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LONG-TERM MAGNETIC MONITORING OF 19 SUN-LIKE STARS

A. Morgenthaler[1,2], P. Petit[1,2], J. Morin[3], M. Aurière[1,2] and B. Dintrans[1,2]

Abstract. A sample of 19 Sun-like stars, probing masses between 0.7 and 1.4 solar mass and rotation rates between 1 and 3 solar rotation rate, was regularly observed using the NARVAL spectropolarimeter at Telescope Bernard Lyot (Pic du Midi, France) since 2006. The data sets enable us to monitor the rotational and long-term evolution of indirect activity indicators such as the width of several magnetically-sensitive spectral lines, the radial velocities, the line asymmetry of intensity line profiles and the chromospheric emission in the cores of the Ca II H and Halpha lines. In the same time, the Zeeman-Doppler Imaging allowed us to study the reconstructed large-scale photospheric magnetic field. I will present the main results of this monitoring, which includes the observations of several polarity reversals and magnetic cycles, and the highlight of links between some of our computed quantities and some fundamental parameters of the stars.

Keywords: stars: atmospheres - stars: low-mass - stars: magnetic field - stars: solar-type

1 Introduction

Sun-like stars are characterized by convective envelopes in which large-scale plasma flows (related, in particular, to radial and latitudinal differential rotation and to the Coriolis force) are able to trigger a global dynamo (Parker 1955). This continuous generation of a large-scale field is related to surface variability affecting a wide range of temporal and spatial scales, including quasi-periodic polarity reversals associated to magnetic cycles. Recent numerical models, in particular global MHD simulations, are able to mimic some characteristics of this cyclic behavior for Sun-like stars (Ghizaru et al. 2010; Brown et al. 2011). In addition to numerical computations, spectropolarimetry now enables us to perform direct measurements of surface magnetic fields and follow the long-term temporal evolution of large-scale magnetic geometries. So far, it allowed the observation in Sun-like stars of one global polarity switch (Petit et al. 2009) and of a full magnetic cycle (Fares et al. 2009).

Our aim is to study the long-term variations of the magnetic field properties of a sample of solar-type stars. Our observed sample includes 19 FGK-type stars on the main sequence, monitored since 2007. We probe here stellar masses between 0.6 and 1.4 solar mass, and rotation periods between 3.4 and 43 days.

After a brief description of the instrumental setup, data reduction and multi-line extraction of Zeeman signatures, we explain the reconstruction technique of the large-scale topology of the stars. We then highlight three representative examples of different types of variability observed in our sample. We finally discuss the results derived from our measurements.

2 Instrumental setup, data reduction, and extraction of the Zeeman signatures

We use data from the NARVAL spectropolarimeter (Aurière 2003), installed at Telescope Bernard Lyot (Pic du Midi, France). The instrumental setup is strictly identical to the one described by Petit et al. (2008). The spectrograph unit of NARVAL benefits from a spectral resolution of 65,000 and covers the whole wavelength domain from near-ultraviolet (370 nm) to near-infrared (1,000 nm). Thanks to the polarimetric module, NARVAL can provide intensity, circularly or linearly polarized spectra. In the present study, we restrict the measurements to Stokes V.

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[1] Université de Toulouse, UPS-OMP, Institut de Recherche en Astrophysique et Planétologie, Toulouse, France
[2] CNRS, Institut de Recherche en Astrophysique et Planétologie, 14 Avenue Edouard Belin, F-31400, Toulouse, France
[3] Dublin Institute for Advanced studies, School of Cosmic Physics, 31 Fitzwilliam Place, Dublin 2, Ireland

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The circularly polarized spectra allow the detection of large-scale photospheric magnetic fields, thanks to the Zeeman effect. However, when observing cool dwarfs, the signal-to-noise ratio of circularly polarized spectra produced by NARVAL is not sufficiently high to reach the detection threshold of typical Zeeman signatures (which amplitude does not exceed $10^{-4} I_c$ for low-activity stars, where I_c is the continuum intensity). To solve this problem, we calculate from the reduced spectrum a single, cross-correlated photospheric line profile using the Least-Squares-Deconvolution (LSD) multi-line technique (detailed by Donati et al. 1997; Kochukhov et al. 2010). Thanks to the large number of available photospheric lines in cool stars (several thousands in the spectral domain of NARVAL), the noise level is reduced by a factor of about 30 with respect to the initial spectrum.

