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THE MAGNETIC FIELD OF THE SUPERGIANT STAR ζ ORI A

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Abstract. We present the results obtained on the O9.7 supergiant ζ Ori with the spectropolarimeter NARVAL at the 2M Telescope Bernard Lyot atop Pic du Midi (France). We detected the presence of a weak magnetic field of about 50-100G, making ζ Ori the third O star known to host a magnetic field and the first magnetic O star with a 'normal' rotationnal velocity. The magnetic field of Zeta Ori is the weakest magnetic field ever detected on a massive star and is lower than the thermal equipartition limit (about 100 G). By fitting synthetic spectra (obtained from NLTE stellar atmosphere models), we derived the physical properties of ζ Ori. This lattest is a 40 $M_\odot$ star, with a radius of 25 $R_\odot$ and appears quite evolved with an age of 5-6Myr. Despite its evolutionnary status, ζ Ori does not show signs of nitrogen surface enrichment. Concerning the wind of ζ Ori, we estimated a mass loss rate of about $2{\times}10^{-6}$ $M_\odot.yr^{-1}$. The magnetic topology of ζ Ori is apparently more complex than a simple dipole and involves two main magnetic polarities located on both sides of the northern hemisphere. Our data also suggest that ζ Ori rotates in about 7.0 days and is about 40 degrees away from pole-on to an Earth-based observer. Despite its weakness, the detected field appears sufficient to affect significantly the wind structure: the corresponding Alfvén radius is however very close to the surface of the star, thus generating a rotational modulation in wind lines different than that reported on the two other known magnetic O stars.

Finally, the rapid rotation of ζ Ori with respect to θ^1 Ori C is surprising since both stars have similar unsigned magnetic fluxes (once rescaled to the same radius). This may indicate that the field of ζ Ori is not a fossil remnant (as opposed to that of θ^1 Ori C and HD191612) but rather the result of exotic dynamo processes produced through MHD instabilities.

1 Introduction

Magnetic fields are detected in a large fraction of cool stars (typically solar-type and later stars), with a complex topology due to dynamo mechanisms occuring in the outer convective layers. In comparison, only a handle of massive stars are known to host a magnetic field, principally chemically peculiar A and B stars. Among O stars, only HD191612 and θ^1 Ori C have a magnetic field.

In massive and luminous stars, it is commonly admitted that the field is not of dynamo origin (the outer layers of these stars being not convective but radiative) but rather a fossil field trapped when the star formed. Theoretical models predict that these fields have a strong impact on the evolution of the star, modifying the internal rotation and enhancing the transport and mixing of species, resulting in a surface chemical enrichment (Maeder & Meynet 2003, 2004, 2005). They can also influence the stellar winds, by confining it along the field lines (ud Doula & Owocki 2002).

Nevertheless, these theoretical findings suffer of a lack of observationnal and statistical support, due to the relative difficulty to detect magnetic fields in the most massive stars. The limited knowledge we have about the

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existence and the statistical properties of magnetic fields in massive O stars is mostly due to the fact that these fields are difficult to detect. Absorption lines of O stars are both relatively few in number in the optical domain, and generally rather broad, decreasing dramatically the size of the Zeeman signatures that their putative fields can induce. With the advent of the new generation spectropolarimeters, such as ESPADONS at CFHT and NARVAL at TBL, detection of the expectedly weak magnetic fields in massive stars becomes within range.

In this context we embarked in october 2007 a campaign of detection of magnetic fields in massive O stars, using the spectropolarimeter NARVAL. Among the observed stars, we found a magnetic field in the O9.7 supergiant ζ Ori. We present here the results obtained from the spectropolarimetric analysis of this star.

2 Observations

ζ Ori A was observed during seven nights in 2007, from October 18 to October 25; the spectropolarimetric observations were collected with NARVAL at TBL and the spectropolarimetric data were reduced with the fully automatic reduction package Libre ESpRIT (Donati et al. 1997; Donati et al., in prep). The spectra cover wavelengths between 370 and 1050 nm and the resolving power is R=65000. In total, 292 circular-polarization sequences were obtained, each consisting of four individual subexposures taken in different polarimeter congurations. We applied Least-Squares Deconvolution (LSD; Donati et al. 1997) to all observations, with a line list especially constructed for ζ Ori, keeping only the lines unaffected by wind contributions (emission, shift in wavelength). From those lines we produced a mean circular polarization profile (LSD Stokes V profile), a mean check (N for null) profile and a mean unpolarized profile (LSD Stokes I profile) for each spectrum. On Oct. 24, the detection probability exceeds 99%, with a reduced-χ^2 value (compared to a null-field, $V = 0$ profile) of 1.33. Similar (though less clear) Zeeman signatures are also observed during the other nights.

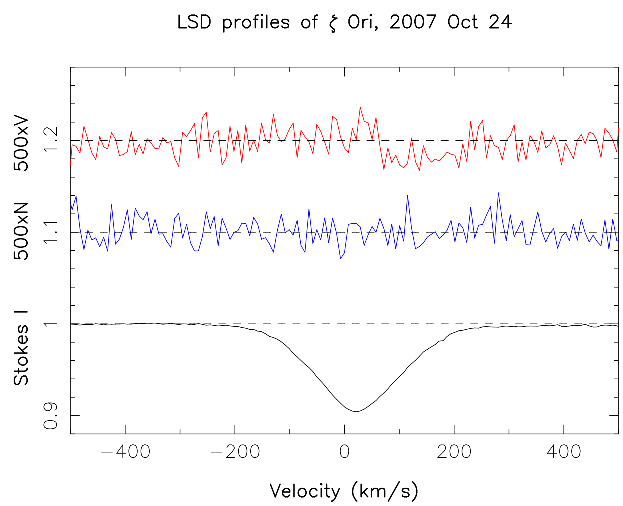

Fig. 1. LSD Stokes V (top), null N (middle) and Stokes I profiles of ζ Ori acquired on october 24. The V and N profiles are expanded by a factor 500 and shifted upwards by 1.2 and 1.1 respectively for more clarity. We can observe a Zeeman signature in the Stokes V profile while the null profile does not show spurious signal.

