

Magnetic fields of non-degenerate stars

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ABSTRACT

Magnetic fields are present in a wide variety of stars throughout the HR diagram and play a role at basically all evolutionary stages, from very-low-mass dwarfs to very massive stars, and from young star-forming molecular clouds and protostellar accretion discs to evolved giants/supergiants and magnetic white dwarfs/neutron stars. These fields range from a few μ G (e.g., in molecular clouds) to TG and more (e.g., in magnetic neutron stars); in non-degenerate stars in particular, they feature large-scale topologies varying from simple nearly-axisymmetric dipoles to complex non-axisymmetric structures, and from mainly poloidal to mainly toroidal topology. After recalling the main techniques of detecting and modelling stellar magnetic fields, we review the existing properties of magnetic fields reported in cool, hot and young non-degenerate stars and protostars, and discuss our understanding of the origin of these fields and their impact on the birth and life of stars.

Key words. stars: magnetic fields; stars: formation; stars: late-type; stars: early-type; stars: rotation; stars: activity; stars: abundances; stars: mass-loss; techniques: spectroscopy; techniques: polarimetry

1. Introduction

Magnetic fields are known to be present in a wide variety of stars, from very low-mass M dwarfs to super-massive O stars. They play a role at basically all evolutionary stages, from collapsing molecular clouds and very young protostars to supernovae, degenerate white dwarfs and neutron stars (e.g., Mestel 1999). Magnetic fields are found to influence significantly a number of physical processes operating within and in the immediate vicinity of stars, such as accretion, diffusion, mass loss, turbulence and fundamental quantities such as mass, rotation rate and chemical composition. The aim of this paper is to summarise the main observational results in this field of research, especially those obtained since the previous review of Landstreet (1992), and to outline our current understanding of how magnetic fields impact the lives of stars of various masses.

The first detection of a magnetic field in a star, our Sun, was obtained one century ago by (Hale 1908) who observed and correctly interpreted the magnetic polarisation of spectral lines in sunspots and attributed it to magnetic fields of nearly 3 kG. This was the first astrophysical application of the Zeeman effect, discovered by Zeeman only 12 yr before the pioneering work of Hale. Searching for magnetic stars other than the Sun to investigate how “normal” the Sun is, Babcock discovered in 1947 the simple large-scale fields of chemically peculiar stars (Babcock 1947) and quickly realised that these magnetic fields are in fact fairly different in nature than that of the Sun. About twenty years later, pulsars were detected for the first time through their radio emission (Hewish et al. 1968) and identified with rotating neutron stars (Gold 1968) with tremendously intense fields of typically TG (10^{12} G) strengths, i.e., about one billion times stronger than those found at the heart of sunspots; shortly afterwards, magnetic fields of several hundreds of MG were reported to exist at the surfaces of some white dwarfs (Kemp et al. 1970). Magnetic fields on cool solar-type stars other than the Sun were suspected for a long time; the solar analogy indeed suggests that the Sun-like activity observed on basically all low-mass stars is due to magnetic fields. After a search of several decades, the first direct detections were only obtained in 1980 (Robinson et al. 1980), more than 30 yr after Babcock’s initial discovery.

Since these initial results, our understanding of stellar magnetic fields has tremendously improved, thanks mostly to the improvement of instrumental performances and to the sophistication of numerical simulations. We know for instance that the magnetic field of the Sun is highly complex, giving rise not only to sunspot (e.g., Solanki 2003) but also to a complex set of magnetic features of smaller sizes such as ephemeral regions, bright points or inter-network fields (e.g., Stenflo 1989; Lites et al. 2008). Most cool stars also host magnetic fields, whose large- and medium-scale topologies can be revealed through tomographic techniques (e.g., Landstreet 1992; Donati et al. 2008b). Magnetic fields of low-mass stars power a wide variety of energetic phenomena (referred to as activity) such as flares, prominences, coronae and winds; the fields themselves most likely result from the interaction of convection and rotation (the so-called dynamo processes) and are highly variable in nature on timescales ranging from minutes (e.g., flares) to years (e.g., activity cycles). They are responsible for slowing down the rotation of most cool stars once they reached the main sequence, on a timescale that depends mostly on the stellar mass.

In contrast to low-mass stars which more or less all show magnetic fields and activity, intermediate- and high-mass stars are mostly non-magnetic with only a small minority (a few % depending on spectral type) showing detectable magnetic fields (e.g., Landstreet 1992). Moreover,

these fields are fairly different in nature; in particular, they often feature a fairly simple large-scale topology and show no intrinsic variability (other than the usual rotational modulation) even on timescales of decades. Magnetic A and late B stars are all chemically peculiar stars; the last decade has revealed that a small fraction of early B and O stars are also magnetic despite having nearly normal abundances. Magnetic fields in hot stars likely have a different origin, and their impact on evolution, although clear (e.g., abundance inhomogeneities likely result from their being magnetic) is still mostly a matter of speculation.

The impact of magnetic fields is actually greatest during the formation stage, when the magnetic energies of molecular clouds are comparable to their gravitational energies (Crutcher 1999). Once they become visible at optical wavelengths (i.e., at an age of about 1 Myr for low-mass stars), low-mass protostars host multi-kG magnetic fields at their surfaces through which they connect to (and accrete matter from) the inner rim of their accretion disc (e.g., Bouvier et al. 2007). Observations also reveal that protostellar accretion discs often exhibit broad outflows and highly-collimated jets that models can only reproduce by invoking magnetic fields redirecting a fraction of the accreted material into the outflows/jets through a propeller-type mechanism powered by magneto-centrifugal forces (e.g., Pudritz et al. 2007). While it is not yet fully clear how massive stars are formed, observations of hot magnetic protostars suggest that they rotate significantly more slowly than normal and thus that magnetic fields have altered the cloud collapse and contraction stage towards the main sequence.

At the other end of the evolution, white dwarfs and neutron stars can exhibit extraordinarily intense magnetic fields, with magnetars hosting the strongest (PG, i.e., 10^{15} G) fields known in the universe. Their magnetic fluxes, however, are similar to those of magnetic hot main sequence stars, suggesting empirically that most of the magnetic flux is conserved during stellar evolution off the main sequence and towards the very last stages. A large fraction of the white dwarfs with strong magnetic fields are found in close binary systems (called cataclysmic variables) where the companion is overflowing its Roche lobe and transferring mass to the white dwarf through magnetic funnels. Numerous studies describing advances in the field have been published recently (e.g., Ferrario & Wickramasinghe 2007); however, for lack of space, we do not include here a description of the magnetic fields of degenerate stars, despite their obvious interest in understanding the fate of main sequence stars and the role of magnetic fields in evolutionary stages such as supernovae and planetary nebulae.

This paper mostly focusses on magnetic field observations of non-degenerate stars of all masses. We start by describing the methods by which magnetic fields in stars are detected and measured (in Secs. 2 and 3); we then detail our current understanding of how magnetic fields are produced and affect the life of stars of various masses (in Secs. 4 and 5) and in particular their formation (Sec. 6). While regularly referring to some of the basic magnetic properties of the Sun, we do not review all aspects of the solar magnetism, a field of research so wide and documented that it requires a complete review of its own. For a more theoretical description of magnetic stars, readers are referred to the reference book of Mestel (1999) and to the forthcoming new edition.

2. Atoms and molecules in a magnetic field

We briefly describe here the methods by which magnetic fields can be directly detected at the surface of non-degenerate stars¹. Such detections/measurements are made possible by the effect of magnetic fields on atoms and molecules in stellar atmospheres, reflecting changes in the structure and energies of atomic/molecular energy levels and thus in the profiles and polarisation properties of stellar spectral lines.

The Zeeman effect is the most well known of these effects and is used to diagnose all types of fields, from very weak (for instance the μ G fields of molecular clouds) to very strong (the MG to GG fields of white dwarfs). The vast majority of measurements and results reported in the literature has been obtained through Zeeman spectroscopy and spectropolarimetry. The Hanle effect is another example, more adapted to very weak tangled fields for which the Zeeman effect fails; since it has never allowed yet to diagnose fields in stars other than the Sun, we will not discuss it here. Both effects apply on both atoms and molecules, and show different behaviour depending on how strong the field is. Only the main points are summarised here; for more details, readers are referred to the comprehensive description of Mathys (1989) and to the reference textbook of Landi degl'Innocenti & Landolfi (2004).

Consider an isolated atom placed in a vector magnetic field \mathbf{B} ; the modifications produced on the atom can be described by adding to the unperturbed Hamiltonian H_0 of the atomic system an additional term H_B called the magnetic Hamiltonian and given by:

$$H_B = \frac{e\hbar}{4\pi mc}(\mathbf{L} + 2\mathbf{S}) \cdot \mathbf{B} + \frac{e^2}{8mc^2}(\mathbf{B} \times \mathbf{r})^2 \quad (1)$$

where m and e are the electron mass and charge, c is the speed of light, \hbar is the Planck constant, \mathbf{L} , \mathbf{S} and \mathbf{r} are the total orbital angular momentum, spin and position operators of the electronic cloud.

The second (quadratic) term of Eq. 1 is called the diamagnetic term; its importance is very limited in practice in stars other than white dwarfs and neutron stars that we do not discuss here. In this context, H_B simplifies to the linear term:

$$H_B = \mu_0(\mathbf{L} + 2\mathbf{S}) \cdot \mathbf{B} \quad (2)$$

where μ_0 is the so-called Bohr magneton. If the magnetic field is weak enough (typically smaller than 1 MG) to keep the magnetic energy smaller than the energy intervals relative to the unperturbed Hamiltonian H_0 , the effect of H_B can be computed by the perturbation theory.

The well-known result is that each degenerate energy level of H_0 splits into $2J + 1$ sublevels with energy shifts given by:

$$\Delta E = \mu_0 g B M \quad (M = -J, -J + 1, \dots, J) \quad (3)$$

where g is a dimensionless factor (usually lying between 0 and 3) called the Landé factor of the atomic level. Assuming the atomic levels are described by the Russell-Saunders (or $L-S$) coupling scheme (a good approximation for light atoms), g can be written as;

$$g_{LS} = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}. \quad (4)$$

¹ Indirect methods and proxies such as emission in various lines (e.g., Balmer lines, Ca H&K and infrared triplet lines) or broad bands (UV, X-ray, radio) suggesting the presence of magnetic fields will be mentioned later, along with the discussion of the stellar class to which they mostly relate.

Transitions between a level E_i and another level E_f of Landé factors g_i and g_f are characterized by a single energy $E_f - E_i$ in the absence of a magnetic field. When a field is applied, the spectral line splits into closely spaced components with energies shifted from the rest energy by:

$$\Delta E = (g_f M_f - g_i M_i) \mu_0 B = (\Delta g M_f + g_i \Delta M) \mu_0 B \quad (5)$$

where $\Delta g = g_f - g_i$ and $\Delta M = M_f - M_i$.

Dipole transitions between the levels obey the selection rule $\Delta M = 0, -1$ or $+1$ and the resulting spectral lines form three corresponding groups. The lines due to transitions $\Delta M = 0$ (π components) are distributed symmetrically around the unsplit line formed in the absence of a field. The two groups of lines formed by transitions with $\Delta M = \pm 1$ (σ components) are shifted symmetrically about the unsplit line, with transitions of $\Delta M = 1$ on one side and transitions of $\Delta M = -1$ on the other side. In general, π and σ groups have several components; when they all overlap within each group (e.g., when $J_f = 0, J_i = 0$ or $g_f = g_i$), the transition is called a Zeeman triplet. Some lines show no Zeeman splitting (e.g., $g_i = 0$ and $J_f = 0$) and are called magnetic null lines.

The average wavelength displacement $\Delta\lambda_B$ (in pm, i.e., 0.001 nm) of a σ component from its zero field wavelength λ (in μm) for a magnetic field B (in kG) is given by:

$$\Delta\lambda_B = 4.67 \lambda_0^2 \bar{g} B \quad (6)$$

where \bar{g} is called the effective Landé factor measuring the average magnetic sensitivity of the line; in practice, values of \bar{g} are typically about 1.2 but can range from 0 up to 3. The actual size of the line splitting is about 1.4 pm (or 0.84 km s^{-1}) for a transition at 500 nm with $\bar{g} = 1.2$ in a 1 kG field; going to a wavelength of $2 \mu\text{m}$ in the near infrared (nIR), the splitting rises to about 22.4 pm (3.36 km s^{-1}) for the same field strength and Landé factor.

If the magnetic energy is comparable to the energy intervals of fine structure splitting of H_0 (i.e., at field strengths larger than 100 kG), the perturbation theory is no longer applicable; the Zeeman effect is entering a non-linear regime called the Paschen-Back regime. The Paschen-Back regime has few astronomical applications in non-degenerate stars. The fields found in main sequence stars (generally of the order of 1 kG, very rarely as large as 30 kG) are not large enough to push most lines into the Paschen-Back regime.

Diatomeric molecules (e.g., TiO, CH, C₂, OH, CN, MgH, CaH or FeH) are also sensitive to magnetic fields, generating Zeeman splitting and polarisation of spectral lines in a way similar to atoms; they can also be used to detect and measure magnetic fields in stars cool enough to show molecular lines in their spectra. The study of the molecular Zeeman effect has, in contrast to the atomic effect, been largely neglected until recently (Schadée 1978); efforts from different groups, both on the theoretical and experimental sides, have been carried out over the last decade (e.g., Berdyugina & Solanki 2002; Asensio Ramos & Trujillo Bueno 2006) to provide observers with updated tools for modelling unpolarized and polarized spectra of magnetic stars.

In practice, the Zeeman effect in stellar spectra can be detected both through the magnetic splitting or broadening of unpolarized spectral lines when the field strength is strong enough - stronger than 1 kG typically. It can also be detected as polarisation signals in spectral lines, even for fields as weak as a few G in the optical domain and a few μG at radio wavelengths; however, polarisation being sensitive to the vector properties of the field, the Zeeman polarisation is basically insensitive to very tangled weak fields, in which regions of opposite polarities mutually cancel out their respective contributions.

3. Detecting, measuring & modelling stellar magnetic fields

Several techniques are currently used to detect, estimate and model magnetic fields at the surfaces of non-degenerate stars, reflecting mostly the different types of instrument that can be used for this purpose. While some methods use high-resolution spectroscopy to study the detailed shape of line profiles, others attempt to measure the polarisation of spectral lines (through either photopolarimetry or spectropolarimetry) that magnetic fields produce through the Zeeman effect. We describe below the various options and mention the typical magnetic diagnostics that they provide.

