Surface magnetic fields of late-type stars

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Abstract. In this paper, I first review the various existing techniques for measuring magnetic fields at the surface of cool stars. I will then describe the main results obtained to date with these different techniques, as well as the implications for our understanding of how dynamo processes operate in convective envelopes of cool stars. I will finally present some of the most promising direction of research to improve our knowledge of how magnetic fields affect the global evolution of late-type stars.

1. Introduction

Magnetic field is very often a crucial parameter in astrophysical problems. It indeed plays a key role basically everywhere in the universe, at all time and spatial scales, and in particular in stars, during their formation, their evolution and the last stages of their lives.

In the particular case of stars, the first concern is to understand the origin of large-scale magnetic fields, whether they are remnants (i.e. fossil fields) from an older evolutionary stage (like those of some chemically peculiar stars), or whether they are self-generated (i.e. dynamo) fields resulting from turbulent motions in a partly ionised plasma within the stellar envelope (such as those of the Sun and other active late-type stars). Studying large-scale magnetic structures can also inform us on the impact of these fields on various transport processes operating within or around stars (such as convection, turbulence, diffusion, large-scale circulation, internal rotation, accretion or mass loss) and therefore on stellar evolution as well. For cool stars and the Sun in particular, a detailed and self-consistent picture of how large-scale fields are produced, evolve on both short and long timescales and affect the Sun and stars as well as their direct circumsolar/stellar environment is still crucially lacking at the moment, even though of obvious interest for us.

The various existing techniques for detecting and modelling surface magnetic fields on cool non-degenerate stars are all based on the fact that magnetic fields, through the Zeeman effect (see e.g. Mathys 1989 for a detailed description of the atomic physics behind the Zeeman effect), affect the shape and polarisation of spectral line profiles. I will first recall the basic principles of these techniques (using either polarimetry, spectroscopy and spectropolarimetry), along with the main results obtained with each of them. Note that I will not mention the possibility of using the Hanlé effect (e.g. Faurobert-Scholl 1993) nor that based on observing cyclotron/synchrotron emission (e.g. Wickramasinghe & Ferrario 1988), as these methods have never been used to estimate magnetic fields at the surfaces of non-degenerate cool stars other than the Sun (as far as I know). I will outline in particular how these results help us understand how dynamo operates in convective envelopes of cool stars. I will then discuss some of the most promising direction of research to improve our knowledge of how magnetic fields affect the global evolution of late-type stars.

2. Conventional polarimetric methods

The very first methods that enabled to diagnose the presence of surface magnetic fields on the Sun (Hale 1908) and stars (Babcock 1947) aim at detecting *wavelength shifts* between spectral lines simultaneously recorded in both orthogonal states of circular polarisation (Stokes V) with a high resolution spectrograph including a polarimetric module. When the field is not too strong, it may be shown (e.g. Mathys 1989) that this shift is approximately proportional to the line-of-sight component of the magnetic field vector averaged over the visible stellar disc (called longitudinal field). This shift being very small (about 1 $\mathrm{km\,s^{-1}}$ for a 1 kG longitudinal field on a spectral line at 600 nm with average magnetic sensitivity), this technique is usually only applicable to slow/moderate rotators. This method has progressively been replaced by a much simpler one, involving a narrow band photopolarimeter measuring *circular polarisation* in either wings of a broad spectral line (usually a Balmer line, Angel & Landstreet 1970). The observed circular polarisation is also translated into an estimate of the longitudinal field. Thanks to the large intrinsic width of the spectral line used, this technique (as opposed to the previous one) is just as efficient for slow and rapid rotators.

Another possibility consists in measuring *broadband linear polarisation* in stellar spectra (Leroy 1962; Tinbergen & Zwaan 1980). What one aims at detecting in this case is the net residual linear polarisation (Stokes Q and U) over the whole profile of one (or several) spectral lines, resulting from the *differential saturation* of π and σ Zeeman components. The broadband filter is usually centred on a spectral domain which maximises the density of spectral lines for the stars of interest. The observed linear polarisation gives access to the disc-integrated component of the field vector perpendicular to the line of sight (called transverse field), as well as its *azimuth* with respect to the instrument angular reference (usually north-south), with an accuracy that does not depend on stellar rotation rate.

