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MAGNETIC GEOMETRIES OF SUN-LIKE STARS : IMPACT OF ROTATION

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Abstract. Sun-like stars are able to continuously generate a large-scale magnetic field through the action of a dynamo. Various physical parameters of the star are able to affect the dynamo output, in particular the rotation and mass. Using new generation stellar spectropolarimeters (ESPaDOnS@CFHT, NARVAL@TBL), it is now possible to measure the large-scale magnetic field of solar analogues (i.e. stars very close to the Sun in the stellar-parameter plane, including strict solar twins). From spectropolarimetric time-series, tomographic inversion of polarized Zeeman signatures allows us to reconstruct the field geometry and its progressive distortion under the effect of surface differential rotation. We detail the first results obtained on a sample of four main-sequence dwarfs, with masses close to 1 solar mass and rotation rates between 1 and 3 solar rotation rate.

1 Introduction

All rotating Sun-like stars show spectral features indicating the presence of magnetic fields in their atmosphere. Chromospheric emission (as measured in the cores of CaII H & K lines) is often taken as a good magnetic tracer, following the correlation observed in the Sun (Schrijver et al. 1989). For a few tens of stars, time-series covering several decades are now available and provide information about the existence and length of magnetic cycles that different types of stars can exhibit (Baliunas et al. 1995, Hall et al. 2007a). From this long-term monitoring, several trends can be derived. First, the chromospheric flux increases with the rotation rate. Also, all active stars do not undergo smooth activity cycles, as the Sun does today. The activity of the most active dwarfs has a tendency to fluctuate erratically, while regular cycles are rather observed in less active (older) dwarfs, like the Sun. It seems as well that the magnetic activity of Sun-like stars is very sensitive to fundamental parameters, so that stars very similar to the Sun can obey to a different magnetic behaviour. While being often considered as the brightest solar twin, 18 Sco was recently reported to follow an activity cycle shorter than solar, with a period of $\approx$7 years (Hall et al. 2007b).

Knowing that many stars go through a series of activity maxima and minima as the Sun does, and bearing in mind that many stars do not, a very natural question is then to determine whether such oscillations are associated to a global polarity reversal of the large-scale magnetic field, as observed on the Sun between two successive solar minima. On the Sun, this global magnetic field component displays a strength limited to a few Gauss only (e.g. Sanderson et al. 2003). If present on a Sun-like star, the detection of this magnetic component requires highly sensitive spectropolarimetry to capture Zeeman signatures that should not exceed 10^{-4} of the continuum in circularly polarized light.

We achieve this detection with the help of spectropolarimetric data sets collected with the NARVAL spectropolarimeter. From a set of observations of a sample of four Sun-like stars covering a range of rotation periods, we reconstruct their large-scale photospheric magnetic geometry and discuss the impact of rotation on their magnetic properties. We then briefly present the extention of this observing project to a larger sample of stars.

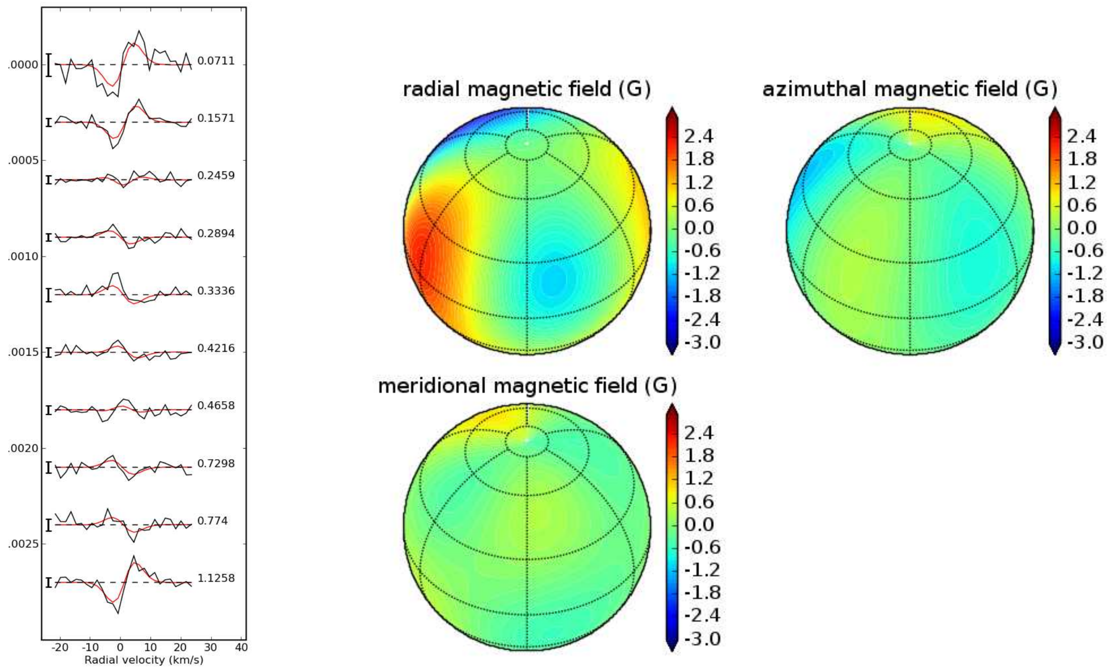

Fig. 1. Left panel: Stokes V profiles of 18 Sco, after correction of the mean radial velocity of the star. Black lines represent the data and red lines correspond to synthetic profiles of our magnetic model. Successive profiles are shifted vertically for display clarity. Rotational phases of observations are indicated in the right part of the plot and error bars are illustrated on the left of each profile. **Right panel:** magnetic map of 18 Sco (here with observer facing the rotational phase 0.5). Each chart illustrates the field projection onto one axis of the spherical coordinate frame. The magnetic field strength is expressed in Gauss.