3.1. High-resolution spectroscopy

The most direct and easily interpreted means of detecting magnetic fields in stars is by observing the Zeeman splitting of spectral lines. In this respect, the most natural instrument is a high-resolution spectrometer with a resolving power of at least 50,000 (i.e., 6 km s^{-1}) and possibly as high as 100,000 (i.e., 3 km s^{-1}). From the separation of the π and σ components of a line with known Landé factor \bar{g} , the intensity of the magnetic field averaged over the visible hemisphere of the star B_s can be measured (see Eq. 6). However, in main sequence stars, the detection of Zeeman splitting is not easy; the broadening to be measured competes with other sources of line broadening, the most important of which is usually rotation. Even for the slowest rotators, turbulent broadening (e.g., in low-mass stars) can easily produce line widths of several km s^{-1} , implying that the splitting can only be detected for field strengths larger than typically 5 kG at optical wavelengths. In practice, Zeeman splitting of optical spectral lines is mostly observed in magnetic chemically peculiar stars with very slow rotation and negligible turbulent broadening, where surface fields of a few kG are routinely detected (e.g., Mathys et al. 1997).

In stars with weaker fields, the magnetic intensity may still be estimated through the broadening of magnetically sensitive spectral lines. For a highly-magnetic $\bar{g} = 2.4$ line at 600 nm for instance, the magnetic broadening reaches 2 km s^{-1} for a 1 kG field, similar to the thermal broadening of a Fe spectral line in the atmosphere of a main sequence star but smaller than the macroscopic turbulence that often widens further the spectral lines of most cool stars. A careful analysis of spectral profiles of low-mass stars, comparing in particular the shapes of lines with similar formation conditions but different magnetic sensitivities, can lead to estimates of the relative area of the visible stellar hemisphere covered with magnetic fields (the filling factor f) and of the average field strength B_s within these active regions (Robinson 1980; Saar 1988); these 2 quantities are degenerate to some extent, with the magnetic flux fB_s being more accurately determined than either f or B_s individually. In intermediate- and high-mass magnetic stars, fields are not spatially intermittent (subsurface convection being either weak or nonexistent) and more or less cover the whole photosphere (i.e., $f \simeq 1$), allowing B_s to be estimated directly.

An extension of this technique to molecular lines (the Wing-Ford band of FeH at $0.99 \mu\text{m}$) was recently proposed and applied to a small set of very-low-mass dwarfs (Valenti et al. 2001; Reiners & Basri 2006). The Zeeman effect of molecular lines, and in particular their Landé factor, is still rather poorly documented, with almost no measurements from laboratory experiments and only very recent estimates from semi-empirical modelling (Afram et al. 2008). As a result, the corresponding technique for measuring fields essentially consists at expressing the FeH spectrum of a star as a linear combination of those of 2 carefully selected reference stars known for their

respectively strong (i.e., multi kG) and weak (i.e., undetectable) magnetic fluxes; although rather crude, this method nevertheless provides an interesting first-order option for extracting the magnetic information coded into FeH lines of low-mass stars. Improvements to this pioneering work are expected soon as laboratory measurements of molecular lines and of their magnetic sensitivities become progressively available.

An obvious way of improving the sensitivities of these various techniques is to use spectral lines at nIR wavelengths; at $2.2 \mu\text{m}$ for instance, a $\bar{g} = 2.5$ line provides a magnetic splitting of 7.7 km s^{-1} for a 1 kG field, easily detectable in most main-sequence stars with only moderate rotational line broadening. This is obviously mainly interesting for low- to very-low-mass stars whose fluxes and spectral-line densities peak at red and nIR wavelengths (depending on spectral type) and whose rotation is usually slow in average; it has been successfully applied over the last two decades (e.g., Saar & Linsky 1985; Valenti et al. 1995). The higher sensitivity allows in particular to derive a rough description of how field strengths spread at the surface of the star, rather than just an estimate of the average magnetic intensity (e.g., Johns-Krull et al. 1999b); in some cases, it is even possible to detect Zeeman splitting directly (e.g., Saar & Linsky 1985). The nIR also provides a good opportunity for studying magnetic fields in cool dark spots of low-mass stars, mostly outshined by the surrounding photosphere at visible wavelengths but accessible in the nIR where the spot/photosphere contrast is much smaller. The advent of new efficient nIR high-resolution échelle spectrographs in forthcoming years (e.g., GIANO on the Telescopio Nazionale Galileo or TNG, and SPIRou on the Canada-France-Hawaii Telescope or CFHT) should further boost such applications.

Although regularly used since the very beginning of solar and stellar magnetometry, these techniques underwent a large burst of applications when first successfully used for detecting magnetic fields in low-mass stars other than the Sun (e.g., Robinson et al. 1980), and in particular on young low-mass protostars (e.g., Johns-Krull et al. 1999b; Johns-Krull 2007). Being insensitive to the field topology, they provide a very easy and efficient way of diagnosing tangled magnetic fields for which polarisation signals are very weak (see below). The drawback is however that the information they yield is rather limited; in particular, they are almost useless at deriving information on how the field is oriented and how it splits into its poloidal and toroidal components.

3.2. Photo- and spectropolarimetry

The polarisation properties of a Zeeman-split line furnish a second major means of measuring magnetic fields. In particular, polarisation gives access to the orientation of the field: circular polarisation (from σ components) is sensitive (at first order) to the line-of-sight (or longitudinal) component of the magnetic field, while linear polarisation (from π and σ components) gives access to the perpendicular (or transverse) component of the magnetic field. Analysing the relative degree of circular and linear polarisation across line profiles requires a polarimeter, i.e., an instrument measuring the differential intensity between two orthogonal states of polarisation (e.g., right- and left-handed circular polarisation).

Polarisation in astronomy is usually described using the Stokes vector $[I, Q, U, V]$. In this vector, I is the total specific intensity of light in the beam. Q and U describe the linear polarisation of the beam, given by $Q = \langle I_{0^\circ} - I_{90^\circ} \rangle$ and $\langle U = I_{45^\circ} - I_{135^\circ} \rangle$ where $\langle \rangle$ denotes the temporal average

and I_{0° , I_{45° , I_{90° and I_{135° correspond to the intensity the beam would have if filtered by a perfect linear polariser with its transmission axis respectively set to 0° , 45° , 90° and 135° with respect to a reference direction (usually the north). Similarly, V describes the circular polarisation of the beam, given by $V = \langle I_{\odot} - I_{\circlearrowleft} \rangle$, where I_{\odot} and I_{\circlearrowleft} correspond to the beam intensities when filtering respectively by perfect circular right and circular left polarisers. More information about Stokes parameters can be found in Landi degl'Innocenti & Landolfi (2004).

At optical and nIR wavelengths, a polarimetric analysis is usually obtained by means of a beam splitter (e.g., a linearly birefringent crystal like a simple calcite block, or a combination of several like a Wollaston prism), associated with retardation devices (e.g., crystalline plates, liquid crystals or Fresnel rhombs) to select the appropriate polarisation state. By yielding two beams with respective intensities equal to I_{0° and I_{90° , a beam splitter (aligned on the polarisation reference direction) provides the most natural method of measuring the Stokes Q linear polarisation of an incoming beam. By introducing a retarder in front of the beam splitter (e.g., a quarter-wave plate oriented at 45° with respect to reference axis), one can measure the polarisation of interest (e.g., Stokes V) by converting it into the beam splitter reference linear polarisation (Stokes Q); rotating the retarder further allows to exchange both beams emerging from the beam splitter, providing a convenient check that the beam difference content is indeed polarisation.

Different flavours of polarimeters have been proposed over the first century of solar and stellar magnetometry. For the first half-century, Hale and followers (including Babcock) turned their high-resolution spectrographs into spectropolarimeters by simply adding a quarter-wave retarder and a beam splitter in front of the spectrograph slit (Hale 1908; Babcock 1947). From the wavelength shifts of magnetically sensitive lines recorded in the two orthogonal circular polarisation states, one could derive the brightness average of the longitudinal field over the observed solar region or the visible stellar hemisphere (called B_ℓ hereafter), with relatively poor accuracies (of typically 300 G) by modern standards.

In the 1970's, a new device was proposed by Angel & Landstreet (1970), consisting at measuring the degree of circular polarisation in the wings of an H line of the Balmer series, usually H β . With its dual-beam polarimetric module and its twin photometers (one for each polarimetric channel) coupled to narrow-band interference filters (to isolate the line wings), this simple design shortcuits the need for a spectrograph and provides a very compact and easy-to-operate instrument. With this device, fields of magnetic chemically peculiar A and B stars were observed regularly for about two decades, providing a wealth of reference longitudinal fields with error bars as low as 50 G for the brightest stars (e.g., Borra & Landstreet 1980; Landstreet 1982). A similar technique can be used to observe the transverse component of the magnetic field through the linear polarisation signatures it generates in line profiles. Although very small, the signal does not cancel out once averaged over wavelengths thanks to differential saturation between the π and σ components (Leroy 1962); this makes broad-band linear polarimetry a viable tool for monitoring transverse magnetic fields at the surfaces of stars and an interesting option for complementing longitudinal field data (e.g., Leroy 1995).

All first-generation techniques mentioned above essentially derive one single magnetic measurement (of either the surface-averaged longitudinal or transverse field) per observation. However, the information available throughout the full circular (Stokes V) and linear (Stokes Q and U) polarisation profiles across spectral lines is far richer. Following Donati & Collier Cameron (1997),

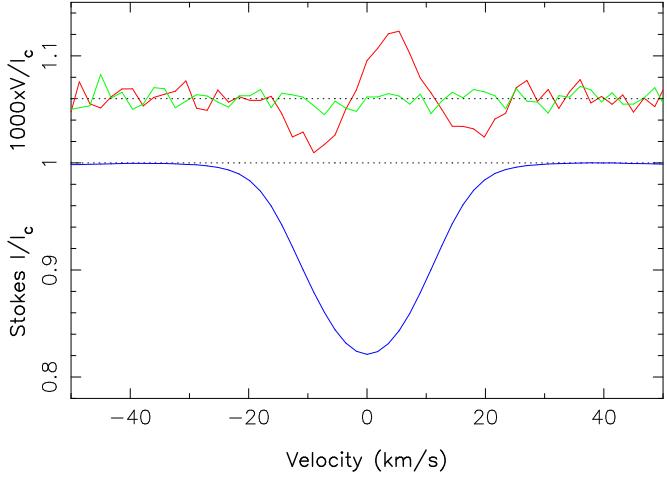
Mean LSD profiles of τ Boo, 2006 June 13

Fig. 1. LSD circular polarisation (Stokes V) Zeeman signature (red line), null polarisation check (green line, both expanded by 1000 and shifted vertically by 1.06 for graphical purposes) and unpolarised (Stokes I) profile (blue line) from the photospheric lines of τ Boo, as derived from ESPaDOnS data. A clear Zeeman signature is detected (with nothing visible in the null polarisation check) with a full amplitude of about 0.01% of the unpolarized continuum. The associated polarimetric sensitivity is 0.001%, i.e., 10 ppm.

the surface-averaged longitudinal field (i.e., B_ℓ , in G) can be derived from the Stokes V profile with a good accuracy using:

$$B_\ell = -714 \frac{\int vV(v)dv}{\lambda \bar{g} \int [1 - I(v)]dv} \quad (7)$$

where v is the velocity shift (in km s^{-1}) with respect to the line central wavelength λ (in μm). The longitudinal field being essentially the first moment of the Stokes V profile, it retains only the global circular polarisation content and smooths out all small-scale polarisation structures. While B_ℓ is adequate to characterise simple large-scale fields, it clearly misses most of the information for complex field structures, explaining *a posteriori* why all early attempts to detect the complex magnetic topologies of cool stars failed.

While using higher order moments of the polarisation profiles in addition to B_ℓ can certainly help (e.g., Mathys 1989), the best solution for losing no polarisation signal is obviously to extract the Stokes profiles themselves rather than some integrated (and thus degraded) quantity. This is achieved by coupling a polarimeter to a digital (usually high-resolution) spectrograph, a technique called spectropolarimetry. Using an échelle spectrograph provides the additional advantage of measuring Zeeman signatures from hundreds or thousands of spectral lines simultaneously, thereby tremendously increasing the overall efficiency of the process; however, it requires the polarimeter to be achromatic enough to derive polarisation spectra from a minimal number of sub-exposures. A cross-correlation-type technique called Least-Squares Deconvolution (LSD, Donati et al. 1997) was introduced to derive average Zeeman signatures from all medium to strong spectral lines available in the wavelength domain. Thanks to LSD, noise levels in the polarimetric signals can be strongly reduced, up to a factor of several tens in late K stars, provided that the instrument can collect the whole optical domain in a single shot.

In the last two decades, several new spectropolarimeters were developed. A first prototype instrument was tested and validated at the Anglo-Australian Telescope (Donati et al. 1997, 2003a), inspired from the initial concept of Semel et al. (1993). A second prototype instrument (Donati et al. 1999) was installed on the 2m Télescope Bernard Lyot (TBL) atop Pic du Midi (southwest France), providing the whole community with a wider access to spectropolarimetry. A new-generation high-resolution spectropolarimeter (called ESPaDOnS, Donati 2003) was installed in 2004 on the 3.6m Canada-France-Hawaii Telescope (CFHT) atop Mauna Kea (Hawaii), soon complemented by a clone version (NARVAL) installed at TBL. Both instruments are fully optimised for spectropolarimetry, perform a very achromatic polarimetric analysis (using modified Fresnel rhombs), and yield full coverage of the optical domain (0.37 to 1 μm) at a spectral resolution of 65,000 and with a peak efficiency of about 15% (telescope and detector included). Thanks to their high throughput and fringe-free polarimetric analysis, ESPaDOnS and NARVAL can reach very high photon-noise-limited polarisation accuracies (e.g., see Fig. 1); their unprecedented sensitivity (as low as 0.1 G on bright narrow-lined cool stars) brings a fresh opportunity to explore magnetic fields across most of the HR diagram and already enabled the discovery of magnetic fields in several stellar classes not previously known as magnetic (see below).

With its polarimetric mode, FORS1 on the ESO Very Large Telescope (VLT) atop Cerro Paranal (Chile) can serve as a low-resolution (about 2,000) spectropolarimeter. While its 150 km s^{-1} resolution element, it essentially amounts to a Balmer line polarimeter for slow rotators (such as chemically peculiar stars), but provides an interesting opportunity for investigating large-scale magnetic fields in very rapid rotators (Bagnulo et al. 2002). Its giant photon collecting power makes it very efficient at exploring magnetic fields in distant stellar clusters and at studying how magnetic fields can influence the evolution of early-type stars off the main sequence (Bagnulo et al. 2006).

3.3. Parametric modelling and tomographic imaging of magnetic fields

Once a magnetic field is detected at the surface of a star, one usually looks at whether the detected Zeeman signatures exhibit temporal variability over time scales of days and weeks. In most cases, cyclic variability is detected and attributed to a non-axisymmetric magnetic field being carried around the star by rotation and viewed under different configurations by the Earth-based observer. By recording time-series of the rotationally modulated Zeeman signatures, one can in principle extract information on the parent magnetic structure that generates the polarisation signals. This model is usually called the oblique rotator.

