Using Optical Interferometry for Studying Stellar Activity and Magnetism

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Abstract. We show how the fringe phase provided by an optical interferometer can be used for mapping patchy surfaces and magnetic topologies. We illustrate this with simulations in two well-known chemically peculiar stars, β CrB and α² CVn.

1. Introduction

Studies of stellar activity and magnetism are mainly based on photometric and spectro-polarimetric observations, which can only provide values integrated over the stellar disk. This introduces much degeneracy in the inversion process. Recent developments in optical interferometry allow high angular resolution (∼1 mas) and may thus reveal local stellar features. Although direct imaging of the stellar surface is not yet possible, important information may still be obtained in marginally resolved observations. We describe an innovative technique called spectro-polarimetric interferometry (SPIN), which couples high angular resolution with spectro(polarimetric abilities. This technique allows us to determine the orientation of the rotational axis, to map abundance distributions and magnetic topologies. We focus on two well-known CP stars, β CrB and α² CVn, and we show simulations with different instruments currently in operation (GI2T, VLTI).
2. Interferometric observables

An interferometer combines different telescope beams coherently. The interferometric configuration is determined by the vectorial relative position of the two telescopes, \( \mathbf{b} \). The Zernicke-Van Cittert theorem shows that the complex coherence factor, \( V e^{-i\phi} \), for the baseline \( \mathbf{b} \) is the Fourier Transform of the angular intensity distribution, \( O(\alpha) \), at spatial frequency \( \mathbf{b}/\lambda \), where

\[
V e^{-i\phi} = TF\{O(\alpha)\}.
\]

If the object is marginally resolved \( (\mathbf{b}/\lambda < \Phi_{\text{object}}) \), it is possible to express the complex coherence factor with the two first moments of the flux distribution: the photocenter \( \mathbf{p} \), and the radius \( \Phi \) (Jankov et al., 2001), where

\[
V = 1 - 4\pi^2 \frac{\Phi^2}{\lambda} \cdot \mathbf{u} \cdot \mathbf{u} + O(u^4)
\]

\[
\phi = -2\pi \frac{\mathbf{p} \cdot \mathbf{u}}{\lambda} + O(u^3).
\]

Random atmospheric perturbations corrupt the fringe phase. For standard turbulence, the variations are larger than \( 2\pi \) and so the phase reference is lost. The SPIN technique proposes a self-calibration method using the spectral dispersion, which allows the differential phases between the continuum and the lines (absorption or emission) to be obtained (Rousselet-Perraut et al., 2000). Thus using spectro-polarimetric observations, it is possible to determine \( \mathbf{p} \cdot \mathbf{u} \) and \( \Phi \) in the I,U,Q,V stokes parameters for each \( \lambda \).

3. Using SPIN for stellar activity and magnetism

3.1. Constraining mass-loss in extended environments

Chesneau & Wolf (2003) have investigated the ability of interferometry to study mass-loss in hot stars. They found that SPIN is a powerful tool for constraining the stellar wind parameters, especially in the case of dense winds or extended atmospheres.

3.2. The orientation of the rotational axis

Spectroscopic measurements can determine the value of \( v \sin i \), because the observed profile, \( S(\lambda) \), is a convolution of the intrinsic profile \( H(\lambda) \) and the "Doppler function" \( D(\Delta \lambda) \), which depends only on limb-darkening and rotation. The corresponding fringe phase for an interferometric baseline \( \mathbf{b} \) is given by:

\[
\phi = \frac{\mathbf{p} \cdot \mathbf{b}}{\lambda} = A(\lambda) \left| \frac{b}{\lambda} \right| \cos(i \cdot \mathbf{j}),
\]

where \( \mathbf{j} \) is the direction orthogonal to the rotational axis and \( i \) the direction of the baseline. Note that \( A(\lambda) \sim H(\lambda) \ast D(\Delta \lambda) \) can be obtained only by measuring the observed spectrum. So different measurements of \( \phi \) for different baseline orientations can be used to determine the orientation of the rotational axis. This is an important parameter in the Magnetic Doppler Imaging inversion method.
Figure 1. Simulation of a patchy surface seen through a line of sight of 50° (left). Two chromium spots, one in each hemisphere, lead to a dynamical spectrum (middle) and to fringe phase signatures (right) during a stellar rotational period.