3 Magnetic mapping

To reconstruct the surface magnetic geometry of the stars, we use the technique of Zeeman-Doppler Imaging (ZDI). This tomographic inversion technique is based on the modelling of the rotational modulation of the circularly polarized signal (Semel 1989). The time series of polarized signatures are iteratively compared to artificial profiles corresponding to a synthetic magnetic geometry, until the best fit is obtained between the model and the observations (Donati & Brown 1997; Donati et al. 2006). ZDI enables to recover, to some extent, the location of magnetic regions, as well as the strength and orientation of the magnetic vector in magnetic spots. The application of this technique to cool stars with low $v\sin i$ is described by Petit et al. (2008). The resulting maps for the three stars presented here are illustrated in Fig. 1, 2 and 3.

4 Results

Since the monitoring began a few years ago, long-term changes in the magnetic properties become observable in some of our targets. The magnetic quantities derived from ZDI exhibit temporal fluctuations over a wide range of timescales, due to rotational modulation and longer-term magnetic trends. Three representative examples of the different kinds of stellar variability we observed is described hereafter.

4.1 *Short magnetic cycle : HD 78366*

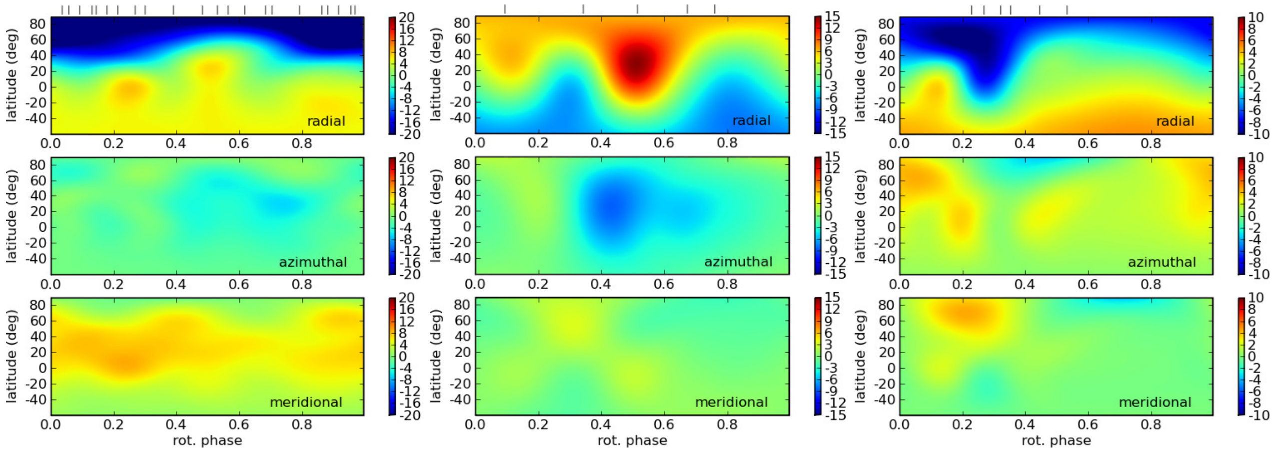

Fig. 1. Magnetic maps of HD 78366, derived from 2008.09, 2010.04 and 2011.08 observations (from left to right). For each data set, the 3 charts illustrate the field projection onto one axis of the spherical coordinate frame with, from top to bottom, the radial, azimuthal, and meridional field components. The magnetic field strength is expressed in Gauss.

A simple type of variability is observed for HD 78366. This target is slightly more massive than the Sun and rotates about two times faster. The data sets of this object are collected over three distant seasons. The corresponding magnetic maps are shown in Fig. 1. We observe two polarity switches, especially visible in the polar area of the radial field component, which is of negative polarity in 2008.09, positive in 2010.04 (and associated at that time with a more complex magnetic field geometry), and negative again in 2011.08. After the two observed polarity reversals, the magnetic field retrieves its initial configuration. Assuming that the magnetic variability of this star is not much faster than the temporal sampling imposed by the right ascension