The first attempts at modelling magnetic topologies simply aimed at adjusting the rotational modulation of the observed longitudinal field with a simple magnetic dipole of polar field strength B_p , whose axis is tilted at an angle β with respect to the stellar rotation axis. This amounts to fitting the observed B_ℓ values and corresponding rotational phases ϕ with the following relation (Preston 1967):

$$B_\ell(\phi) = B_p \frac{15 + u}{20(3 - u)} [\cos \beta \cos i + \sin \beta \sin i \cos 2\pi(\phi - \phi_0)] \quad (8)$$

where i is the angle of the rotation axis to the line of sight, ϕ_0 the phase of longitudinal field maximum and u the linear limb darkening constant. This approach usually succeeds at fitting B_ℓ data of moderate precision and yields a gross estimate of the large-scale field (e.g., Borra & Landstreet 1980) but usually fails at matching the detailed modulation whenever very high quality data are

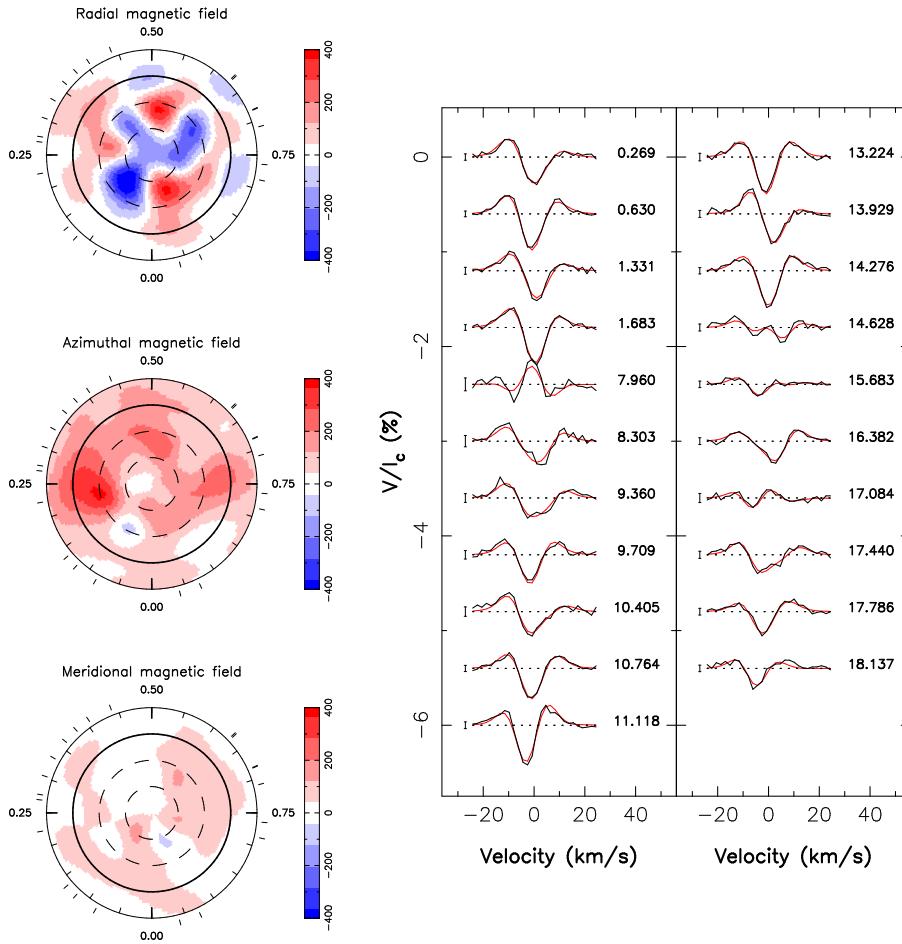


Fig. 2. Magnetic imaging of the large-scale field of the early-M dwarf DT Vir using ZDI (left panel) from a time series of circular polarisation (Stokes V) Zeeman signatures covering the whole rotation cycle (right panel). The reconstructed magnetic topology includes a significant toroidal component (showing up as unipolar azimuthal fields over the visible hemisphere) and a mostly non-axisymmetric poloidal component, typical of F to early-M dwarfs. **Left panel:** the 3 components of the field in spherical coordinates are displayed (from top to bottom) with magnetic fluxes labelled in G, the star being shown in flattened polar projection down to a latitude of -30° . Radial ticks around each plot indicate phases of observations. **Right panel:** observed Zeeman signatures are shown in black while the fit to the data is shown in red. The rotational cycle and 3σ error bars of each observation are shown next to each profile (from Donati et al. 2008c).

available and when the field is significantly more complex than a dipole (e.g., Wade et al. 2000; Donati et al. 2006c). More sophisticated models were also proposed, e.g., involving a combination of non-aligned dipole, quadrupole and octupole terms (Bagnulo et al. 1996), in an attempt to fit simultaneously constraints from independent data sets (e.g., B_ℓ values and broad-band linear polarisation). Despite the apparent success, detailed comparisons with time-series of Stokes profiles on several stars demonstrated that this basic model is far too limited and cannot yield a precise description of the parent magnetic topologies, even in the case of the fairly simple fields of magnetic chemically peculiar stars (Bagnulo et al. 2001).

By modelling the rotationally-modulated Zeeman signatures directly rather than a few of their low-order moments only, one can in principle recover to some extent (through indirect tomographic

techniques like those used for medical imaging) the parent magnetic topology. This technique, combining the advantages of Zeeman spectropolarimetry and Doppler imaging (e.g., Vogt et al. 1987), is called Zeeman-Doppler Imaging (ZDI) and was first proposed by Semel (1989) in the particular case of rapidly rotating stars. The initial implementation of ZDI (Brown et al. 1991; Donati & Brown 1997) inverted sets of Zeeman signatures into surface distributions of the vector magnetic field, described as 3 series of independent image pixels (one series for each component of the magnetic field in spherical coordinates). In the latest implementation (Donati 2001; Donati et al. 2006c), the magnetic field is decomposed in its poloidal and toroidal components, both expressed as spherical harmonics expansions; this newer method is found to be not only much more robust (especially for low-order large-scale fields like dipoles) and more physical (for the field description), but also more convenient (e.g., allowing to fine tune the respective weight of spatial scales) and informative (poloidal and toroidal field components are key ingredients in most theoretical studies on magnetic stars, Mestel 1999). While most efficient for rapidly rotating stars, this method is also applicable to slow rotators, though limited to low-order spherical harmonic modes (e.g., Donati et al. 2006c, 2008b). Note that magnetic mapping is practical both for stars with no intrinsic field variations and for stars with variable fields, provided that the typical timescale on which the field evolves is long compared to the rotation period. Numerous results have been obtained with ZDI on all types of stars, from sets of LSD Stokes V profiles. An example reconstruction in the case of a moderately rotating star is shown in Fig. 2; other examples in the case of rapid and slow rotators can be found in the literature (e.g., Morin et al. 2008a,b).

By mapping Zeeman signatures over several successive rotation cycles, ZDI can also estimate the amount of azimuthal shear (i.e., surface differential rotation) that stellar magnetic topologies are subject to. This method assumes a Sun-like surface rotation pattern with the rotation rate varying with latitude θ as $\Omega_{\text{eq}} - d\Omega \sin^2 \theta$, Ω_{eq} being the angular rotation rate at the equator and $d\Omega$ the difference in angular rotation rate between the equator and the pole. By carrying out magnetic reconstructions (at constant information content) for a range of Ω_{eq} and $d\Omega$ values, one can investigate how the quality of the fit to the data varies with differential rotation. A well defined minimum at physically sensible values of Ω_{eq} and $d\Omega$ suggests that differential rotation is present at the surface of the star (e.g., Donati et al. 2003b).

A variation of ZDI, called Magnetic Doppler Imaging (Piskunov & Kochukhov 2002), also aims at mapping magnetic fields on stellar surfaces from sets of time-resolved Zeeman signatures, incorporating polarised radiative transfer in the reconstruction process. This alternate method, applied to sets of Q , U , and V profiles of individual lines proved successful at reconstructing detailed magnetic topologies of a few chemically peculiar stars (e.g., Kochukhov et al. 2004). However, using only a few individual lines drastically reduces the polarimetric accuracy, limiting in practice the applicability of this technique to the brightest and most magnetic stars only; moreover, as of today, it does not allow to recover directly the poloidal and toroidal components of stellar magnetic fields, making it more difficult for comparing observations with theoretical predictions.

4. Magnetic fields of low-mass stars

4.1. Activity, rotation and magnetic fields

Most cool stars exhibit a large number of solar-like activity phenomena; dark spots are present at their surfaces (e.g., Berdyugina 2005), where they come and go on timescales ranging from days (as they are carried in and out of the observer's view by the star's rotation) to months (as they appear and disappear over a typical spot lifetime) and years or decades (with spots fluctuating in number and location throughout activity cycles). Prominences are also detected in cool stars, both as absorption and emission transients (e.g., in Balmer lines) tracing magnetically confined clouds (e.g., Collier Cameron & Robinson 1989; Donati et al. 2000) either transiting the stellar disc (and scattering photons away from the observer, as for dark filaments on the Sun) or seen off-limb (and scattering photons towards the observer, as for bright prominences on the Sun). Cool stars are also surrounded by low-density coronal plasma at MK temperatures showing up at various wavelengths in the spectrum (e.g., radio, X-ray and optical line emission) and associated with frequent flaring, recurrent coronal mass ejections, and winds. Activity phenomena in cool stars scale up with faster rotation and later spectral types (e.g., Hartmann & Noyes 1987; Hall 2008).

The current understanding is that activity phenomena are a by-product of the magnetic fields that cool stars generate within their convective envelopes through dynamo processes, involving cyclonic turbulence and rotational shearing (Parker 1955). In the particular case of the Sun, dynamo processes are presumably concentrating in a thin interface layer (the so-called tachocline) confined at the base of the convective zone (CZ) and where rotation gradients are supposedly largest (e.g., Charbonneau 2005). The spectacular images of the Sun collected with TRACE and (more recently) HINODE demonstrate that the activity of the Sun very tightly correlates with the presence of magnetic field emerging from the surface, either in the form of large closed loops (mostly at medium latitudes) or open field lines (mostly at high latitudes); the exact process through which magnetic fields succeed at heating the tenuous outer atmosphere to MK temperatures is however still unclear.

Cool stars are assumed to behave similarly. This is supported by observations showing that activity scales up with rotation rate (at any given spectral type), as suggested by dynamo theories. One of the key parameter for measuring the efficiency of magnetic field generation is the Rossby number Ro , i.e., the ratio of the rotation period of the star to the convective turnover time. It describes how strongly the Coriolis force is capable of affecting the convective eddies, with small Ro values indicating very active stars rotating fast enough to ensure that the Coriolis force strongly impacts convection. The observation that activity correlates better with Ro than with rotation (e.g., Noyes et al. 1984; Mangeney & Praderie 1984; Kiraga & Stepien 2007), or equivalently, that cooler stars are relatively more active at a given rotation rate, agrees well with the theoretical expectation that convective turnover times increase with decreasing stellar luminosities.

Magnetic fields are also responsible for slowing down cool stars through the braking torque of winds magnetically coupled to the stellar surface (Schatzman 1962; Mestel 1999). This is qualitatively compatible with the fact that most cool stars rotate slowly (like the Sun itself), with the exception of close binaries (whose spin angular momentum is constantly refueled from the orbital reservoir through tidal coupling) and young stars (which have not had time yet to dissipate their initial load of angular momentum). Magnetised wind models yield a good match to the observed distribution of rotation periods in young open clusters of ages ranging from several tens to sev-

eral hundreds of Myr (e.g., Bouvier 2007), further confirming that magnetic fields are likely what triggers the spinning down of cool stars as they arrive on the main sequence.

The main lesson from the solar paradigm is thus that dynamo processes are essentially ubiquitous in all cool stars with outer convective layers and generate magnetic fields with a high degree of temporal variability at all timescales. Extrapolating the solar analogy much further is potentially hazardous; in particular, assuming that conventional dynamo models (entirely tailored to match observations of the Sun) also apply to cool stars with very different convective depths and rotation rates is subject to caution. In very active stars rotating 100 times faster than the Sun for instance, the magnetic feedback onto the convection pattern may be strong enough to distort theoretical dynamo patterns; similarly, very-low-mass fully-convective stars obviously lack the interface layer where conventional dynamo processes are expected to concentrate, but are nevertheless strongly active. Magnetic studies of low-mass stars are therefore our best chance for exploring the various faces of dynamo processes over a large range of masses and rotation rates.

4.2. Magnetic properties of cool stars: field strengths, large-scale topologies, differential rotation and activity cycles

The very first estimates of magnetic fields in cool stars other than the Sun were obtained by measuring the differential broadening of spectral lines as a function of their magnetic sensitivities (Robinson 1980; Robinson et al. 1980), making it possible to derive the first trends on the magnetic properties of low-mass stars (e.g., Saar 2001). These studies find that the average surface magnetic strength B_s is, in most cases, roughly equal to the equipartition field, i.e., the field whose magnetic pressure balances the thermal pressure of the surrounding gas; only very active stars with rotation periods lower than about 5 d (among which fully-convective M dwarfs and young low-mass protostars) strongly deviate from this relation (e.g., Johns-Krull & Valenti 1996; Johns-Krull et al. 1999b; Valenti & Johns-Krull 2001). A similar behaviour is observed in the Sun, where fields of moderately active plages are close to equipartition while those of active sunspots are stronger by a factor of 2 or more. This suggests that magnetic regions at stellar surfaces progressively evolve from a plage-like to a spot-like structure, with flux tubes having increasingly larger sizes or being more tightly packed, as activity increases.

These studies also find that the average magnetic flux fB_s at the surfaces of cool stars increases more or less linearly with $1/Ro$ until it saturates at $Ro \simeq 0.1$ (corresponding to a rotation period of about 2 d for a Sun-like star), with most of the increase being attributable to the filling factor f (at least in moderately active stars). The detection of a saturation regime, confirmed with new magnetic flux measurements from molecular lines in M dwarfs (Reiners et al. 2008), supports the idea that magnetic fields are eventually capable of modifying, if not controlling, the convective motions through some feedback mechanism; this may potentially explain in particular why magnetic regions at low and high activity levels are morphologically different.

The first detections of Zeeman polarisation signatures from solar-type stars (e.g., Donati et al. 1997) and their tomographic modelling with stellar surface imaging tools such as ZDI opened up an alternative option for studying dynamo processes. In particular, the medium- and large-scale magnetic fields accessible through ZDI, though energetically less important than magnetic fluxes derived from Zeeman broadening, are nevertheless optimally suited for checking topological

predictions of dynamo models on global fields and their potentially cyclic variations, to which other methods are insensitive.