2 Observations

Our stellar sample is constituted of four nearby dwarfs (18 Sco, HD 76151, HD 73350 and HD 190771). Their fundamental parameters are chosen to be as close as possible to the Sun's (Valenti & Fischer 2005). The observational material consists of high-resolution spectra obtained simultaneously in classical spectroscopy (Stokes I) and circularly polarized light (Stokes V) in 2007 winter and summer, using the newly installed NARVAL stellar spectropolarimeter at Télescope Bernard Lyot (Observatoire du Pic du Midi, France). The data reduction is performed by Libre-Esprit, a dedicated, fully automated software described by Donati et al. (1997) and implementing the optimal spectral extraction principle of Horne (1986) and Marsh (1989).

A single, average photospheric line profile was extracted from each spectrum using the LSD technique (Donati et al. 1997), according to a line-list matching a solar photospheric model. Using this cross-correlation method, the noise level of the mean Stokes V profiles is reduced by a factor of about 40 with respect to the initial spectrum. The resulting noise level are in the range $2 \times 10^{-5} - 8 \times 10^{-5}$ I_c (where I_c denotes the continuum level), enabling us to detect the Zeeman signatures of 18 Sco's large-scale photospheric field (Fig. 1, after Petit et al. 2008).

Assuming that the rotation alone is responsible for the variability observed throughout the time-series, we

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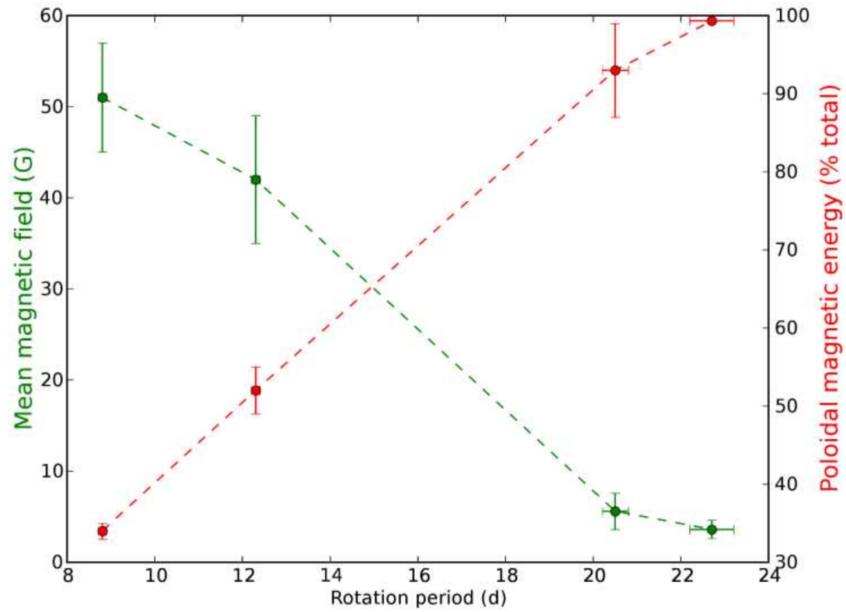

Fig. 2. Rotational dependence of the mean (unsigned) magnetic field (green line) and of the fraction of magnetic energy stored in the poloidal field component (red curve).

derive the rotation period of the targets, with measured values between 8.8 d (for HD 190771) to 22.7 d (for 18 Sco). For HD 190771, the data set cannot be modelled down to the noise level without further including some latitudinal shear in our magnetic model. By doing so, we obtain a difference of rotation rate between polar and equatorial regions of 0.12 ± 0.03 rad.d^{-1}.

The magnetic map of 18 Sco is shown in the right panel of Fig. 1. The large-scale magnetic field can be modelled under the assumption of a purely poloidal field geometry. The mean strength over the stellar surface is about 4 Gauss, with $34 \pm 6\%$ of the magnetic energy showing up as a dipole, $56 \pm 6\%$ in the quadrupole and no detectable magnetic energy above the octopolar expansion.

We illustrate in Fig. 2 the results obtained for the full sample and observe two clear tendencies. First, the unsigned magnetic field of the reconstructed maps increases with the rotation rate (green line). The second noticeable effect of rotation is to increase the fraction of the magnetic energy stored into a large-scale toroidal component of the surface magnetic field (red curve). From our observations, we infer that a rotation period lower than ≈12 days is necessary for the toroidal magnetic energy to dominate over the poloidal component.

3 Exploring the mass-rotation plane

This first stellar sample has been enlarged to offer a sampling of the mass-rotation plane, from 0.7 to 1.3 $M_\odot$. The full sample is now constituted of about 20 main-sequence dwarfs. We plan to monitor the selected targets over 5 to 10 years to estimate the long-term variability of their magnetic topologies. The temporal evolution of the total magnetic energy, the poloidal/toroidal distribution of the surface field or the distribution of the magnetic energy between the axisymmetric and non-axisymmetric components will then provide us with a new set of surface observables that will help to constrain numerical models of stellar dynamos.

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