Figure 2. Simulations of a pole-on rotator (top) and a equator-on rotator (bottom) with the same patchy surface distribution as in Fig. 1 and the corresponding spectra and fringe phase signatures during the stellar rotational period.

3.3. Mapping abundances with SPIN

The fringe phase information is of great interest since:

- it is sensitive in the limb region. We have simulated the spectrum and the photocenters for two standard geometries with a sight angle of 50°. The
star has two spots with realistic Chromium over-abundances, one in each hemisphere. Because it appears only in a very limb-darkened region, the southern spot leaves only a small signature in the dynamic spectrum. On the other hand, the $x$-coordinate of the photocenter is highly sensitive in this region (Fig. 1).

- it allows the absolute position to be determined. For an equator-on rotator, we show that the photocenter removes the degeneracy in the spectrum when the two spots are symmetrically located - there is no mirror effect in the fringe phase information (Fig. 2).

![Figure 3](image)

Figure 3. Integrated spectra $I(\lambda)$ (left) and photocenter $p(\lambda)$ in the $y$ (middle) and the $x$ (right) directions of the Cr II $\lambda4824$ line for a 50-m baseline and infinite spectral resolution. The profiles extend over $\pm 0.47\text{Å}$ from the line center. Abundance maps at the left allow us to follow the different spots over the rotational phase (overabundances are shown as darker patches).

We have computed a realistic patchy surface for $\alpha^2$ CVn thanks to data provided by Kochukhov (Kochuchov et al, 2002). We have selected several metallic lines of various elements (Fe, Cr, Si) and have calculated the fringe phases for various stellar phases (Fig. 3). The $x$ and $y$ fringe phases allow us to locate the spots quite precisely. The SPIN signals clearly appear to be complementary to the “classical” Doppler signals. As an example, the SPIN signals allow us to disentangle north – south spot positions thanks to the sign of the $x$ fringe phase. At rotational phase $\phi = 227^\circ$, we locate a large overabundance at the top left and a smaller one at the bottom right. Phase effects of several degrees can be
observed across the spectral lines in the visible and near-infrared ranges, even for limited spectral resolution.

3.4. Constraining the magnetic field of β CrB

We have adopted the magnetic field configurations for the well-known magnetic star, β CrB as described by Bagnulo et al. (2000). By inverting spectropolarimetric data, they have derived two possible models. We have computed the fringe phases for each one in the Fe i λ6430.8 line. The phase variations are in antiphase for the two models. For a given baseline orientation or at a given stellar phase, the photocenter is not in the same hemisphere for the two models, as clearly shown in the reconstructed field maps displayed in Fig. 4 (right). The two models can therefore be disentangled, provided that we are able to measure a fringe phase smaller than 1° with a 50-m baseline (GI2T for example). The phase effects are twice as large with a 100-m baseline (VLTI for instance).

![Figure 4. Fringe phase of V Stokes parameter in the Fe i λ6430.844Å line versus baseline orientation and rotational phase for Model 1 (solid line) and the Model 2 (dashed line). The spectral resolution is 30000 and the fringe phase is computed in the spectral channel for which the phase effect is maximal. The baseline is 50 m, the stellar angular diameter is 1 mas and the rotational velocity v sin i = 3.5 km s⁻¹.](image)

4. Instrumental perspectives

Since SPIN observations appear to be feasible within the measurement accuracy of existing or planned instruments, we foresee two-telescope polarimetric measurements with the GI2T/REGAIN in the visible, and three-telescope near-infrared observations with AMBER in the VLTI. Such observations are highly desirable in future observations with large imaging arrays. Moreover, they will contribute to the development of numerical tools dedicated to this innovative technique. We need to calculate simulations of expected SPIN signals for any stellar configuration and also to develop inversion algorithms for SPIN data in order to obtain very high angular resolution maps. Different interferometers compliment each other and provide interesting contexts for SPIN (Fig. 5):
Figure 5. Collecting area as a function of angular resolution for existing and planned instruments.

- the multiple-baselines and angles of IOTA, CHARA or the planned VLTI imaging mode are important to determine rotational parameters;
- the R=10,000 spectral resolution and high sensitivity of AMBER on VLTI for abundance studies;
- the spectro-polarimetric mode of the French interferometer GI2T for magnetic topologies.

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References