Initial studies, concentrating on a few very active rapidly rotating stars in the saturated-dynamo regime brought surprising results. In particular, they demonstrated that strong toroidal fields can show up directly at the stellar surface, in the form of monopolar regions of dominantly azimuthal fields or even complete rings encircling the star at various latitudes (e.g., Donati et al. 1992; Donati & Collier Cameron 1997; Donati 2003); while tori of strong azimuthal fields are likely present in the Sun at the base of the CZ (e.g., to account for the non-stochastic arrangement of surface sunspots, known as Hale's polarity law), they do not build up at the surface of the Sun - hence the surprise. The poloidal components detected on all 3 active stars mainly consist of a significant non-axisymmetric term with alternating patterns of opposite radial field polarities. Other studies confirmed and amplified these initial results, reporting the presence of strong and often dominant toroidal fields at photospheric level (e.g., Dunstone et al. 2008b), even in less active stars with longer rotation periods (e.g., Petit et al. 2005) or earlier spectral types (e.g., Marsden et al. 2006). A recent study focussing on main-sequence Sun-like stars with different rotation periods suggests that significant surface toroidal fields are detected whenever the rotation period is lower than ≈ 20 d (Petit et al. 2008a), i.e., $\approx 25\%$ shorter than the rotation period of the Sun.

ZDI observations also demonstrated that large-scale magnetic topologies of active stars are latitudinally sheared by surface differential rotation at a level comparable to that of the Sun (Donati & Collier Cameron 1997), with the equator lapping the pole by one complete rotation cycle about every 100 d (the so-called lap-time, equal to $2\pi/d\Omega$, where $d\Omega$ is the difference in rotation rate between the equator and the pole). This conclusion agrees with previous results derived from indirect tracers of differential rotation (photometric monitoring, e.g., Hall 1991). Differential rotation displays a steep increase with earlier spectral types, reaching values of 10 times the solar shear or more in late F stars (Barnes et al. 2005; Marsden et al. 2006; Dunstone et al. 2008a; Donati et al. 2008d). This trend is independently confirmed from observations of spectral line shapes (e.g., Reiners 2006) and suggests that F stars with shallow CZs are departing very strongly from solid-body rotation. Observations indicate that magnetic topologies remain more or less stable over timescales of $\approx 20\%$ the lap-time, suggesting that differential rotation is responsible for most of the observed mid-term temporal variability. Tidal effects in close binary stars apparently have very little impact either on magnetic topologies or on differential rotation patterns (e.g., Dunstone et al. 2008b,a) apart from maintaining a high rotation rate for both system components.

The major improvement in instrumental sensitivity brought by ESPaDOnS@CFHT and NARVAL@TBL made it possible to start surveying the magnetic topologies of cool stars, from mid F to late M stars. It allowed in particular the large-scale field properties of M dwarfs to be investigated for the first time on both sides of the full convection threshold (presumably occurring at spectral type M4, i.e., at a mass of $0.35 M_\odot$, Baraffe et al. 1998). Spectropolarimetric monitoring of the rapidly rotating M4 dwarf V374 Peg revealed that the star hosts a strong large-scale mostly-poloidal, mainly axisymmetric field despite its very short period (0.44 d), high activity level and low Ro (Donati et al. 2006a; Morin et al. 2008a); additional observations of active mid-M dwarfs further confirmed that dynamo processes in fully-convective stars with masses of about $0.3 M_\odot$ are apparently very successful at generating strong poloidal fields with simple axisymmetric configurations (Morin et al. 2008b).

Comparing to partly-convective early M dwarfs reveals that the transition in the large-scale field properties is fairly sharp and located at a mass of about 0.4 to 0.5 M_{\odot} (Donati et al. 2008c), i.e., slightly above the $0.35 M_{\odot}$ theoretical full-convection threshold. This sharp transition also coincides with a strong decrease in surface differential rotation (with photospheric shears smaller by a factor of 10 or more than that of the Sun) and, logically, with a strong increase in the lifetime of large-scale fields (Morin et al. 2008b). Preliminary results on very-low mass stars ($< 0.2 M_{\odot}$) suggest that the situation is even more complex, with some stars hosting very strong and simple large-scale fields (like those of mid-M dwarfs) and some others with much weaker and complex magnetic topologies (resembling those of early-M dwarfs). Observations of a larger sample are needed to clarify the situation but the preliminary results already demonstrate that at least some very-low-mass stars are capable of producing a strong large-scale axisymmetric poloidal field. This conclusion is independently confirmed by the detection of highly-polarised rotationally-modulated radio emission from late M and early L dwarfs attributable to intense large-scale magnetic fields (e.g., Berger et al. 2005; Berger 2006; Hallinan et al. 2006) through electron cyclotron maser instability (Hallinan et al. 2008).

Figure 3 presents graphically the main results obtained so far in the framework of the ongoing survey effort, aimed at identifying which stellar parameters mostly control the field topology. To make it more synthetic, the plot focusses only on a few basic properties of the reconstructed magnetic topologies, namely the reconstructed magnetic energy density e (actually the integral of B^2 over the stellar surface), the fractional energy density p in the poloidal field component, and the fractional energy density a in mostly axisymmetric modes (i.e., with $m < \ell/2$, m and ℓ being the order and degree of the spherical harmonic modes describing the reconstructed field). Each selected star is shown in the plot at a position corresponding to its mass and rotation period, with a symbol depicting these three characteristics of the recovered large-scale fields, i.e., e (symbol size), p (symbol colour) and a (symbol shape). This plot clearly illustrates the two main transitions mentioned above:

- below $Ro \simeq 1$, stars more massive than $0.5 M_{\odot}$ succeed at producing a substantial (and sometimes even dominant) toroidal component with a mostly non-axisymmetric poloidal component;
- below $0.5 M_{\odot}$, stars (at least very active ones) apparently manage to trigger strong large-scale fields that are mostly poloidal and axisymmetric.

Long-term monitoring of large-scale magnetic topologies can potentially reveal whether the underlying dynamo processes are cyclic like in the Sun (with the field switching its overall polarity every 11 yr), constant or chaotic. Initial studies carried over a decade demonstrated indeed that both the field topologies and the differential rotation patterns are variable on long-timescales (e.g., Donati et al. 2003a,b) but have failed to catch stars in the process of switching their global magnetic polarities, suggesting that their dynamos (if cyclic) do not reverse much more often than that of the Sun; similar conclusions are obtained from long-term monitoring of solar-type stars using indirect proxies like overall brightness or chromospheric emission (e.g., Hall 2008). Very recently, first evidence for global polarity switches was reported in a star other than the Sun, namely the Jupiter-hosting F8 star τ Boo (Donati et al. 2008d). During repeated spectropolarimetric monitoring (see Fig. 4), two successive polarity switches of τ Boo were recorded within about 2 yr, suggesting

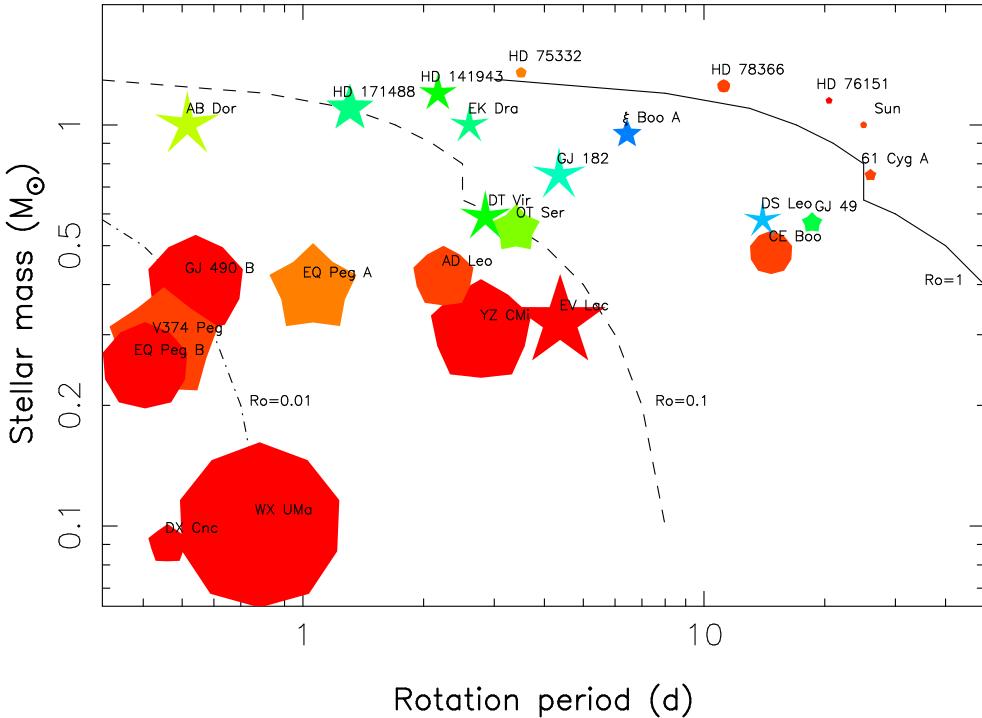


Fig. 3. Basic properties of the large-scale magnetic topologies of cool stars, as a function of stellar mass and rotation rate. Symbol size indicates relative magnetic energy densities e , symbol colour illustrates field configurations (blue and red for purely toroidal and purely poloidal fields respectively) while symbol shape depicts the degree of axisymmetry of the poloidal field component (decagon and stars for purely axisymmetric and purely non-axisymmetric poloidal fields respectively). The full, dashed and dash-dot lines respectively trace where the Rossby number Ro equals 1, 0.1 and 0.01 (using convective turnover times from Kiraga & Stepień 2007). The smallest and largest symbols correspond to mean large-scale field strengths of 3 G and 1.5 kG respectively. Results for stars with $M_\star < 0.2 M_\odot$ are preliminary (from Donati et al. 2008b).

an activity cycle about 10 times faster than that of the Sun (Donati et al. 2008b). Although still fragmentary, observations already show that the poloidal and toroidal field components do not vary in phase across the cycle period.

4.3. Benchmarking dynamo models with observations of cool stars

Observational evidence that magnetic fields of cool stars are generated through dynamo processes is very strong. As recalled above, magnetic fields are ubiquitous to all stars with significant outer convection (i.e., spectral type later than mid F), and direct spectroscopic estimates demonstrate that magnetic fluxes scale up with rotation rate (and more tightly with $1/Ro$) until they saturate - in agreement with what conventional dynamo theories predict. The other option, i.e., that these fields would be fossil remnants from a prior evolutionary stage, finds little support either from observations or theory; while models predict fossil fields to be dissipated by convection (as a result of the very high turbulent magnetic diffusivity) in as little as 1000 yr (e.g., Chabrier & Küker 2006), observations indicate that fields are very often highly variable (both locally and globally) on timescales of months to decades and thus cannot reasonably result from an evolutionary process

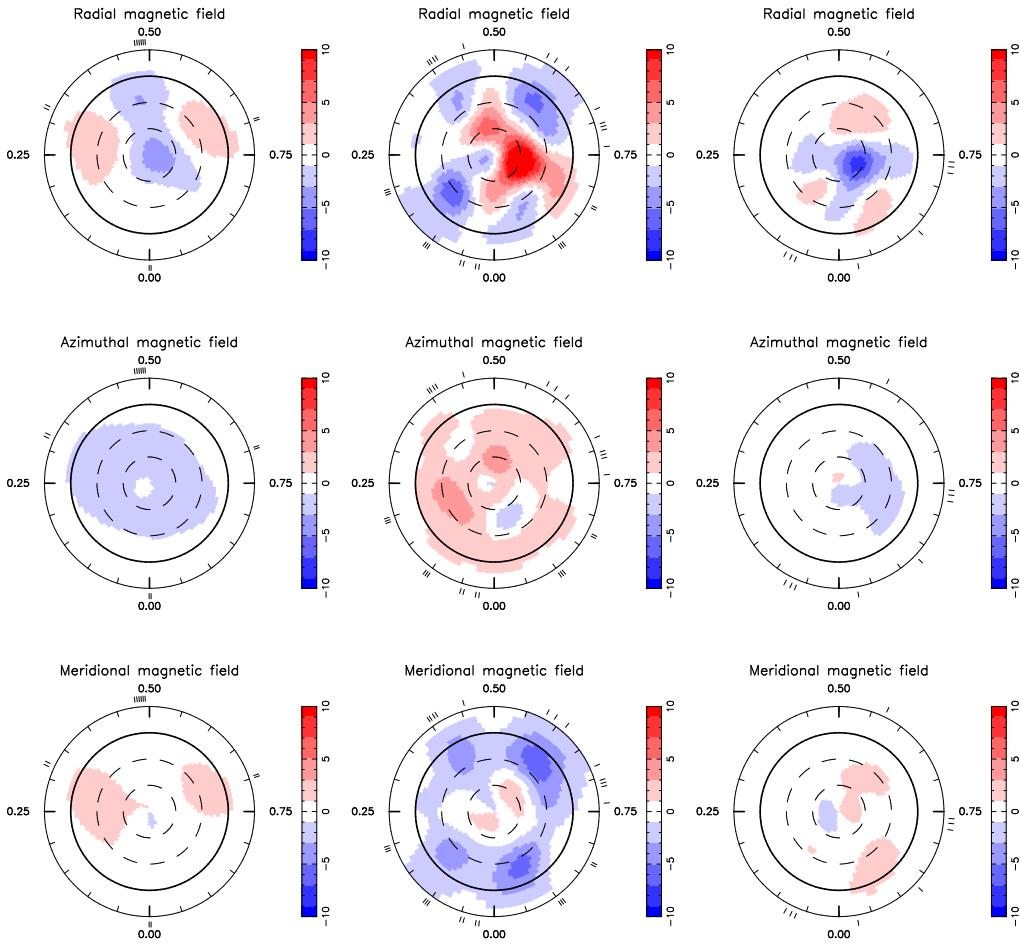


Fig. 4. Large-scale magnetic topology of the F7 planet-hosting star τ Boo derived with Zeeman-Doppler imaging in 2006 June (left panel, from Catala et al. 2007b), 2007 June (middle panel, from Donati et al. 2008d) and 2008 June (right panel, from Donati et al. 2008b, Farès et al, in preparation). Plotting conventions are as in Fig. 2. Both poloidal and toroidal fields globally switched polarities between successive epochs.

that ended at least tens of Myr before. Magnetic field measurements on cool stars thus bring, at first order, strong and independent support to generic dynamo models.