All attempts at detecting magnetic fields in solar-type stars other than the Sun with these methods have essentially failed (e.g. Brown & Landstreet 1981; Borra et al. 1984; Leroy & Leborgne 1989; Bedford et al. 1995) despite a few controversial claims (e.g. Huovelin et al. 1985). It is well known now that this failure is mostly attributable to the extremely intricate structure of magnetic fields on late-type stars, which feature multiple bipolar spot pairs cancelling their mutual effect in circular polarisation and yielding undetectable longitudinal fields (see Sect. 4).

3. Stokes I spectroscopy

Another option consists in extracting magnetic information from the *shape* of spectral lines in *unpolarised light* (Stokes I), recorded at high spectral resolution and high signal to noise ratio (Robinson 1980). With this technique, a measurement of the *differential broadening* between lines that are highly and weakly sensitive to magnetic fields yields an estimate of the disc area covered with magnetic fields (called filling factor), as well as an average field strength within these regions. The obvious advantage of this method is that magnetic field regions with opposite polarities at the surface of the star no longer cancel their mutual spectroscopic signatures, as they used to do with conventional polarimetric techniques. This method requires however the observed star to spin slowly enough (with $v \sin i < 8$ km/s) to avoid rotational drowning of the potential magnetic information contained in line profiles (Saar 1988). When the magnetic field is strong enough, spectral lines can even be split into individual Zeeman components, allowing the mean magnetic field *modulus* (called surface field) to be measured very accurately (Johns-Krull & Valenti 1996). In most cases though, magnetic field signatures in unpolarised light are fairly small and can easily be confused with small blends in line wings. For this reason, magnetic parameters inferred with this method are subject to large systematic errors (as much as a factor of three) as recently evidenced through the results of multiline techniques (e.g. Valenti et al. 1995; Rüedi et al. 1997), which are presumably less prone to systematic errors and thus more reliable.

Spectral lines are also subject to an increase in *equivalent width* in the presence of a magnetic field, whose magnitude depends on the actual Zeeman pattern of the selected line and orientation of field lines (Babcock 1949). However, the dependence of this effect on parameters such as field orientation for instance, is sufficiently complex that this method can only be used to indicate the presence of a field rather than to provide an accurate estimate of its strength.

Both methods have been very successful in detecting, or at least suggesting, the presence of magnetic fields in new type of stars, and in particular late-type stars (Saar 1988) and T Tauri stars (Basri et al. 1992). Altogether, magnetic fields have been detected with these methods in about 50 objects up to now. From a critical selection of all newest measurements obtained with these methods, Saar (1996) confirms earlier claims that the area covered by magnetic regions scales up with stellar rotation rate, while the magnetic strength within these regions is roughly equal to the equipartition value (up to a unit filling factor at least). This result is taken as strong evidence that magnetic fields of active stars are indeed produce through dynamo processes.

The major drawback of these techniques is that they only provide extremely limited spatial information on the details of the actual magnetic topology. In an attempt to solve this problem, Saar et al. (1994) proposed to couple these techniques with a stellar surface imaging package and get magnetic maps of faster rotators. This new method is however still subject to caution as no simulation has been published to date to demonstrate unambiguously that the tiny magnetic broadening/amplification effects can indeed be reliably recovered in Doppler broadened line profiles. Moreover, none of these methods enables one to derive information on the *orientation* of field lines within magnetic regions.

