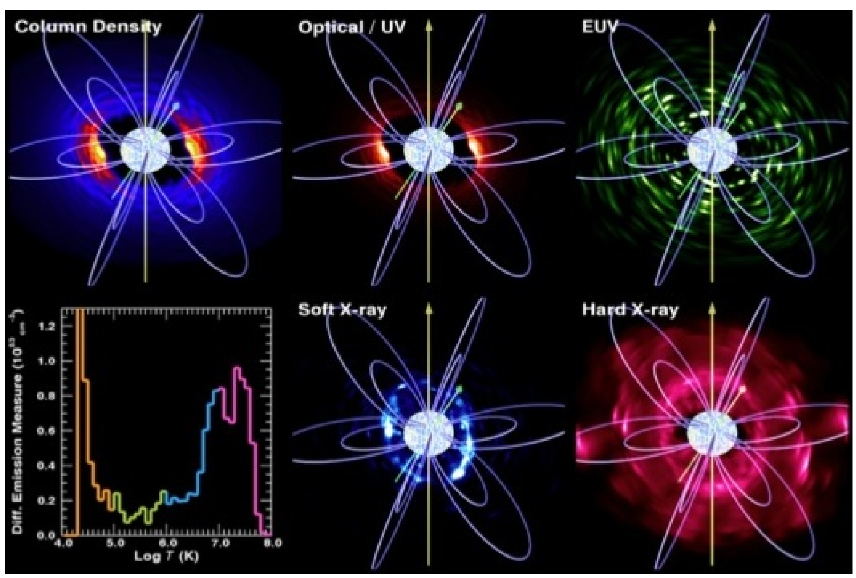

Figure 2.6: Snapshots of the emission measure distribution throughout the magnetosphere of σ Ori E, calculated using the Rigid Field Hydrodynamics formalism of Townsend et al. (2007). The center and right-hand panels show the emission measure in different temperature ranges: optical/UV ($T < 1e5$ K), EUV ($1e5 < T < 1e6$), soft X-ray ($1e6 < T < 1e7$) and hard X-ray ($T > 1e8$). The top-left panel shows the overall mass distribution, and the bottom-left panel plots the differential emission measure for the magnetosphere as a whole. Detailed model of magnetic field geometry (assumed to be a simple dipole in these calculations for σ Ori E) are essential for understanding the properties of massive-star magnetosphere.

Chapter 3

Competitive instruments

Here we describe existing and planned optical spectropolarimeters with high spectral resolution, broad wavelength coverage, and polarimetric precision better than 1%:

1. ESPaDOnS - The "Echelle SpectroPolarimetric Device for the Observation of Stars at CFHT" is an $R = 68000$, dual-fiber, cross-dispersed, echelle spectrograph with wavelength coverage 370-1050 nm. Quarter-wave and half-wave Fresnel rhombs have polarimetric accuracy of 0.3% and negligible fringes. Cross-talk is now less than 2%.

2. NARVAL, an ESPaDOnS clone instrument at the 2m. Télescope Bernhard Lyot at Pic du Midi observatory in France.

3. HiVIS the recently commissioned Nasmyth spectropolarimeter at the 3.6 m AEOS telescope on Haleakala, Maui. It covers the spectral range of 500-1000 nm at $R_{max} = 49000$. It suffers from pointing-dependent instrumental polarization as large as 6%.

4. PEPSI - The "Potsdam Echelle Polarimetric and Spectroscopic Instrument" will be a full-Stokes (four component) polarimeter feeding an $R = 120000$ echelle spectrograph. Polarimetric precision will be 10^{-2} for faint targets and 10^{-4} for bright targets. Professors Piskunov and Keller contributed significantly to the design of PEPSI. Commissioning of the polarimeter is scheduled for the end of 2009.

5. CAOS - The "Catania Astrophysical Observatory Spectrograph" is an $R = 60000$, dual-fiber, cross-dispersed, echelle spectrograph with wavelength coverage 390-710 nm (Spanò et al. 2006). The spectrograph is planned to have polarimetric capability, but the number of feasible targets is limited by the relatively small size of the 0.91 m telescope on Serra La Nave in Italy.

All of these instruments are in the northern hemisphere. Of these spectropolarimeters, only ESPaDOns/NARVAL is currently producing high-quality science. ESPaDOns faces severe proposal pressure, so that many interesting targets will never be observed, especially since the highest science return requires synoptic observing.

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