Dynamo models have undergone considerable progress in recent years; mean-field models are now implementing more physics (e.g., the presence of an interface layer or the effect of meridional circulation, Parker 1993; Dikpati & Charbonneau 1999) while direct numerical simulations are now able to reach strongly turbulent regimes capable of producing intense mean magnetic fields (e.g., Brun et al. 2004; Browning 2008). However, despite such progress, there is still a large number of open questions, some of them concerning the very basic physics of dynamo processes, e.g., the identification of the primary mechanism through which the large-scale poloidal component is regenerated (Charbonneau 2005). Above all, dynamo models are almost completely tailored for the Sun, with all model parameters finely tuned to reproduce solar observations as well as possible; checking them against observations of other stars with different masses and rotation rates in particular is a mandatory validation test that they yet have to undergo. The growing body of published results on large-scale magnetic topologies of cool stars should provide the opportunity

for doing this in the near future. Meanwhile, we will summarize here the main topics on which the recent results provide new insight into dynamo processes.

The presence of toroidal fields at the surface of partly-convective stars with $Ro < 1$ is undoubtedly a surprising discovery, leading some to conclude that dynamo processes in very active stars must be operating either throughout the whole CZ or at the very least within a subphotospheric layer (e.g., Donati & Collier Cameron 1997; Donati et al. 1999; Donati 2003) rather than just at the base of the CZ (as usually assumed in conventional dynamo theories). Interestingly, a similar idea - a distributed dynamo shaped by near-surface shear - was recently invoked and investigated theoretically in the particular case of the Sun as an alternative to conventional interface dynamo models (Brandenburg 2005); in particular, this new model can potentially solve a number of long-standing issues (e.g., the large number of toroidal flux belts produced by interface dynamos) if further validated by new simulations. Very recent spectropolarimetric observations of the Sun with the HINODE spacecraft revealed that the quiet inter-network regions (i.e., the inner regions of supergranular cells of the quiet Sun) are pervaded by transient mainly-horizontal magnetic flux (Lites et al. 2008) possibly generated by a near-surface dynamo (Schüssler & Vögler 2008), giving still further support for a non-conventional distributed and/or near-surface dynamo in the Sun. Admittedly, surface toroidal fields detected in cool active stars are more stable than those seen on the Sun and participate to the large-scale field; they could however share a similar origin and scale up in strength and size with $1/Ro$, being only visible at low ZDI-like spatial resolutions for stars with $Ro < 1$. In turn, this may suggest that the newly-discovered horizontal fields of the Sun also participate to the activity cycle.

Despite their high level of activity, fully-convective stars obviously lack the interface layer where dynamo processes presumably operate; understanding their magnetism thus represents a major challenge for theoreticians. A wide range of predictions has been made about the kind of fields that such dynamos can produce; while early studies speculate that they generate small-scale fields only (Durney et al. 1993), newer models find that they can potentially trigger purely non-axisymmetric large-scale fields (Küker & Rüdiger 1999; Chabrier & Küker 2006) with CZ's rotating as solid bodies (Kuker & Rudiger 1997). The latest simulations show that axisymmetric poloidal fields can also be produced with significant differential rotation (Dobler et al. 2006), but that toroidal fields are usually dominant and differential rotation rather weak whenever Ro is low enough (Browning 2008). In this context, the recent discovery (from both spectropolarimetry and radio observations) that fully-convective stars are able to generate strong and simple large-scale mostly-axisymmetric poloidal fields while rotating almost as solid bodies (Donati et al. 2006a; Morin et al. 2008a,b) is very unexpected and hard to reconcile with any of the existing models.

The first results of the spectropolarimetric survey indicate that the sharp transition in the large-scale magnetic topologies and surface differential rotation of M dwarfs more or less occurs where the internal structure of the star drastically changes with mass (the inner radiative zone shrinking in radius from $0.5 R_\star$ to virtually nothing when M_\star decreases from $0.5 M_\odot$ to $0.4 M_\odot$, Baraffe et al. 1998; Siess et al. 2000). It is also worthwhile noting that X-ray luminosities of M dwarfs (relative to their bolometric luminosities) are roughly equal (at similar Ro) on both sides of the full-convection threshold, while the strengths of their large-scale fields feature a clear discontinuity (at a mass of about $0.4 M_\odot$, Donati et al. 2008c). All this suggests that dynamo processes become much more efficient at producing large-scale mainly-axisymmetric poloidal fields essentially as a response to

the rapid growth in convective depths with decreasing stellar masses; this is qualitatively compatible with the idea that the geometry of the CZ may control the kind of dynamo wave that a cosmic body can excite (Goudard & Dormy 2008).

The first detection of global magnetic polarity switches in a star other than the Sun is a major first step towards a better understanding of activity cycles of low-mass stars. Looking at, e.g., how cycle periods vary with stellar mass and rotation rate, or how poloidal and toroidal fields fluctuate with time across the cycle period, should ultimately reveal what physical processes mostly control the cycle. Results using a Babcock-Leighton flux transport dynamo model on the Sun (Dikpati & Charbonneau 1999) suggest that meridional circulation is a crucial parameter; while meridional circulation is difficult to estimate directly in stars other than the Sun, its relation to rotation and differential rotation can potentially be tracked back from how cycle periods vary with stellar parameters. The geometry of the CZ is potentially also important (Goudard & Dormy 2008).

4.4. Magnetic braking and coronal structure of low-mass stars

As mentioned above, the main impact of magnetic fields on low-mass stars is to generate extended outer atmospheres including in particular MK coronae and magnetised winds; these magnetised winds, as well as the frequent ejection of massive coronal prominences trapped in large-scale magnetic loops (e.g., Collier Cameron & Robinson 1989; Donati et al. 2000), are usually invoked as the main mechanism by which low-mass stars efficiently lose their angular momentum and rapidly spin down on the early main sequence. Most constraints on how fast stars are spinning down as they age come from empirical modelling of distributions of, e.g., rotation periods in young open clusters of various ages (e.g., Bouvier 2007), or activity levels and line broadening at various ages or vertical distances from the Galactic plane (e.g., Delfosse et al. 1998; West et al. 2008; Reiners & Basri 2008). Results indicate that low-mass stars typically spin down in a timescale of about 100 Myr down to about $0.4 M_{\odot}$; very-low-mass fully-convective stars spin down 10 times more slowly, with brown dwarfs having spin-down times that continue to increase as mass decreases. This modelling however tells us little about how exactly angular momentum is lost and why stars suddenly start to lose much less angular momentum once they get fully-convective.

Modelling coronal structures of cool stars other than the Sun is a promising option to address this issue. This is performed by extrapolating large-scale surface magnetic topologies obtained with ZDI up to the corona, assuming the field is current-free (e.g., Jardine et al. 2002a); field lines are also forced to open (e.g., under the coronal pressure) at a given distance above the stellar surface from which the field is radial (e.g., simulating the base of the wind), with the radial extent, temperature and density of the corona being used as free model parameters (Jardine et al. 2002b). The free model parameters can be derived by matching model predictions to X-ray emission measures and their rotational modulation whenever available; this modelling suggests for instance that X-ray emitting coronae of cool stars concentrate fairly close to the stellar surface (Hussain et al. 2007). Applying standard wind models to open field lines derived from such three-dimensional magnetic mapping can potentially predict angular momentum losses at each spectral type and thus determine whether the drastic change in large-scale magnetic topologies reported to occur at very-low masses can account for the coincidental 10-fold increase of spin-down times.

5. Magnetic fields of intermediate- and high-mass stars

5.1. General properties of upper-main sequence magnetic stars

In contrast to the low-mass stars discussed previously, the intermediate-mass (from 1.5 to $8 M_{\odot}$) and high-mass (above $8 M_{\odot}$) stars have relatively quiescent envelopes, with at most rather shallow CZs (near the surface where H, He or He^+ is partially ionised). Instead these stars have strong convection in the core where nuclear energy is produced. As mass increases, stellar luminosity grows very rapidly while main sequence lifetime shrinks fast (1 Gyr for $2 M_{\odot}$, 100 Myr for $5 M_{\odot}$, and 10 Myr for about $17 M_{\odot}$). Unlike their low-mass counterparts, higher-mass stars tend to rotate rapidly, i.e., at rotation rates of more than 20% of the critical speed (the rotation rate at which the equatorial velocity equals the Keplerian velocity). Intermediate-mass stars generally appear to have almost no mass loss, while massive stars usually lose mass (as a result of their intense outflowing radiation field) at such a rate that their subsequent evolution is significantly modified.

Up to now, magnetic fields have only been found among a small minority of higher-mass stars. For intermediate-mass stars, Babcock's initial discovery (Babcock 1947) of a magnetic field in a star with fairly narrow spectral lines and peculiar atmospheric abundances (belonging to the small subgroup of stars called "peculiar A/B" or Ap/Bp stars) has ultimately led to the empirical demonstration that all stars of the Ap/Bp class host detectable magnetic fields; in contrast, there are no well-established cases of other intermediate-mass stars with fields. These magnetic Ap/Bp stars constitute a few percent of all intermediate-mass main-sequence stars of similar spectral types. In more massive stars, a number of field detections have recently been reported, for example in a few (mostly massive) young Herbig Ae/Be stars and early B and O stars, all showing marginal or no signs of chemical peculiarities. These fields are similar in size and structure to those found in the Ap/Bp stars and probably represent a higher-mass continuation of the same magnetic phenomenon.

In contrast to those of low-mass stars, the magnetic fields of intermediate- and high-mass stars often have simple large-scale topologies and exhibit virtually no intrinsic variability even on time-scales of decades. Furthermore, the observed field strengths do not scale up with rotation rates; some of the largest fields occur in stars with rotation periods of months or years. From the positions of Ap/Bp stars with accurate parallaxes and temperatures in the Hertzsprung-Russell (HR) diagram, and from their location essentially on the isochrones of open clusters, it is clear that magnetic Ap/Bp stars are very similar in bulk structure to normal A and B stars, and their striking abundance anomalies seem to be primarily a near-surface effect. More on general properties of magnetic Ap/Bp stars can be found in Landstreet (1992).

5.2. Magnetic fields measurements in intermediate- and high-mass stars

The fields of middle and upper main sequence stars, and their pre-main sequence precursors, are mostly detected through circular spectropolarimetry, which reveals (as in lower-mass stars) the presence of the Zeeman effect in spectral lines. In addition, some of these stars have sufficiently large fields and sufficiently small projected rotation velocities that Zeeman splitting is visible directly in the intensity (Stokes I) spectrum. The result of a measurement of circular polarisation is usually described by deducing the mean longitudinal field B_L ; typical values vary over about two orders of magnitude from one star to another, between about 100 G and 10 kG; when Zeeman

splitting is visible, the resulting mean surface field intensities B_s range from about 2 to 30 kG. Additional information on the orientation of transverse magnetic fields in Ap/Bp stars is also available through broad-band linear polarisation measurements (e.g., Leroy 1995, see also Sec. 3).

The observed fields are usually (though not always) periodically variable, as a result of a non-axisymmetric magnetic geometry (about the rotation axis) carried around the star by rotation. Among the magnetic stars that show the specific chemical abundance anomalies of Ap/Bp stars, unpolarised spectral lines are often also variable with the same rotation period, indicating an inhomogeneous distribution of chemical elements over the stellar surface. This in turn usually leads to small periodic photometric variations. More massive stars also show magnetic and spectrum (and sometimes even photometric) variability; their spectrum variability however shows up mainly in lines formed at the base of the wind, indicating that the fields of massive stars impact their winds rather than their near-surface distribution of chemical elements (as in Ap/Bp stars).

The observed temporal variations of B_ℓ (as well as of B_s and broad-band linear polarisation whenever available) are usually compatible with dipole or low-order multipole fields inclined to the rotation axis (the oblique rotator model mentioned in Sec. 3), leading early studies to conclude that large-scale magnetic fields of Ap/Bp stars are globally simple (e.g., Landstreet 1982; Leroy 1995; Bagnulo et al. 1996). Although rough, this modelling provides a simple way of characterising the very-large-scale geometries and strengths of magnetic fields in early-type stars; in particular, it enabled to demonstrate that magnetic Ap stars with rotation periods of a month or less tend to have magnetic fields perpendicular to their rotation axis, while magnetic Ap stars with longer rotation periods tend to align their fields on the rotation axis (Landstreet & Mathys 2000). More recently, similar modelling applied to a survey of weak-field Ap/Bp stars established that their large-scale fields always have a minimum strength of about 300 G at the surface (Aurière et al. 2007); this minimum field, roughly equal to the thermal equipartition field in Ap/Bp stars, is apparently necessary to lead to the chemical patterns and spectrum variability of the Ap/Bp stars. Complete time-series of Stokes V profiles (as well as Stokes Q and U profiles whenever available) of magnetic Ap/Bp stars collected over full rotational cycles (e.g., Wade et al. 2000) show that these stars also feature a significant amount of medium-scale magnetic structures that are not properly described with the simple descriptions first used (e.g., Bagnulo et al. 2001) but that can be mapped using more sophisticated tomographic imaging tools (e.g., Kochukhov et al. 2004; Donati et al. 2006c).

Efforts have been made to study empirically the evolution of magnetism with time through the (rather long) main sequence phase in Ap/Bp stars. For nearby field stars, for which the magnetic fields are often well characterised, this is done by using the HR diagram positions with computed stellar evolution tracks to deduce the ages and fractions of the main sequence lifetime elapsed for many individual stars, which are then studied as an ensemble to search for correlations and trends. The main difficulty with this method is that it requires highly optimistic (and probably unrealistic) assumptions about the uncertainties in effective temperature and mass, and about the appropriateness of using specific sets of evolutionary tracks for given bulk chemistries, in order to derive usefully accurate ages for stars. Although various authors have claimed to obtain definite conclusions using this method, it is not at all clear that such results are meaningful.

Attention has therefore shifted to studying magnetic stars in open clusters, a possibility which has only recently opened up with advances in spectropolarimetry. No suitable sample of magnetic cluster members existed, and so a large survey was required (Bagnulo et al. 2006), which has re-

vealed more than 80 magnetic cluster members for which the fields are now roughly characterised. Ages for these stars are determined within about $\pm 30\%$, making it possible to discern clearly that both fields and magnetic fluxes in Ap/Bp stars in the range of 2 to $5 M_{\odot}$ decline by a factor of several during their main sequence evolution, with much of the decline taking place early in the main sequence phase (Landstreet et al. 2007, 2008).

Intermediate- and high-mass magnetic stars have the peculiarity that they generally rotate more slowly than most normal stars of the same mass, typically by a factor of five to ten, but sometimes by a factor of 1000 or more. Apparently, most of the extra loss of angular momentum that magnetic stars experience (with respect to non-magnetic stars) occurs during pre-main sequence phases². Another bizarre and mysterious aspect of upper main sequence magnetic stars is that they are very rarely members of close binary systems (Abt & Snowden 1973), although wide binaries are not uncommon. This fact makes the slow rotation of most Ap stars even more striking; most other slowly rotating A and B stars are members of close binary systems.