4. Stokes Q, U, and V spectropolarimetry of rapid rotators

Recently, Semel (1989) proposed to measure, in the particular case of rapidly rotating late-type stars, the full profiles of magnetic Zeeman signatures in circular and (whenever possible) linear polarisation, rather than their lowest moment as in conventional polarimetric techniques (see Sect. 2). For such stars, regions of opposite magnetic polarities located at different longitudes on the stellar surface (and therefore at different radial velocities with respect to the observer) contribute to the global Zeeman signature at different wavelengths and therefore no longer mutually cancel their effects in circular (or linear) polarisation.

Optimally, one would like to measure Zeeman signatures in individual line profiles, as one can do for solar magnetic regions for instance. However, in the particular case of late-type stars where Stokes V signatures rarely exceed 0.3% in relative peak-to-peak amplitude, one has to extract the desired polarisation information from thousands of spectral lines simultaneously, with the help of cross-correlation tools such as 'Least-Squares Deconvolution' (Donati et al. 1997). Magnetic fields have been detected in about 20 objects of various evolutionary stages up to now (e.g. Donati et al. 1992a, Donati et al. 1997) and mapped in six of them (e.g. Donati & Cameron 1997; Donati 1998). As an illustration, Fig. 1 shows the rotationally modulated Stokes V signature (extracted from about 1,500 spectral lines with Least-Squares Deconvolution) for the rapidly rotating young K0 dwarf AB Doradus (Donati et al. 1998a).

Simulations have established that, with this method (often referred to as Zeeman-Doppler imaging or ZDI), one can convert, using a stellar surface imaging package, sets of rotationally modulated Zeeman signatures into surface maps of the vector magnetic field. Note that both the spatial distribution of magnetic regions and, to a certain extent, the *orientation* of field lines within them can in principle be recovered with this method (Brown et al. 1991; Donati & Brown 1997).

Results from ZDI (Donati et al. 1992b; Donati & Cameron 1997; Donati et al. 1998a; Donati 1998) reveals that magnetic images of rapidly rotating cool stars are indeed extremely complex (see for instance Fig. 2 for the K1 subgiant HR 1099), explaining *a posteriori* the failure of conventional polarimetric methods on late-type stars. A particularly intriguing characteristic of these images is that they often include magnetic regions in which the field is mainly *azimuthal*, i.e. directed along lines of constant latitude. The polarity of these azimuthal field features is essentially longitude independent at a given latitude (e.g. clockwise and counterclockwise at high and low latitudes respectively on HR 1099, see Fig. 2) while the latitude dependence is constant on a year-to-year basis (Donati 1998). These features are interpreted as the detection, at photospheric level, of the *toroidal component* of the mostly axisymmetric large-scale dynamo field. Observations also tell that the latitudinal structure of this toroidal large-scale field component gets more complex for increasing rotation rates and convective depths, featuring for instance up to three rings of opposite polarities in the upper hemisphere of the ultra fast rotator AB Dor (Donati et al. 1998a).

In principle, such images could be used to study the temporal evolution of the magnetic field structure as the star evolves on its activity cycle, in a way very similar to what is done for the Sun. Data already suggest that toroidal components of large scale field structures do indeed evolve on a timescale of

