Detection of the linearly polarised spectrum of the red supergiant star $\alpha$ Ori

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Abstract. In the solar limb, linear polarisation is due to anisotropy of the radiation field induced by limb darkening. It is maximal when it is seen parallel to the limb and it vanishes when it is integrated over the spherically-symmetric solar disk. Therefore for distant stars, that present spherical symmetry, linear polarisation signatures are very difficult to observe. However strong linear polarisation features have been reported in the prototypical red supergiant star $\alpha$ Ori (Betelgeuse). With an analytical model we propose to explain them.

1. Introduction

Red supergiant stars (M type supergiants, hereafter RSG) are cool ($T_{\text{eff}}$ between 3,000 K and 4,000K) and massive ($M > 10 M_\odot$) stars. They have a very extended atmosphere (from $100R_\odot$ to $100000R_\odot$ for the biggest ones) rich in molecules and dust grains. They undergo an important mass loss ($10^{-6} - 10^{-4} M_\odot$/yr) and are therefore among the main recycling agents of the interstellar medium. While the mass loss is a key ingredient in stellar evolution models (Ekström et al. 2013) it is still poorly understood and the mechanisms triggering it are not well constrained. Josselin & Plez (2007) proposed that a vigorous convection, taking place at the base of the extended atmosphere (hereafter, the photosphere), could explain how a mass loss event starts. It is therefore important to study the photosphere of RSG and to characterise its dynamics. Spectroscopic and interferometric observations in the visible and near infra-red have been widely used to study the photosphere and are in good agreement with hydrodynamic simulations (MHD). Indeed, MHD simulations of Freytag et al. (2002) and Chiavassa et al. (2011) predict that giant convective cells lie above the photosphere, with sizes of about 10% of the stellar radii. Moreover, Aurière et al. (2010), using spectropolarimetry, have detected a weak magnetic field at the surface of $\alpha$ Ori. Because of the very long rotation period of the stars (of about 15 years) a small-scale dynamo generating a global magnetic field is supposed. This detection comforts the idea that turbulent motions in the giant convective cells may generate a global magnetic field (see for instance Dorch 2004). From recent observations of RSG stars, Aurière et al. (2016) and Tessore et al. (in preparation) have shown that spectropolarimetry, taking advantage of the great
quantity of informations tangled in linear polarisation, could be a promising tool to study the surface dynamics of these evolved stars.

2. Observations and data analysis

\(\alpha\) Ori is the brightest and closest RSG. It has naturally deserved many observations (with spectroscopy and interferometry) in all wavelength ranges so that it is possible to have an extensive overview of the star itself and to link one part of its extended atmosphere with another. \(\alpha\) Ori belongs to an observing program we have initiated in 2015 at Télescope Bernard-Lyot (TBL, Pic du Midi France) with the Narval instrument, the twin of the spectropolarimeter ESPaDOOnS (Donati et al. 2006). This large program is dedicated to the spectropolarimetric study of cool evolved stars using both circular and linear polarisation spectra. Each polarimetric sequence (one spectrum) collected by Narval covers a spectral range from 375 nm to 1,050 nm in a single exposure with a resolving power of about 65,000. The optimal extraction of spectra is performed with Libre-ESpRIT (Donati et al. 1997), an automatic and dedicated reduction package installed at TBL and it includes wavelength calibration, continuum normalisation and correction to the heliocentric rest frame. A Null spectrum is also computed for each observations. This Null diagnosis has no physical meaning but in absence of spurious polarisation it is featureless. In all linear polarised observations of \(\alpha\) Ori the Null signal is always flat at the noise level, this indicates the good quality of the polarimetric observations as well as the stellar origin of the detected polarised features. Since March 2015 the star has been observed once per month and eight Stokes Q and Stokes U spectra are collected for each observational date.

Furthermore we have analysed each spectrum with the Least-Square Deconvolution (LSD) method (Donati et al. 1997). The LSD method extracts from thousands of spectral lines a mean information called LSD profile. Each LSD profile is a set of a mean line profile, mean polarimetric profile and the mean Null signal \( (I/I_c, Q/I_c, U/I_c, N\) and \( P_\ell = \sqrt{(Q^2 + U^2)} \)). Figure 1 shows a typical LSD profile of \(\alpha\) Ori.