Magnetic surveys have been carried out over hundreds of intermediate and massive main sequence stars, including a significant number of normal F, A and B stars (Landstreet 1982; Shorlin et al. 2002; Bagnulo et al. 2006), with typical error bars on longitudinal fields ranging from 15 to 135 G; no fields were found in any normal stars. Fields have been sought to no avail in F, A and B stars with other chemical peculiarities than those of the Ap/Bp type, such as metallic line (Am) stars, mercury-manganese (HgMn) stars, and λ Boo stars (Bohlender & Landstreet 1990; Shorlin et al. 2002; Wade et al. 2006, with similar error bars). The relative frequency of magnetic Ap/Bp stars with respect to all main sequence stars of similar mass drops rapidly from a maximum of about 10% around $3 M_{\odot}$ to zero at about $1.6 M_{\odot}$ (Power et al. 2008), a fact which has so far no explanation. In solar-type stars, fields are detected up to masses of about $1.5 M_{\odot}$ (see Sec. 4) suggesting that there is basically no magnetic stars in a narrow mass range above $1.5 M_{\odot}$.

Recently, magnetic fields were discovered in several O and early-B stars which show little to no chemical abundance peculiarities (compared to Ap/Bp stars). Stars in which fields were found are relatively slow rotators and usually show periodic variations in spectral proxies formed within their strong radiative wind (e.g., X-ray fluxes and UV C iv and Si iv lines). Detecting magnetic fields in massive stars is much more difficult than in intermediate-mass ones, in spite of the apparent brightness of some. Such stars have far fewer suitable spectral lines in the optical domain available with current spectropolarimeters, and most of the available lines are either intrinsically broad (lines of H, triplet lines of He), or quite weak (high-excitation lines of light elements), or contaminated by emission. As a result, the threshold for significant detection is substantially higher for OB stars than for Ap/Bp stars and only 9 reliable detections have been obtained so far, 6 in early B stars (namely β Cep, ζ Cas, τ Sco, ξ^1 CMa, Par 1772 ν Ori, e.g., Henrichs et al. 2000; Neiner et al. 2003; Donati et al. 2006c; Petit et al. 2008b) and 3 in O stars (namely θ^1 Ori C, HD 191612 and ζ Ori A, Donati et al. 2002, 2006b; Bouret et al. 2008).

The magnetic fields of OB stars show obvious similarity with the well-known ones of the magnetic Ap/Bp stars; in particular, they are rather simple topologically (except in the young B star τ Sco where the field is significantly more complex than usual, Donati et al. 2006c, see Fig. 5) with global field strengths of some hundreds or thousands of G; periodic modulation of spectral

² Rare cases have been reported of magnetic Ap stars changing rotation period by an observable amount in recent years (e.g., Pyper et al. 1998) through a mechanism that is not yet clearly understood.

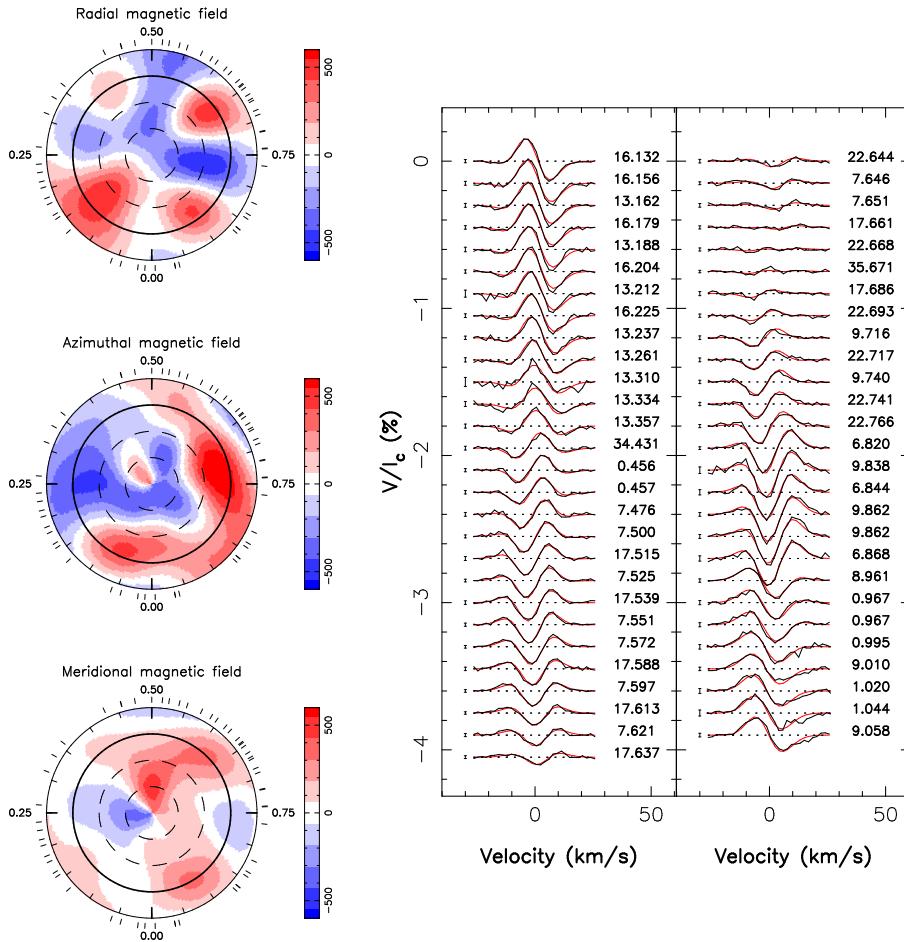


Fig. 5. Large-scale magnetic topology of the young early B star τ Sco derived with ZDI (left panel) from a time series of circular polarisation (Stokes V) Zeeman signatures covering the whole rotation cycle (right panel). The reconstructed magnetic field is relatively complex (by the standards of intermediate- and high-mass stars) and mostly poloidal. Both panels are as Fig. 2. Note the extremely good reproducibility of Zeeman signatures collected at very similar phases but very different rotational cycles (rotation period $\simeq 41$ d) over a total timespan of 4 yr (from Donati et al. 2006c, with new material added).

or photometric features usually correlate well with the magnetic field, and the relative fraction of magnetic stars, while still uncertain, is certainly low.

Another recent discovery concerns magnetic fields of intermediate- and high-mass stars as they approach and land on the main-sequence. A subset of A and B stars in this situation, known as Herbig Ae/Be stars, are usually found in regions of current or very recent star formation. Their positions in the HR diagram place them on tracks leading to the main sequence or close to the main sequence itself, and their spectra show emission lines usually interpreted as produced in (accretion) disks (e.g., Waters & Waelkens 1998). Initial studies of magnetic fields in Herbig Ae/Be stars have yielded a number of discoveries (e.g., Wade et al. 2007; Catala et al. 2007a; Alecian et al. 2008a,b) and already established in particular that only a few percent of Herbig Ae/Be stars have significant fields whose properties are again very much like those of magnetic Ap/Bp stars.

Since fields of most magnetic intermediate- and high-mass stars are phenomenologically very similar, it is reasonable to suppose that they arise from the same origin, with class-to-class dif-

ferences being due to the secondary effects the fields produce on stellar atmospheres, winds, and spectra. A large-scale 4 yr survey (called “Magnetism in Massive Stars” or MiMeS) using both ESPaDOnS@CFHT and NARVAL@TBL has just begun and should ultimately bring a more precise observational description of early-type magnetic stars.

Recently, substantial fields were detected in evolved intermediate-mass stars ascending the red giant branch (Aurière et al. 2008). Such stars are cool and convective enough to trigger dynamo processes and related activity phenomena despite their slow rotation, as suggested by the correlation found between their X-ray luminosity and rotation velocities (e.g., Gondoin 1999). A small number of these giant stars are expected to be the evolutionary descendants of upper main-sequence magnetic stars and thus to show substantial fields and enhanced activity; with a rotation period of over 300 d and a field of about 300 G, the late G giant EK Eri is likely one of them.

5.3. *Dynamo versus fossil fields*

As discussed in Sec. 4, the fields of low-mass main sequence stars (and of the Sun in particular) are likely generated by contemporary dynamo action. Observations demonstrate that these fields (and all related activity processes) are ubiquitous to all cool stars, strongly correlate with the presence of a deep-enough outer convective zone, scale up with rotation rate and vary on multiple timescales, in gross agreement with what theory predicts. None of these characteristics are found in upper main sequence stars; magnetic fields are present in no more than a small fraction of stars, are usually fairly simple topologically, do not strengthen with rotation rate (in fact, equally strong fields are often observed in stars having rotation rates of days and years), and do not evolve significantly in timescales of many years. In addition, such stars typically have only one or two shallow convection zones in their envelopes, vigorous convection occurring only within the stellar core.

Theorists have nevertheless investigated whether the observed fields could be due to dynamos operating either in the fully-convective core or in a sheared radiative zone, i.e., where the basic ingredients of dynamos (turbulence and shear) are present. Dynamos in fully-convective M dwarfs are obviously capable of producing strong axisymmetric fields (Dobler et al. 2006; Browning 2008) and can presumably do the same in the core of upper main sequence stars (Charbonneau & MacGregor 2001; MacGregor & Cassinelli 2003; Brun et al. 2005). The real difficulty is however to bring the magnetic flux to the surface (while not preventing at the same time dynamo action to operate; Charbonneau & MacGregor 2001; MacDonald & Mullan 2004) and produce very simple and stable magnetic fields with similar properties to those observed in early-type stars - in particular the non-correlation of magnetic strengths with rotation rates. The idea of a more exotic shear dynamo operating within radiative zones of early-type stars was also proposed (with the radial shear stretching the field into a toroidal configuration that the Tayler/Spruit instability eventually destabilises, Spruit 2002; MacDonald & Mullan 2004; Mullan & MacDonald 2005; Braithwaite 2006a). Predicted fields are however still expected to scale-up with rotation rate and exhibit temporal variability, in contradiction with observations. Last but not least, fields observed in intermediate- and high-mass stars are in most cases strong enough to prevent the field from being sheared by differential rotation and therefore the instability from operating (Aurière et al. 2007).

In this context, the original theoretical idea, i.e., that the fields of early-type stars were generated at some earlier time in the star’s history and have been retained by magnetic self-induction ever

since (without any important current field generation taking place), still provides the most convincing picture. In this theory, known as the fossil field hypothesis, magnetic fields from the interstellar medium thread molecular clouds from which stars form, and are advected and amplified as clouds collapse into protostars (see Sec. 6 for a more detailed description); most of the initial magnetic flux is presumably lost (by ohmic dissipation or ambipolar diffusion, see Sec. 6) during the contraction process, with only the most magnetic protostars being able to retain a significant fraction of their magnetic flux (e.g., Mestel 1999) and populating the (sparse) class of early-type magnetic stars. In these stars, the magnetic field cannot simply decay away through ohmic dissipation. Given the high conductivity of their (almost fully ionised) plasma, early-type stars have typical ohmic dissipation timescales of order 10 Gyr, i.e., considerably longer than their main sequence lifetime. Any (highly compressed) interstellar magnetic field surviving the whole formation process is thus likely to be retained by the main-sequence star. Such fields are expected to be very nearly static, relatively simple in structure (and even more so as stars evolve), and not to scale up in strength with rotation rate (highly magnetic early-mass protostars actually having more chance of being slow rotators, see Sec. 6). This is in fair agreement with what one finds in upper main sequence stars, leading most to conclude that their magnetic fields are fossil fields.

The issue of whether simple fossil fields are stable remains however open. Purely poloidal and toroidal fields are known to be unstable (Tayler 1973; Wright 1973; Braithwaite 2006b, 2007); a mixture of both is likely necessary for stabilising a large-scale field. Recent numerical experiments (Braithwaite & Spruit 2004; Braithwaite & Nordlund 2006) suggested that many initially unstable global field topologies spontaneously develop such a mixed poloidal/toroidal field configuration and become stable in doing so. The apparent existence of a lower limit to the field strengths found in magnetic Ap stars (Aurière et al. 2007) may be related to this very instability; whenever the internal field is too weak, a radial shear develops and stretches the field into a predominantly toroidal and unstable configuration. The only magnetic early-type star whose field is potentially subject to this instability is the (otherwise normal and thus rapidly rotating) O star ζ Ori A (Bouret et al. 2008); future observations should reveal whether its magnetism indeed results from an exotic shear dynamo capable of generating fields in radiative zones.

5.4. Diffusion, mass-loss and evolution

Magnetic fields can have various effects on early-type stars depending on their mass.

In magnetic Ap/Bp stars, surface abundances are drastically different from those of normal non-magnetic stars and obviously correlate with the presence of magnetic fields. With no convection and weak turbulence (e.g., large-scale horizontal motions being frozen by the strong large-scale magnetic field), microscopic atomic diffusion cause heavy atoms to settle slowly while outward radiative acceleration (transmitted to specific ions through their spectral lines) forces them to levitate, to rise into the atmosphere and possibly even to escape from the star. Depending on the respective strength of the two forces for each species, and on the field orientation, atoms will accumulate within (or disappear from) the photosphere, presumably leading to the observed persistent chemical anomalies and surface abundance inhomogeneities. This scenario fails at reproducing quantitatively existing data of Ap/Bp stars, suggesting that it is still lacking some ingredients.

The more luminous magnetic OB stars show little or no chemical peculiarities, a direct consequence of their much higher mass-loss rates. At about $10 M_{\odot}$ (i.e., spectral type B2), microscopic diffusion can no longer compete with mass loss and no longer influences the surface chemistry significantly (e.g., Michaud 1986); the field however is capable of reshaping the wind by forcing the escaping plasma to follow field lines (at least up to the Alfvén radius, i.e., wherever the magnetic energy density dominates the wind ram pressure). In this context, wind flows from the two magnetic hemispheres collide with each other at the magnetic equator, produce a strong shock and generate a corona-like environment trapped at the top of closed magnetic loops, with X-ray emitting plasma heated to temperatures of up to 100 MK, and massive prominence-like clouds of cooling material corotating with the star (Babel & Montmerle 1997b,a).

This is indeed observed in early-type magnetic stars, and in particular in those massive enough (e.g., θ^1 Ori C) to power strong winds. The model provides a good match to the data whenever detailed observations are available (Donati et al. 2001, 2002; Gagné et al. 2005). MHD numerical simulations have been carried out for various cases, confirming and extending the predictions of the earlier models (ud-Doula & Owocki 2002; Owocki & ud-Doula 2004; Townsend et al. 2005; ud-Doula et al. 2006; Townsend et al. 2007; Ud-Doula et al. 2008). In particular, these computations are able to reproduce the anomalously high and hard X-ray emission of magnetic massive stars. They also account for the presence and dynamical evolution of corotating prominence-like clouds trapped within the magnetosphere of strongly magnetic, rapidly rotating Bp stars (initially identified in σ Ori E by Landstreet & Borra 1978); in this respect, the success of theory at reproducing simultaneously magnetic field measurements along with the observed H α and photometric variability for σ Ori E itself is outstanding (Townsend et al. 2007).