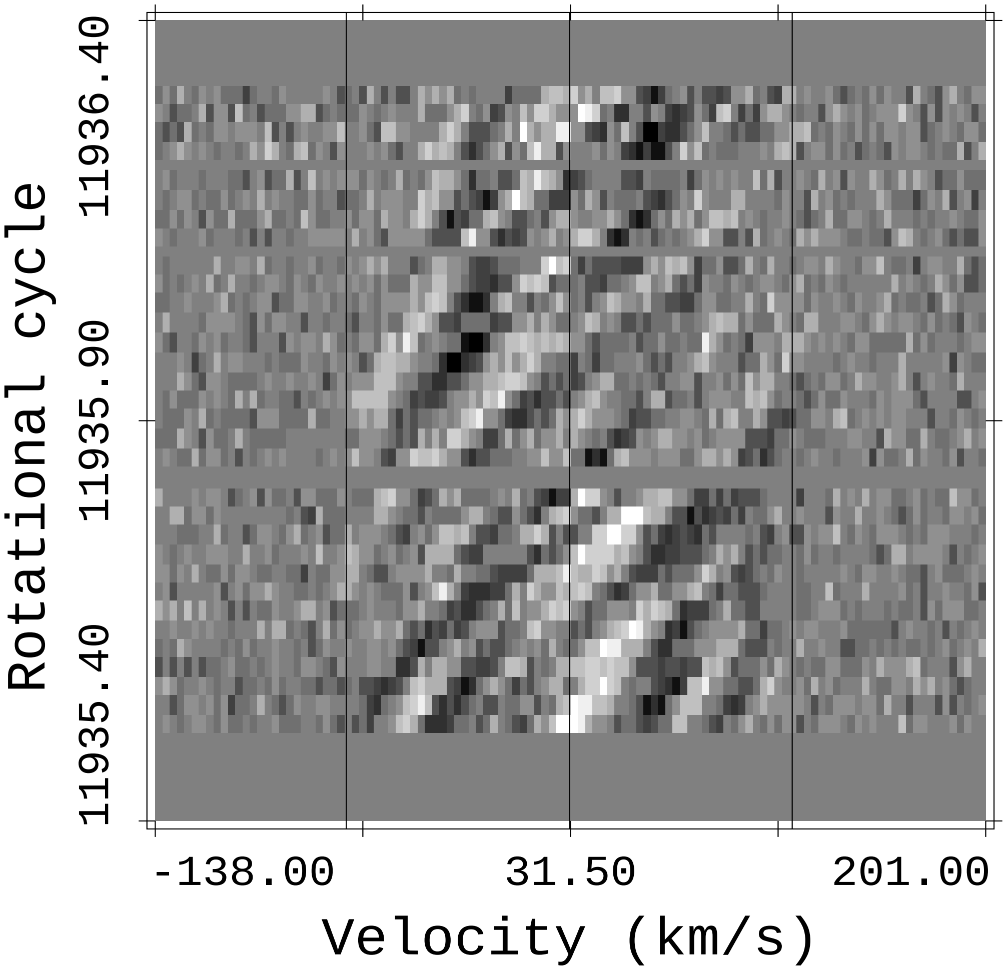

Figure 1. Rotationally modulated Least-Squares Deconvolved Stokes V signature of AB Dor in 1996 December. Black and white code relative circular polarisation levels of –0.06 and 0.06% respectively. The central and side vertical lines depict the radial and rotational velocities of AB Dor

about a decade; the recent detection of a new azimuthal field polarity appearing at high latitudes on the young active star LQ Hydrae (confirmed with new observations in 1998 Jan., see Fig. 3) may for instance be a forerunner of a global polarity switch in the magnetic field of this object (Donati 1998).

The detection at photospheric level of the toroidal component of the large-scale dynamo field is interpreted as strong evidence that very active late-type stars trigger dynamo processes which are *distributed* throughout the whole convective envelope, rather than being confined to an interface layer with the radiative interior as in the Sun. An independent confirmation of this conclusion is that rising flux tubes from a deep-seated magnetic structure located at the base of the convective zone are expected to emerge at latitudes higher than 50° or so in rapidly rotating late-type stars (Schüssler et al. 1996), in strong contradiction with the brightness, radial and azimuthal field maps we reconstruct