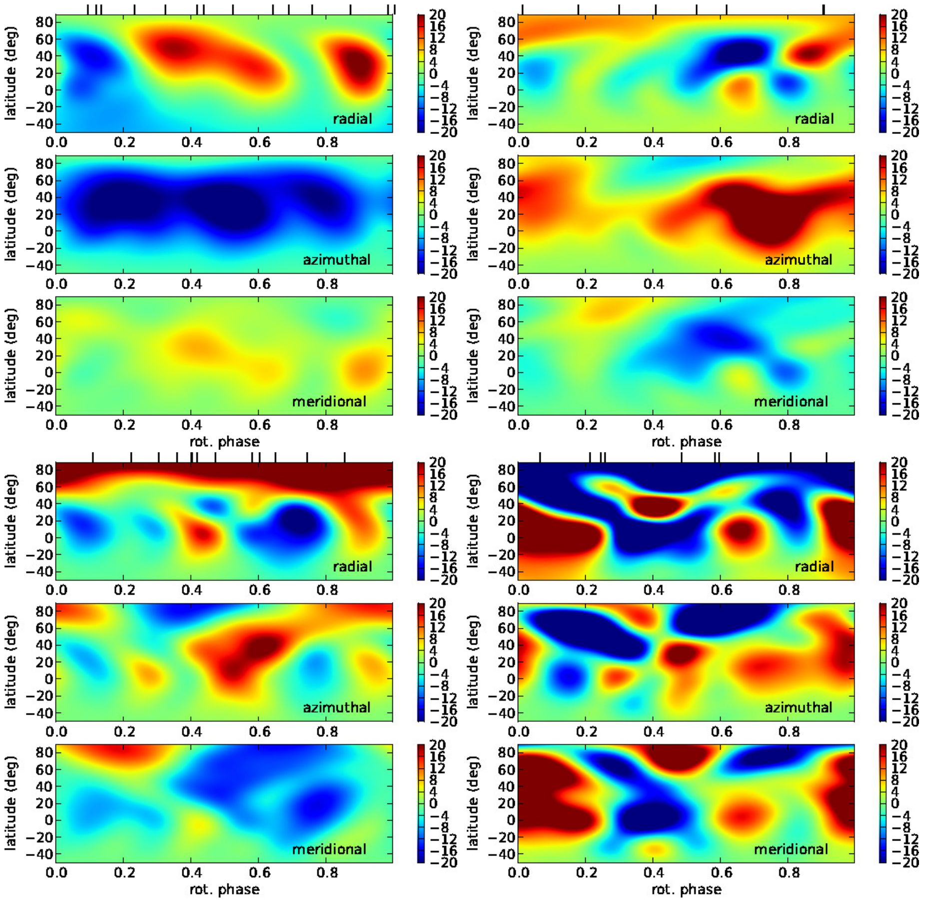

Fig. 2. Same as Fig. 1 for HD 190771, for 2007.59, 2008.67, 2009.47 and 2010.50 data sets (from left to right and top to bottom).

of the star (visible only during winters), this first time-series suggests that HD 78366 may obey to a magnetic cycle of about three years.

4.2 *Fast polarity reversals : HD 190771*

A more complex type of variability is illustrated by HD 190771. It has a mass similar to the Sun's, but has a rotation period of 8.8 days. In Fig. 2, we plot the magnetic maps derived for this star. A polarity reversal is visible on the strong azimuthal component between 2007.59 and 2008.67 (Petit et al. 2009). Between 2008.67 and 2009.47, the magnetic geometry changed in a different manner : the magnetic field which was mainly toroidal in 2008.67 became mostly poloidal in 2009.47. A second polarity reversal took place between 2009.47 and 2010.50, this time on the radial field component. In this case, the two successive polarity switches do not imply that the initial magnetic state is reached again, so that the observed variability is not taking the form of a cycle.

4.3 *Fast and complex variability : ξ Bootis A*

Finally, another, more complex type of variability is observed with ξ Boo A, the less massive and most rapidly rotating star of our three examples. It was observed at seven epochs, for which the magnetic field geometry was derived (Morgenthaler et al. 2011). Here we highlight two results of this long-term monitoring.

The first one refers to the 2007.59 and 2008.09 data sets (top part of Fig. 3). We observe that within a six months interval, the intensity of the magnetic field decreased by about 50% and that the magnetic geometry, which was quite simple in 2007.59 with an aligned dipole and a prominent ring of azimuthal field, became more complex and less axisymmetric in 2008.09, with a less pronounced toroidal surface component.