The slow rotation of most early-type magnetic stars (with respect to the non-magnetic ones of similar spectral type) - including those that are just approaching the main-sequence - is definite evidence that magnetic fields have a drastic impact on the formation of massive stars. One possibility is that progenitors of early-type magnetic stars suffer an extra loss of angular momentum through a wind or jet, or through interactions with their accretion discs (Stępień 2000); another promising option is that magnetic stars collect less angular momentum from their parent molecular cloud during the collapse as a result of their stronger initial magnetic flux (see Sec. 6). This latter mechanism could also potentially explain the unusually small fraction of close binaries among Ap/Bp stars.

Magnetic fields are also expected to impact significantly the evolution of massive stars. Due to their strong angular rotation gradient, massive stars are potentially capable of stretching/amplifying their magnetic fields, reducing/suppressing their differential rotation and modifying their evolution (Maeder & Meynet 2003, 2004, 2005). Massive stars hosting large-scale fields strong enough to resist the shear and freeze differential rotation are therefore expected to have an even more deviant evolution than those on which models focussed up to now. Evolution of early-type stars off the main-sequence may be studied observationally by following stars of a given mass at different evolutionary stages (e.g., Donati et al. 2006b; Bouret et al. 2008); the very recent detection of unusually strong large-scale magnetic fields in active giants (Aurière et al. 2008) may similarly hint at how magnetic Ap/Bp stars evolve on the long term. Ultimately, these same magnetic fields may reappear as fields of white dwarfs, neutron stars or magnetars.

6. Magnetic fields & star formation

6.1. Quick overview of the star formation process

In the previous sections, we briefly reviewed the main properties of magnetic stars of various masses and the typical phenomena they are subject to, from just before they arrive on the main sequence and until they evolve into the giant stage; the strong rotational braking that low-mass stars like the Sun are suffering on the early-main sequence is an obvious and famous example. These phenomena produce significant effects on evolutionary timescales, both in low-mass and massive stars; however, they remain in most cases a second order effect, the magnetic energy of a mature star being always a small fraction of its total energy. The situation is very different in the diffuse interstellar medium (ISM) and in the dense cores of giant molecular clouds from which stars form, where magnetic, kinetic and gravitational energies are roughly comparable to each other (e.g., Troland & Heiles 1986; Crutcher 1999).

As a result of turbulence (inherited from the diffuse ISM), giant molecular clouds form clusters of dense self-gravitating condensations called prestellar cores (measuring about 0.1 pc across). Dense prestellar cores are roughly critical, i.e., their mass is close to the magnetic critical mass $M_\Phi = \Phi/2\pi\sqrt{G}$ at which the magnetic and gravitational energies are equal (Φ and G being respectively the core magnetic flux and the gravitation constant). Supercritical dense cores start collapsing while subcritical cores may become supercritical through ambipolar diffusion (i.e., with neutral gas and dust contracting through the field lines and the ions, e.g., Mouschovias & Spitzer 1976). A rotating accretion disc (hundreds to thousands of AU in size) is formed within an accretion shock, usually triggering a powerful magnetocentrifugally driven low-velocity molecular outflow (e.g., Snell et al. 1980). A protostar progressively forms at the centre of the accretion disc and is often associated with a magnetically-collimated jet-like high-velocity outflow from the innermost disc regions. Almost all the magnetic flux and angular momentum initially present in the dense core at the beginning of the collapse is eventually dissipated, while most of the initial cloud mass returns to the diffuse ISM (e.g., Mestel 1999).

Low-mass star formation is understood best, especially in the later formation stages; at this time (a few Myr after the collapse started), the central protostar (called a classical T Tauri star or cTTS) hosts a large-scale magnetic field strong enough to disrupt the inner accretion disc (e.g., Camenzind 1990; Königl 1991), and to generate a central hole (about 0.2 AU across). Accretion from the inner disc rim to the surface of the protostar proceeds through discrete magnetic funnels or veils until the disc finally dissipates at an age of $\simeq 10$ Myr, with the star/disc magnetospheric interaction apparently forcing the star into slow rotation (Edwards et al. 1993; Rebull et al. 2006). Before it dissipates, the accretion disc may also form planets. While some phenomena are likely common to the formation of low- and high-mass stars (e.g., the presence of molecular outflows), some significant differences are expected; for instance, massive stars presumably form in dense clusters of highly-turbulent cores, growing quickly in mass and initiating nuclear burning while still accreting, with radiation pressure and photoionisation having powerful feedback effects on the formation process. Our present understanding of high-mass formation is only fragmentary and poorly constrained by observations (e.g., Zinnecker & Yorke 2007).

6.2. Magnetic properties of dense cores, accretion discs and protostars

Direct magnetic measurements constraining models of star formation are difficult and rare. For the moment, they mostly concern only three stages of the formation process: the dense cores of molecular clouds, the protostellar accretion discs and the cTTSs.

As for stars, the Zeeman effect is the only available technique for measuring directly magnetic fields in molecular clouds. From circular polarisation signatures in atomic or molecular lines at radio frequencies (typically H I, OH and CN lines, e.g., Troland & Heiles 1986; Crutcher 1999; Crutcher et al. 2008), one can derive an estimate of the magnetic flux within the cloud with an expression very similar to Eq. 7, yielding accuracies on the longitudinal field component of order a few μ G for lines like the 1420 MHz (21 cm) H I line or the 1667 MHz (18 cm) OH line. Linearly polarised thermal emission from elongated dust grains (with their short axis usually aligned along field lines) can also be used to probe the magnetic field morphology in molecular clouds and provide an indirect estimate of its strength (from estimates of its small-scale randomness of orientation, Chandrasekhar & Fermi 1953; Houde 2004).

Observations are however difficult and results remain sparse, in particular in the dark cloud cores that presumably probe best the very early stages of stellar formation. Actual Zeeman detections are obtained in only about 2 dozen clouds (Crutcher 1999; Troland & Crutcher 2008). Moreover, only the longitudinal component of the field is detected, implying that the derived mass-to-flux ratio (characterising whether or not the cloud is magnetically critical) is overestimated; a statistical correction is possible for a large sample of clouds with random magnetic orientations. The result is that dense cores are on average only slightly supercritical with mass-to-flux ratios of about 2, confirming that magnetic fields are energetically important in star formation. Magnetic maps derived from linearly polarised emission indicate that the magnetic field lines are rather regular (with only limited small-scale orientation dispersion), suggesting that the cloud cores are roughly critical, in agreement with Zeeman measurements; they also sometimes show a conspicuous hour-glass morphology (e.g., Girart et al. 2006), indicating that the bending of field lines may provide extra support to the cloud and delay its collapse. Average magnetic strengths in clouds are observed to scale up with number densities n as $n^{0.47}$ above densities of about 10^3 cm^{-3} (Troland & Heiles 1986; Crutcher 1999), providing evidence that the cloud contraction is not spherical and significantly influenced by the field. A very recent study, exploring how the mass-to-flux ratio varies from the core to the envelope of the cloud, suggests that the envelope is significantly more supercritical than the core (Crutcher et al. 2008).

Magnetic fields are also detected in protostellar accretion discs, i.e., at a later stage of the formation process. Masers from different species (usually OH, H₂O, methanol) commonly occur in association with high-mass protostellar objects and are thought to trace the surrounding circumstellar discs and associated outflows. Polarisation measurements indicate the presence of magnetic fields of order a few mG at typical distances of 1000 AU from the central object; magnetic intensities again scale with number densities as $n^{0.47}$ (extrapolating the relation derived from cloud cores to densities of up to 10^9 cm^{-3} , Vlemmings 2008) suggesting that the field is still partly coupled to the gas at these more evolved phases of the collapse. In a few properly oriented (i.e., edge-on) objects, the longitudinal magnetic field derived from Zeeman signatures switches sign on opposite sides of the object, possibly suggesting a disc magnetic field with a mostly toroidal orientation

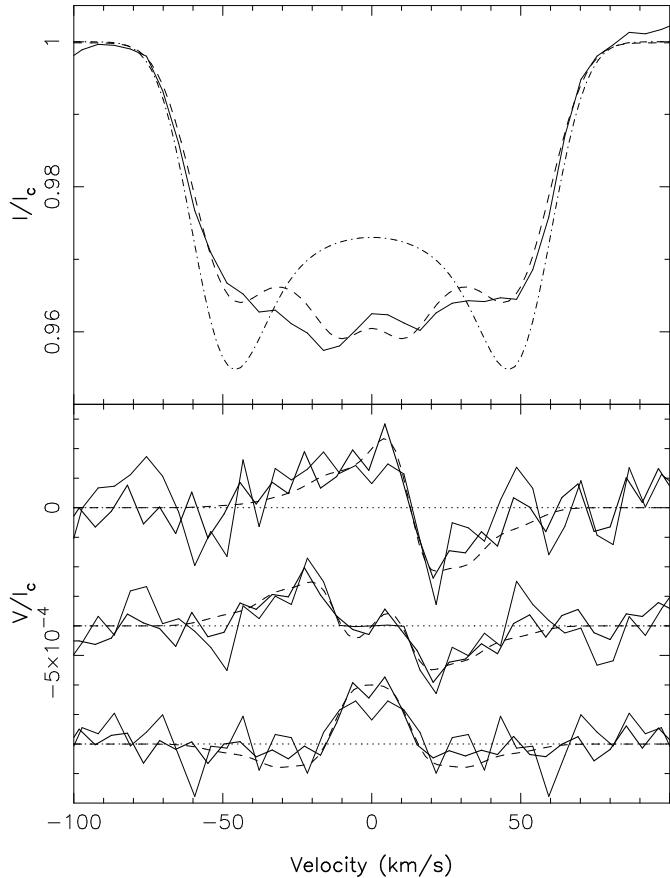


Fig. 6. Unpolarised and circularly polarised profiles of the protostellar accretion disc FU Ori. **Top panel:** observed Stokes I profile (solid line) and model profiles assuming either a Keplerian disc (dash-dot line) or a non-Keplerian disc (with 20% of the plasma rotating at strongly sub-Keplerian velocities, dashed line). **Bottom panel:** observed Zeeman signature (top curve) split into its anti-symmetric and symmetric components (middle and bottom curves, shifted by -4 and -8×10^{-4}) respectively characterising the vertical and azimuthal axisymmetric magnetic fields. The model (dashed line) requires the slowly rotating disc plasma to host a 1 kG vertical field plus a 0.5 kG azimuthal field (from Donati et al. 2005).

(e.g., Hutawarakorn & Cohen 2005). Paleomagnetic records from meteorites suggest typical magnetic strengths of 0.1–10 G at a distance of a few AU for low-mass protostars; with their randomly organised magnetisations, chondrules (whose parent bodies are believed to originate in the asteroid belt) are indeed thought to record magnetic fields that predate accretion (e.g., Shu et al. 2007).

A strong magnetic field was recently detected using optical spectropolarimetry in the innermost regions of an accretion disc around a low mass protostar (FU Ori, Donati et al. 2005) in a supposedly early cTTS stage (with an age of about 10^5 yr). The detected field has a strength of about 1 kG at a distance of only 0.05 AU (where the number density is estimated to be 10^{17} cm $^{-3}$) and is found to concentrate in the $\approx 20\%$ of the disc plasma that rotates at strongly sub-Keplerian velocities. From the shape of the Zeeman signature, the orientation of the magnetic field of FU Ori (assumed axisymmetric given the low level of rotational modulation) is found to be mainly perpendicular to the disc plane and to include a smaller azimuthal component (see Fig. 6).

Among all protostellar objects, cTTTs are those on which we have most information thanks to their visibility at optical wavelengths. In particular, magnetic fields of cTTTs are well documented, in comparison with those of cloud cores and accretion discs. Magnetic fields with typical strengths of 1–3 kG are measured at the surfaces of most cTTTs from Zeeman broadening of (mostly nIR) unpolarised line profiles (e.g., Johns-Krull et al. 1999b; Johns-Krull 2007). These magnetic intensities are often much larger than thermal equipartition, as in very active cool dwarfs. Magnetic strengths are found to correlate poorly with predictions from current magnetospheric accretion models in which fields are assumed to disrupt the inner regions of the accretion disc and to ensure approximate corotation between the inner disc rim and the stellar surface (Johns-Krull 2007); this discrepancy is however not surprising, Zeeman broadening methods being sensitive to small-scale fields whereas predictions of magnetospheric accretion models concern the large-scale field.

Large-scale magnetic fields are also detected with spectropolarimetry. Circularly polarised Zeeman signatures from emission lines (e.g., the He I D_3 line at 587.6 nm, or the Ca II infrared triplet at 850 nm) probe magnetic fields at the footpoints of the accretion funnels linking the star to the inner disc rim (e.g., Johns-Krull et al. 1999a; Valenti & Johns-Krull 2004; Symington et al. 2005), whereas Stokes V signatures from photospheric lines trace the large-scale magnetic fields permeating the non-accreting fraction of the stellar surface (Donati et al. 2007). Average longitudinal fields from accreting regions typically reach several kG and display a smooth and simple rotational modulation, suggesting a simple large-scale magnetic geometry; however, longitudinal fields from the quiet photosphere rarely exceed a few hundred G as deduced from complex Zeeman signatures, and apparently trace a more tangled parent topology. Modelling Zeeman signatures from photospheric lines and accretion proxies simultaneously (whenever available) reveals that the large-scale field is indeed significantly more complex than a dipole (e.g., see Fig. 7) and includes in particular a strong octupole component (Donati et al. 2007, 2008a). In the 2 cTTTs for which a magnetic map has been published (namely the $1.4 M_\odot$ and $0.7 M_\odot$ cTTTs V2129 Oph and BP Tau), the dipole component of the large-scale field is much weaker when the star is not fully convective, as in main-sequence M dwarfs (Morin et al. 2008b; Donati et al. 2008c).

Extrapolating the large-scale magnetic maps of cTTTs to the whole magnetosphere allows to estimate the typical distance at which a protostar magnetically connects to its accretion disc, and to provide independent constraints on where the inner accretion disc rim is located. Producing high-latitude accretions spots in a magnetic topology with a dominant octupolar field at the stellar surface requires the disc plasma to be injected into the magnetosphere from a distant region where the dipole field dominates, i.e., at distances of at least $5 R_\star$ (or 0.06 AU) in the particular case of the partly convective cTTT V2129 Oph (Donati et al. 2007; Jardine et al. 2008; Gregory et al. 2008; Mohanty & Shu 2008). This result agrees with independent estimates of magnetospheric gap sizes from nIR interferometry (e.g., Pinte et al. 2008).