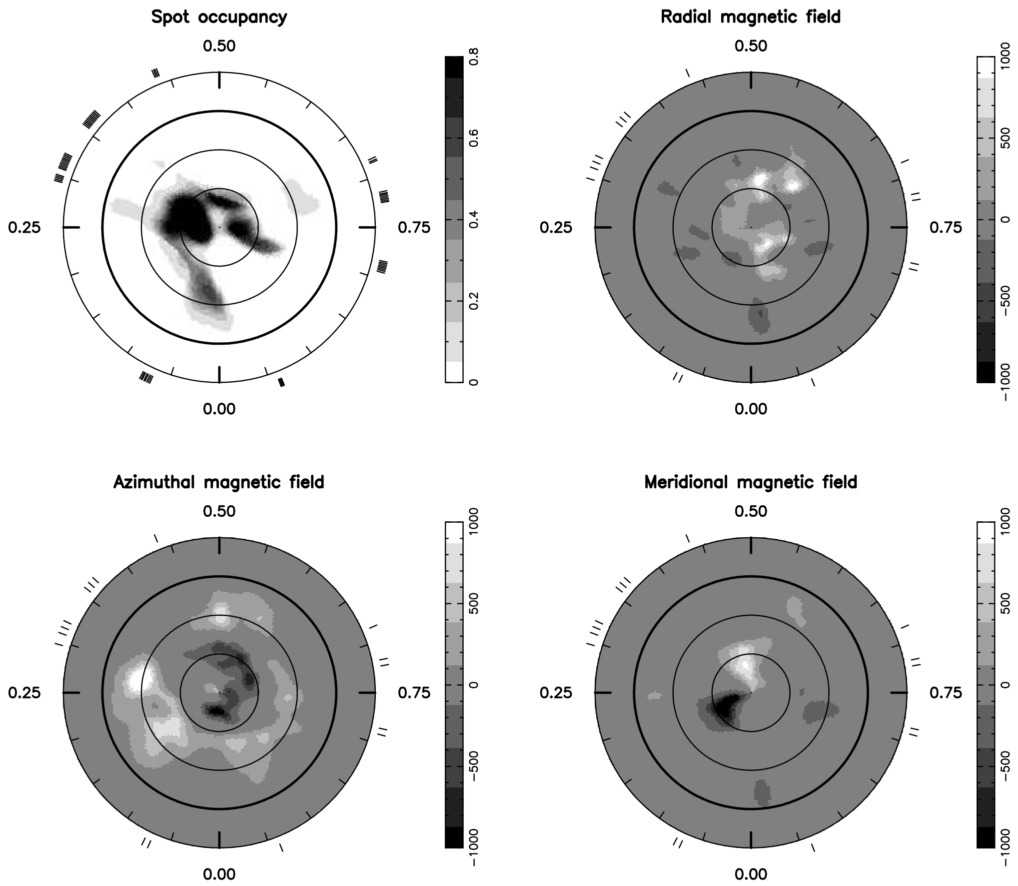

Figure 2. Flattened polar view of the brightness (upper left), radial field (upper right), azimuthal field (lower left) and meridional field (lower right) distributions at the surface of the K1 subgiant of HR 1099 at epoch 1995.94. Parallels are shown (as concentric circles) every 30° down to a latitude of –30° (the bold one featuring the equator). Magnetic fields are labelled in G. The radial ticks around each plot depict the rotational phases of observations.

for these objects that clearly show features at latitudes lower than 30° (Donati & Cameron 1997; Donati et al. 1998a; Donati 1998). Furthermore, the orbital period fluctuations detected for RS CVn systems (and interpreted as evidence for changes in the quadrupole moment of the primary star, Applegate 1992) also argue in favour of this picture; generating the observed quadrupole moment changes indeed requires the associated change in the internal rotation of the primary star (and therefore also the underlying dynamo processes producing them) to be distributed in a large fraction of the convective zone (Lanza et al. 1998).

In addition to this, magnetic regions detected on late-type stars do not apparently correlate with photospheric brightness and are not confined within a restricted latitude range, making them more similar to the smallest scale magnetic structures on the Sun (i.e. intranetwork fields) than to the large scale active/ephemeral regions (Donati 1998). It may in turn indicate that these small-scale solar structures are solar analogues of the magnetic regions detected