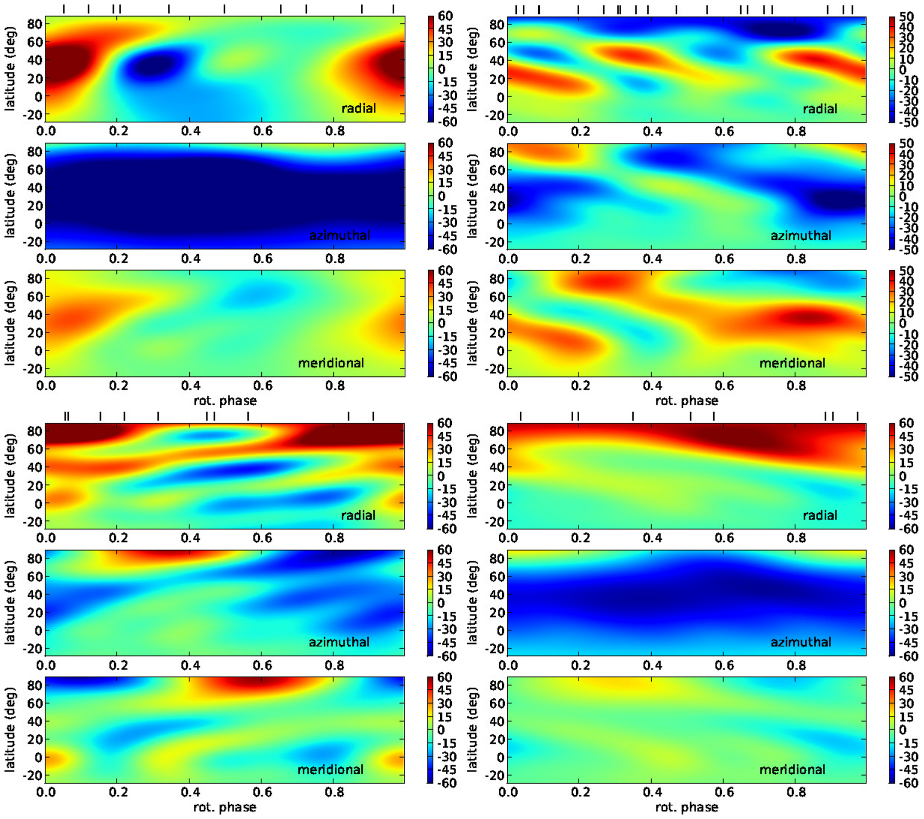

Fig. 3. Same as Fig. 1 for ξ Bootis A, for 2007.59, 2008.09, 2010.48 and 2010.59 data sets (from left to right and top to bottom).

The second example is visible in the set of observations collected during the summer of 2010, which we decided to split in two subsets (2010.48 and 2010.59) to take into account the fast variations of the Zeeman signatures over this short timespan. In the correponding magnetic maps (bottom part of Fig. 3), the most striking evolution is a sharp increase of the azimuthal magnetic field.

ξ Boo A is therefore submitted to fast and complex surface changes that are different from those of the two previous stars, and reminiscent of the complex behavior of other rapid rotators observed in the past (e.g. Donati et al. 2003).

5 Discussion

All stars of our sample show variability over the four years of our monitoring, but of different types. Stars which show at least one field reversal over this timespan have in common a fast rotation period (at least twice the solar one) and masses equal or slightly larger than that of the Sun. We note that the solar-type star τ Bootis, which is not part of our sample but which is reported to be affected by a short magnetic cycle of two years at most (Fares et al. 2009), shares also these mass and rotation properties. We stress also that active stars with masses below our lower mass boundary (in particular, mid-M dwarfs with masses just below the fully convective limit) are reported to possess strong, simple and stable surface magnetic fields (Morin et al. 2008a,b).

τ Boo and HD 78366 were also observed at Mount Wilson as chromospherically active stars. For τ Boo, Baliunas et al. (1995) report a cycle of twelve years, versus two years from spectropolarimetry. Concerning HD 78366, periods of six and twelve years were identified using the Mount Wilson time-series, against about three years in our investigation. We therefore note that, at least for these two examples, the cycle lengths derived by chromospheric activity seem to be longer than those derived by spectropolarimetry. We suggest that this apparent discrepancy may be linked to the different temporal sampling inherent to the two approaches, so that the sampling adopted at Mount Wilson may not be sufficiently tight to unveil short activity cycles.

Future observations of our target list will allow us to investigate longer timescales of the stellar magnetic evolution. The sample includes several solar twins (Petit et al. 2008) which have not shown cycles yet, and which will help us to determine how small departures from the solar fundamental parameters may affect the characteristics of magnetic cycles. More generally, a regular monitoring of our targets over more than one decade will enable us to determine more precisely the relation between the length/occurrence of magnetic cycles and the rotation/mass of Sun-like stars.

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