Information on how magnetic topologies depend on the fundamental parameters of the accreting protostar (in particular mass, rotation rate and age) as well as on the accretion and outflow properties is still lacking and requires a detailed study on a large enough sample of cTTTs; this is the aim of the Large Program called Magnetic Protostars and Planets (MaPP) recently initiated using ESPaDOnS@CFHT and NARVAL@TBL. Little information yet exists on magnetospheric accretion processes of more massive protostars (for instance the Herbig Ae/Be stars); while indirect proxies suggest that similar processes may also be at work and that magnetic fields could also be

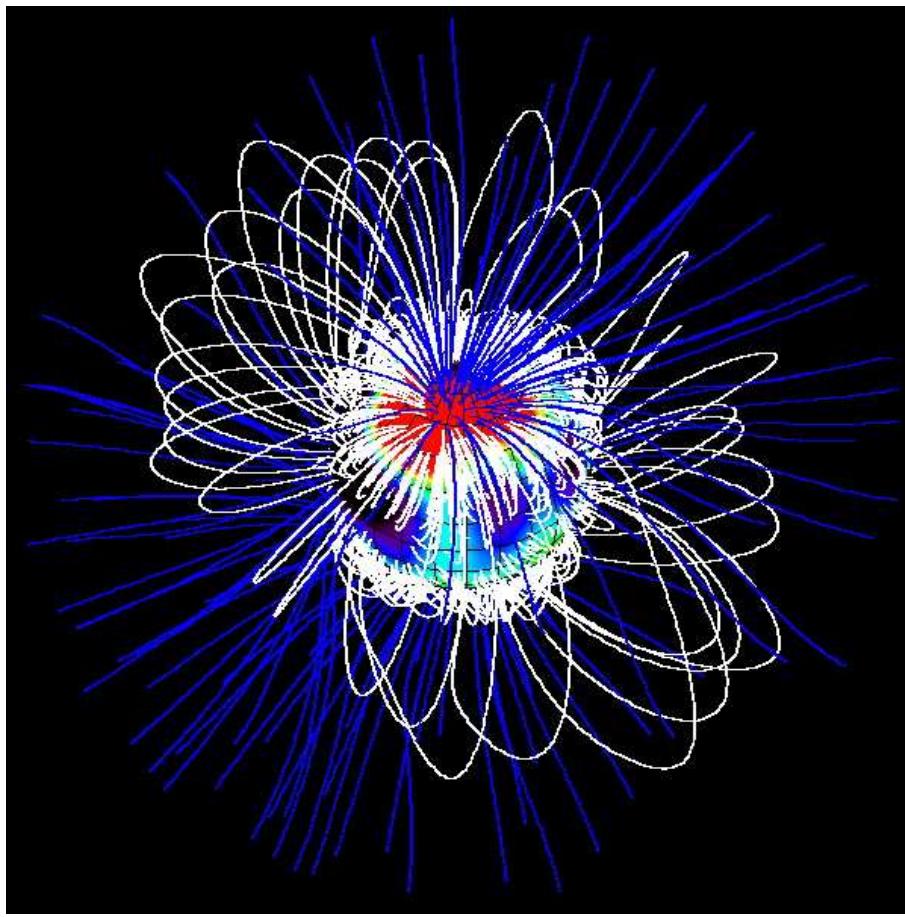


Fig. 7. Magnetosphere of the cTTS V2129 Oph, extrapolated from the surface magnetic map derived from spectropolarimetry of both photospheric lines and accretion proxies. Open and closed field lines are shown in blue and white respectively, while colours at the surface of the star depict the radial field component, with red and blue corresponding to positive and negative polarities (from Donati et al. 2007; Jardine et al. 2008).

involved in at least a small fraction of massive stars (e.g., the UX Ori-type objects, Muzerolle et al. 2004), conclusive and direct evidence such as that available for cTTSSs is still lacking.

6.3. Magnetised collapse of molecular clouds

Until recently, star formation was more or less understood in the framework of the standard magnetic model, where magnetic fields control the formation and evolution of molecular clouds - including the formation of cores and their gravitational collapse to form protostars (e.g., Mouschovias 1987; Shu et al. 1987; Basu 1997; Li & Shu 1997). In this model, neutral gas and dust contract gravitationally through the field and the ions (by ambipolar diffusion), triggering the collapse (when the core becomes supercritical) and leaving most of the magnetic flux behind in the envelope. However, in recent years a new picture has been proposed, suggesting that turbulence (rather than magnetic fields) controls the formation of clouds and cores (e.g., Padoan & Nordlund 2002) - with clouds forming at the intersection of turbulent supersonic flows in the ISM and locally collapsing into cores and protostars wherever dense enough to be self-gravitating; in this model, magnetic fields (while potentially present) are too weak to be energetically important.

The observed scaling law for magnetic strengths with respect to densities ($B \propto n^{0.47}$, e.g., Crutcher 1999) better agrees with analytical ambipolar diffusion models (e.g., Li & Shu 1997; Basu 1997); however, the mass distribution of prestellar cores that the standard model predicts does not match observations (e.g., André et al. 2008). While the magnetic paradigm implies longer cloud core lifetimes than the turbulent paradigm, they are both roughly compatible with observations (indicating intermediate core lifetimes of a few free-fall times, e.g., André et al. 2008). The very tangled field topologies that the turbulence model predicts in cloud cores mostly contradicts observations, field lines being rather regular with limited small-scale orientation dispersion; the very recent result suggesting that dark cores are less supercritical than their envelopes (Crutcher et al. 2008) would however challenge the standard magnetic picture if confirmed. Given these constraints, theoreticians are now exploring new models in which both magnetic fields and turbulence play a significant role in the formation of cloud cores (e.g., André et al. 2008).

The detection of molecular outflows and collimated jets from protostellar objects (e.g., Snell et al. 1980) indirectly demonstrates that magnetic fields actively participate in the subsequent phase of the cloud collapse. Magnetocentrifugal models were proposed soon after as a tentative explanation; in these models, the collapsing cloud pinches and twists the primeval field into an helical magnetic structure very efficient at firing outflows and jets (thanks to the magnetocentrifugal force and/or the toroidal magnetic pressure, e.g., Pudritz & Norman 1983; Ferreira 1997). Detailed simulations have been carried out in recent years primarily for low-mass stars (e.g., Machida et al. 2004; Banerjee & Pudritz 2006; Hennebelle & Fromang 2008; Mellon & Li 2008), and in a few cases for massive stars as well (e.g., Banerjee & Pudritz 2007), mostly using numerical techniques such as adaptive mesh refinement or nested grids to model properly the wide range of spatial scales and densities involved in the computations. The formation steps include the isothermal collapse of the cloud core into a flattened structure (the accretion disc) up to the formation of an adiabatic core (the first core), the adiabatic collapse within the first core, a second isothermal collapse occurring within the first core (triggered by the dissociation of molecular hydrogen) and the formation of a second core (the protostar itself). Collapse simulations are able to reproduce both the large-scale low-velocity outflows (from the outer cloud regions) and the highly-collimated high-velocity jet (from the innermost cloud regions) that observations conspicuously show (Banerjee & Pudritz 2006; Pudritz et al. 2007; Hennebelle & Fromang 2008; Machida et al. 2008a).

Observations unambiguously show that most of the angular momentum (and magnetic flux) initially present in the cloud core is dissipated in the collapse, presumably by magnetic effects (e.g., Mestel 1999; Machida et al. 2007). Simulations indicate that, for slightly supercritical clouds, the magnetic collapse occurs primarily along the field lines, making the collapsing envelope denser and flatter than in the non-magnetic case; moreover, no centrifugally supported disc is apparently able to form (less angular momentum being delivered to the inner parts and significant angular momentum being expelled through magnetic braking, Hennebelle & Fromang 2008; Mellon & Li 2008). The detection of magnetised plasma rotating at strongly sub-Keplerian velocities in the innermost regions of FU Ori (Donati et al. 2005) may be evidence that this is indeed what happens. Simulations further suggest that clouds with higher magnetic fields may form first cores (and presumably protostars as well) containing less angular momentum (e.g., Hennebelle & Fromang 2008) and are less prone to fragmentation (e.g., Machida et al. 2008b; Hennebelle & Teyssier 2008).

The magnetic field detected in FU Ori corresponds to magnetic fluxes of order a few hundred G (1 kG threading about 20% of the disc, Donati et al. 2005) at typical number densities of 10^{17} cm $^{-3}$, in surprisingly good agreement with the $B \propto n^{0.47}$ power law derived from magnetic clouds. If confirmed, this result suggests that magnetic fluxes can potentially survive at densities much higher than initially predicted; in particular, this would indicate that yet unidentified ionisation mechanisms may operate within protostellar accretion discs (e.g., Shu et al. 2007). The field orientation in FU Ori (compatible with predictions of MHD collapse simulations, Ferreira 1997; Banerjee & Pudritz 2006, but not with disc-dynamo models, Brandenburg et al. 1995; von Rekowski et al. 2003) further suggests that fields of protostellar accretion discs are of primordial origin.

The role of magnetic fields in the formation of massive stars is still poorly documented, with little direct observations and few numerical simulations of the magnetic collapse yet available (e.g., Vlemmings 2008; Banerjee & Pudritz 2007). Observations of intermediate- and high-mass magnetic stars on and immediately before the main sequence indicate that these stars rotate much more slowly and form close binaries much more rarely than their non-magnetic equivalents, a likely result of a different formation process (see Sec. 5). This is qualitatively similar to what magnetic collapse simulations predict for low-mass stars, with clouds having larger initial magnetic fluxes forming in average first/second cores rotating slower and being more often single (e.g., Machida et al. 2008b; Hennebelle & Fromang 2008; Hennebelle & Teyssier 2008); it is however unclear yet how much of this can be extrapolated to more massive stars.

6.4. Magnetospheric accretion, angular momentum regulation and protoplanet formation

Once formed at the end of the second collapse, low-mass protostars host strong large-scale magnetic fields whose origin, though not fully clear yet, is likely attributable to dynamo processes. Any fossil field that survived the collapse is indeed unlikely to survive (for more than typically 1,000 yr, e.g., Chabrier & Küker 2006) the fully convective phase that low-mass stars undergo. The topological similarity of cTTSSs large-scale fields with those of main-sequence M dwarfs further strengthens this conclusion. Moreover, the lack of large-scale magnetic fields in most intermediate-mass protostars (e.g., in Herbig Ae/Be stars, Wade et al. 2007, see also Sec. 5) is additional evidence that fossil fields from the ISM (while potentially still present in the inner regions of protostellar accretion discs, Donati et al. 2005) eventually perish within most protostars.

These large-scale magnetic fields strongly impact the life of cTTSSs by forcing them to interact with their accretion discs; they evacuate the central disc regions, connect the protostars to the inner disc rim, confine the accreting material into discrete funnels or veils and slow down the rotation rate of the protostar (e.g., Camenzind 1990; Königl 1991; Cameron & Campbell 1993; Shu et al. 1994; Bouvier et al. 2007). Several theoretical models and numerical simulations have been proposed and carried out to study this complex magnetospheric interaction and attempt to reproduce observations, in particular the typical sizes of magnetospheric gaps and rotation periods of cTTSSs. Initially restricted to dipolar magnetospheres (Romanova et al. 2002; von Rekowski & Brandenburg 2004; Bessolaz et al. 2008), simulations and models now incorporate more complex fields resembling those derived from observations (e.g., Gregory et al. 2006; Long et al. 2008; Mohanty & Shu 2008; Gregory et al. 2008). Such studies are able to reproduce the presence of accretion funnels linking

the disc to the star and of accretion spots at funnel footpoints, whose locations and geometries are found to depend strongly on the inclination of the magnetosphere with respect to the rotation axis of both the disc and the protostar (e.g., Romanova et al. 2003, 2004) as well as on the large-scale topology of the field (e.g., Gregory et al. 2006; Long et al. 2008). The size of the magnetospheric gap is however still difficult to reconcile with observed large-scale field strengths (Bouvier et al. 2007; Bessolaz et al. 2008; Gregory et al. 2008) and simulations fail to confirm that the magnetic torque from the accretion disc is strong enough to spin the star down as observations suggest (e.g., Bessolaz et al. 2008); a braking contribution from an accretion-powered magnetised stellar wind may help solving the problem (Matt & Pudritz 2005).

Magnetic fields in accretion discs are also expected to impact the formation and migration of protoplanets. In particular, the disc fields and associated MHD turbulence can potentially inhibit disc fragmentation through gravitational instabilities and the subsequent formation of giant planets (Fromang 2005); they can modify as well the migration rate and angular momentum of protoplanets (Fromang et al. 2005; Machida et al. 2006). By disrupting the inner regions of accretion discs, magnetic fields of cTTSs may stop the inward migration of giant planets formed earlier in the outer disc (which would no longer experience the gravitational torque from the disc once they enter the magnetospheric gap, Romanova & Lovelace 2006); orbital distances of most close-in giant planets discovered in the last decade around main sequence stars (smaller than 0.1 AU) are indeed compatible with typical sizes of magnetospheric gaps in cTTSs.

7. Conclusion

Starting from how magnetic fields of non-degenerate stars can be detected and measured and how their large-scale topologies can be reconstructed, we have reviewed most observational results available to date and described their implications for our understanding of where magnetic fields originate and how they impact the formation and evolution of stars at different ages and for different masses.

While the first detection of a magnetic field in a star (the Sun) was obtained over a century ago, progress in the field has been rather slow until the last few decades when the advent of new techniques and instruments made it possible to unveil the magnetic fields (and particularly the magnetic topologies) in a wide sample of stars throughout the HR diagram. Observations have revealed that magnetic fields strongly influence the formation of stars and are ubiquitous to low-mass stars like the Sun; while only present in a small fraction of intermediate- and high-mass stars, magnetic fields are nevertheless found to have a profound signature on their atmospheres and winds and are able to modify their long-term evolution significantly. This progress has triggered a wealth of theoretical studies involving magnetic fields, and predictions from many detailed MHD simulations can now be checked directly with observations and be used to devise new modelling ideas and observational tests.

New instruments, either in construction or in design phase, should further boost this field of research in the coming decade. The Atacama Large Millimeter Array (ALMA, operational in 2011–2013) will soon provide direct magnetic measurements in various types of protostars at early formation stages and down to spatial scales of about 10 AU (thanks to its high angular resolution). The nIR spectropolarimeter SPIRou (a nIR, high radial-velocity-accuracy version of ESPaDOnS and NARVAL proposed as a new CFHT instrument for implementation in 2015) should give the opportunity of exploring for the first time the magnetic properties of obscured protostellar objects and very cool dwarfs; for protostellar accretion discs in particular, SPIRou should be able to access the innermost regions, thus nicely complementing magnetic measurements in the outer regions obtained with ALMA.

These new observations, along with updated models and simulations, should ultimately bring a much clearer view of where stellar magnetic fields come from, and how they shape the birth and life of stars and their planets.

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