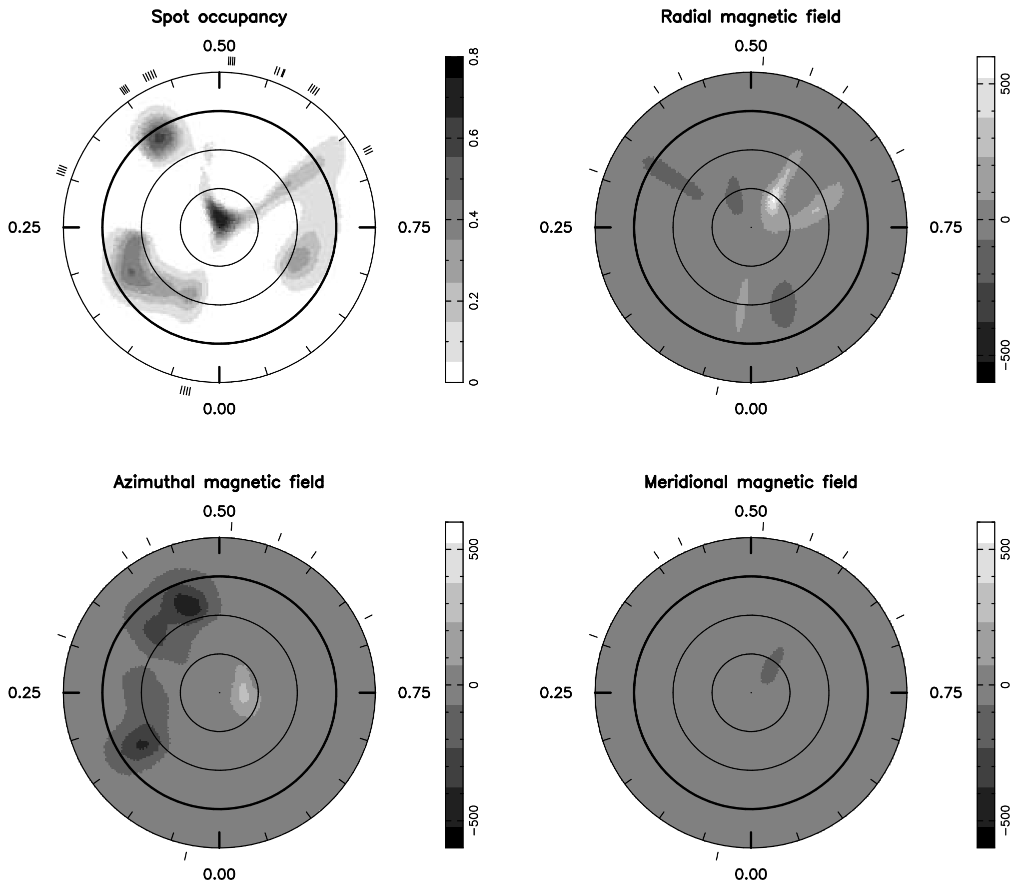

Figure 3. Same as Fig. 2 for the young K0 dwarf LQ Hya at epoch 1998.03. Note the new azimuthal field polarity (showing up as a high latitude region of positive, i.e. counterclockwise, field) that recently appeared at the surface of this star.

on rapidly rotating late-type stars, and therefore contribute to the solar magnetic cycle and to the large-scale field of the Sun (as suggested by Stenflo 1994) just as their scaled-up versions obviously do on rapidly rotating late-type stars. If confirmed, it may imply at the same time that a significant fraction of the large scale magnetic field of the Sun is also produced through a distributed dynamo.

5. Prospectives

Our knowledge of both the intensity and structure of the magnetic field of late-type stars other than the Sun has considerably improved in the last decade. The most recent results demonstrate in particular that we are now able to study the temporal evolution of the large scale magnetic structures of such stars as they evolve on their activity cycle, in a way very similar to that used in the particular case of the Sun. One of the obvious observational goals is thus to follow this temporal evolution for a small sample of carefully selected active stars (sampling in particular all evolutionary states from pre-main sequence to red-giant branch stage) and derive from such time sequences of magnetic images some detailed information on where and how dynamo processes operate within the convective layers of late-type stars. Simultaneous monitoring of orbital period fluctuations (Donati 1998) or surface differential rotation (see e.g. Fig. 4, Donati & Cameron 1997; Donati et al. 1998a) can also bring additional information on how angular rotation is distributed within convective zones and how this distribution is affected as the star evolves on its activity cycle. Altogether, we should learn how dynamo fields react onto the internal velocity fields that generated them, and more generally, on how magnetic fields affect various transport processes in the interior of late-type stars (e.g. convection, turbulence, circulation) and thus the whole dynamics of convective zones.