3. Linearly polarised spectrum of \(\alpha\) Ori

The complex linearly polarised spectrum of the Sun, known as the "Second Solar Spectrum" (Stenflo & Keller 1997) has two main contributions. A few lines show polarisation such as the Strontium line at 460.7 nm and the Sodium D lines around 588.9 nm which can be explained by complex quantum interferences while the majority of the lines depolarise the polarised continuum spectrum. At the depth where the continuum get polarised, polarised photons (and unpolarised ones) are emitted. These photons are absorbed by the surrounding stellar gas and re-emitted, unpolarised, during the line forming process. Therefore at the frequencies of the lines the continuum polarisation presents a depression having the shape of the lines. The continuum spectrum of the Sun gets polarised by Rayleigh scattering at neutral Hydrogen and Thomson scattering at free electrons. This polarisation is modified by the geometry of the radiation field that defines how the atoms are illuminated. In the Sun, the centre-to-limb variation (CLV) of the intensity introduces anisotropy in the radiation field that is stronger near the limb. Red supergiant stars also present polarisation of their continuum. Doherty (1986) has
measured the continuum polarisation of \( \alpha \) Ori at 0.5\% in the blue. Because RSG are cooler than the sun, the main contributors to the continuum polarisation are Hydrogen atoms and molecules.

For symmetry reasons, looking at the Sun as a star, the Second Solar Spectrum would not be observable. It is therefore very difficult to observe such a polarised spectrum for distant stars. However the strong brightness contrasts introduced by the giant convective cells lying at the surface of RSG are likely sufficient to break the spherical symmetry of the stellar disk, so that after integrating over the stellar disk a little fraction of the continuum polarisation may remain. Aurière et al. (2016) have detected a complex linearly polarised spectrum of \( \alpha \) Ori. Figure 2 shows the linearly polarised spectrum of \( \alpha \) Ori around two different regions. Because the surface magnetic field of \( \alpha \) Ori is at the Gauss level, Aurière et al. (2016) have disregarded a Zeeman origin of the linear polarisation. Furthermore, by looking at the Sodium D lines in \( \alpha \) Ori and comparing it with the same lines in the Sun (see Fig. 3) Aurière et al. (2016) have shown that depolarisation of continuum dominates the linearly polarised spectrum of \( \alpha \) Ori. This explains why there are many features in the polarised spectrum of \( \alpha \) Ori facing the intensity lines and showing a similar shape. Indeed, Fluri & Stenflo (2003) explained that the depolarising lines have statistically the same shape (that is why the LSD methods is well suitable).
At this time we know that the continuum of α Ori (and RSG) is polarised by Rayleigh scattering and that we mainly observed depolarisation by the photospheric lines.

Figure 2. Linearly polarised spectrum of α Ori around the sodium D lines (left panel) and Hα line (right panel). The black solid lines (upper part of each panel) are the unpolarised flux (Stokes I). The blue solid lines (lower part of each panel) are the total amount of linear polarisation. The 1σ level is shown by the horizontal lines.

Figure 3. The Sodium D lines in the linearly polarised spectrum of α Ori (solid line) as compared to the solar case (dot-dashed line). The horizontal line is the 1σ level of the observation of α Ori. No scaling factor has been applied to the second solar spectrum. The solar data are taken from www.irsol.ch/data-archive/ (Gandorfer 2000)
4. Spectropolarimetry as a diagnostic tool to study the surface dynamics of red supergiant stars

As explained in the previous sections the photosphere of RSG is very complex. The brightness contrasts introduced by the giant convective cells are responsible for the small changes in the luminosity of the star. Haubois et al. (2009) from interferometric observations have reconstructed two bright spots at the surface of α Ori. More recently, Montargès et al. (2015) using their interferometric model have inferred two Gaussian spots at the surface of α Ori. From the point of view of the observations there is a clear link between the surface convective patterns of the star and the measured linear polarisation. Therefore, Aurière et al. (2016) have developed an analytical model that link the observed LSD profiles of α Ori to bright spots at the surface of the star. The main idea of this model is that each maximum in the LSD profile corresponds to one bright spot at the surface of the star. This spot is in expansion if it is shifted to the blue in the LSD profile or sinking if it is shifted to the red. Therefore the amplitudes of Stokes Q and Stokes U and their positions give us the polar coordinates of the spots, θ and μ. However, the exact dependence of the polarisation with the intrinsic brightness of each spot is not known and only the ratio of the polarisation between each spot with respect to the brightest one, corrected by the angular dependence of Rayleigh scattering, is given. For each observation, for each LSD profile the positions of several spots are inferred on the disk of α Ori. Figure 4 shows the possible positions of the bright spots inferred by the model for α Ori using all the spectropolarimetric observations collected on this star since November 2013.
Remarkably the spectropolarimetric model of spots described by of Aurière et al. (2016) is in good agreement with the interferometric model of Montargès et al. (2015). Although this analytical spectropolarimetric model does not reproduce a continuous distribution of brightness (more realistic) and does not provide absolute values of polarisation it is still a good tool to study the time variation of the photosphere and it has proven is ability to complement interferometric observations.

Therefore with these preliminary results we have shown how spectropolarimetry could be a great tool in characterising the photosphere of red supergiant stars. New ongoing observations of α Ori as well as other RSG such as CE Tau and μ Cep will help in improving the model and will open a new way to study convection and mass loss in massive evolved stars. Moreover, new joint Narval observations with interferometric observations are planned.

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