Another goal is to understand the role and interaction of the magnetic field at the surface of a late-type star onto the immediate circumstellar environment. A first possibility consists in studying how dynamo field structures participate in producing, confining and ejecting coronal prominences around rapidly rotating stars (Cameron & Robinson 1989a, b; Donati et al. 1998a) where the centrifugal force plays a very important role (Jardine & Cameron 1991), and comparing the results to those obtained on the Sun. Another very promising direction of research would be to assess observationally the role of magnetic fields in the interaction of pre-main sequence stars (classical T Tauri stars, FU Ori objects) with their direct environment (circumstellar discs, jets, e.g. Ferreira & Pelletier 1993; Cameron & Campbell 1993) and thus on the global structure and rotation evolution of these stars. Detect magnetic fields of *accretion discs* (in which all ingredients for a vigorous dynamo are present, e.g. Horne & Saar 1991) is also an important issue, which should help constraining the exotic shear-flow dynamo mechanisms invoked for these objects (e.g. Brandenburg et al. 1995).

To achieve these goals, we need to be able to observe new classes of objects, and in particular classical T Tauri stars or late-type stars in young open clusters, targets that are still hardly observable with the existing techniques and instruments. There is definitely a need for more efficient instruments, that can collect spectra in all polarisation states (circular and linear), with the widest possible spectral domain (possibly up to the infrared where the sensitivity to magnetic fields is stronger) and highest possible spectral resolution (up to 200,000 optimally). The new spectropolarimeter that CFHT has started building (called ESPaDOnS), which should yield full optical spectral coverage (i.e. 370 to 1,000 nm) at a spectral resolution of over 50,000 in a single exposure with 20% peak efficiency (atmosphere, telescope and detector included) is clearly a first step in this direction (Donati et al. 1998b). New generation instruments on 8 m telescopes will nonetheless be necessary to achieve our ultimate goals.

New magnetic imaging techniques must be explored as well. Computing spherical harmonics coefficients (up to orders 50 or so) from fitting sets of rotationally modulated Zeeman signatures is certainly an interesting possibility; in addition to provide an independent check for surface field maps obtained with the present imaging tools, it can also be used to derive an estimate of the 3D topology of the (assumed potential) field structure (as done in the particular case of the Sun), and allow us to check at the same time (from the accuracy level at which data can be adjusted) how far the observed field departs from

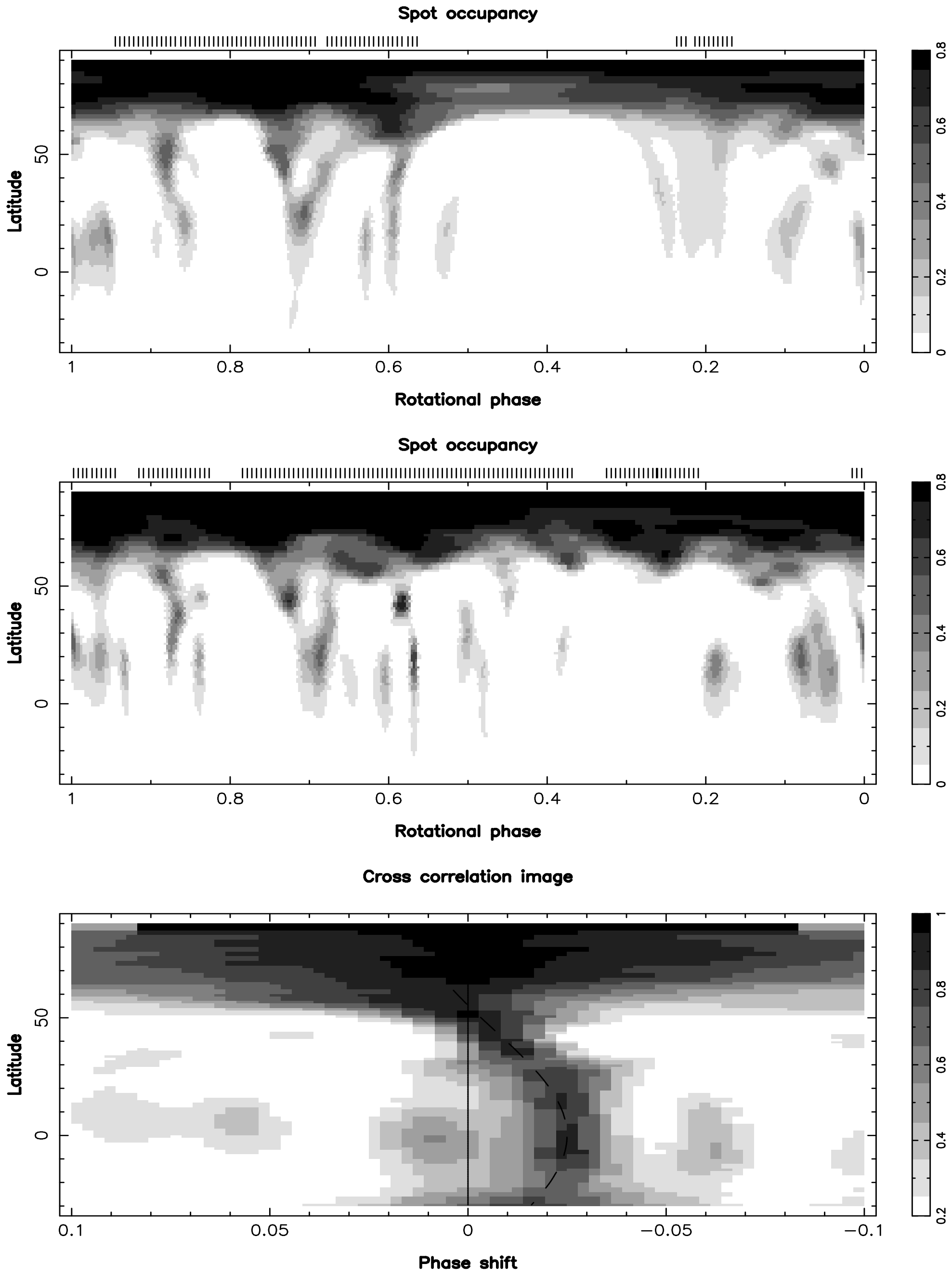

Figure 4. Cross-correlation image (lower panel) obtained by cross-correlating latitude belts of two brightness images (upper panels, rectangular projection) of AB Dor obtained 4 d (i.e. 8 rotation cycles) apart in 1995 Dec. Note that cross-correlation is performed on the fraction of the rotational cycles that was continuously monitored at both epochs, i.e. on phase interval [0.55,0.90] (phases of observations being indicated by vertical ticks above brightness images).

a potential configuration. These developments should be very interesting for studying the interaction of the large scale field structure with the immediate circumstellar environment.

All these results should improve our knowledge of how magnetic fields are produced and react on some of the most crucial transport processes operating within late type stars, and eventually bring us to the point where existing theories (on e.g. dynamo processes, prominence dynamics, coronal heating, accretion/ejection phenomena) that were specifically built to explain solar observations (i.e. the only available data at that time) will need to be reassessed and most likely revised in the broader context of both solar and stellar observations. Ultimately, we should be able to get a better insight on how magnetic fields influence the evolution of late-type stars.

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