3 Spectral analysis: physical parameters

We performed the (unpolarized) spectral analysis with NLTE, line-blanketed models calculated with the radiative transfer code CMFGEN (Hillier & Miller 1998; Hillier et al. 2003). Effective temperature was derived from HeI and HeII photospheric lines while surface gravity was derived from the wings of hydrogen Balmer lines (H_δ, H_β and H_ϵ). We gave particular interest to CNO abundances, which were derived from the photospheric lines of each element. An interesting point is that ζ Ori does not show any enrichment in nitrogen or depletion in carbon. The wind parameters ($\dot{M}$ in particular) were derived from the H_α profile. Since this profile showed variations throughout the run, we derived a maximum and a minimum value of the mass loss rate $\dot{M}$ when H_α presented a maximum (respectively minimum) emission (Fig. 2).

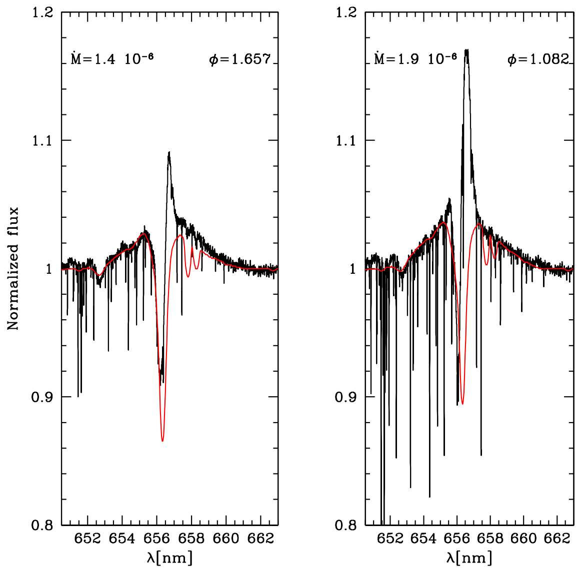

Fig. 2. Example of determination of the stellar parameters, here the minimum and the maximum mass loss rates based on the wings of the H_α profile. In black bold line is represented the spectrum observed with Narval and the red line is our best fit model.

Spectral type	O9.7 Ib
Distance (pc)	414.
Rotation Period (d)	7.0
v sin i (km.s^{-1})	110.
T_{eff} (K)	29500
log g (cgs)	3.25
log L ($L_\odot$)	5.7
M_* ($M_\odot$)	48.
ξ_t (km.s^{-1})	10.
$\dot{M}$ ($M_\odot$.yr^{-1})	1.4 - 1.9
v_∞ (km.s^{-1})	2100.
f_∞	0.1
v_{cl} (km.s^{-1})	200.
v_{rad} (km.s^{-1})	45.
y	0.1
$C/C_\odot$	1.
$N/N_\odot$	1.
$O/O_\odot$	0.5

Fig. 3. Summary of the physical parameters derived from the spectral analysis.

Fourier transforms of photospheric lines indicate a rotationnal velocity of 110 km.s^{-1}. In addition we estimated a rotation period of 7 days based on the cycle of variations of different lines. This implies that ζ Ori is seen at 40 degrees away from pole-on to an Earth-based observer.

4 Spectropolarimetric analysis: magnetic field

The Zeeman signatures were modelled with the imaging code designed by Donati et al. (2006). The code reconstructs the magnetic topology at the surface of the star using spherical harmonics expansion. The reconstrued field is mapped in Fig. 4, assuming either a simple dipole field or a more complex magnetic geometry (limited to $\ell = 3$). The second, more complex, topology was preferred since it provides a unit χ^2_ν fit to the data while a simple dipole gave a χ^2_ν significantly larger than 1. The reconstructed magnetic field has a strength of ± 61 G and an inclination angle of 83 degrees with respect to the rotation axis.

Calculation of the wind confinment parameter showed that the magnetic field measured on ζ Ori is just sufficient not to confine, but to distort the wind, which is compatible with the observed variability in H_α profile and some other lines.

When compared to the other two massive magnetic stars, one would expect ζ Ori to rotate, if not as slowly as HD 191612 (whose intrinsic magnetic flux is much higher), at least more slowly than θ^1 Ori C (whose intrinsic magnetic flux is similar) given its later evolution stage; this is however not what we observe. No more than speculations can be proposed at this stage. One possibility is that the magnetic field of ζ Ori is not of fossil origin (as opposed to that of θ^1 Ori C and HD 191612) but rather dynamo generated, making the rotational evolution of ζ Ori and θ^1 Ori C hardly comparable. The detected magnetic field is indeed much weaker than the critical limit above which MHD instabilities are inhibited (about six times the equipartition field or 600 G in the case of ζ Ori (Aurière et al. 2007) and may thus result from exotic dynamo action; the non-dipolar nature of the detected field could be additional evidence in favour of this interpretation, fossil fields being expected to have very simple topologies in evolved stars.

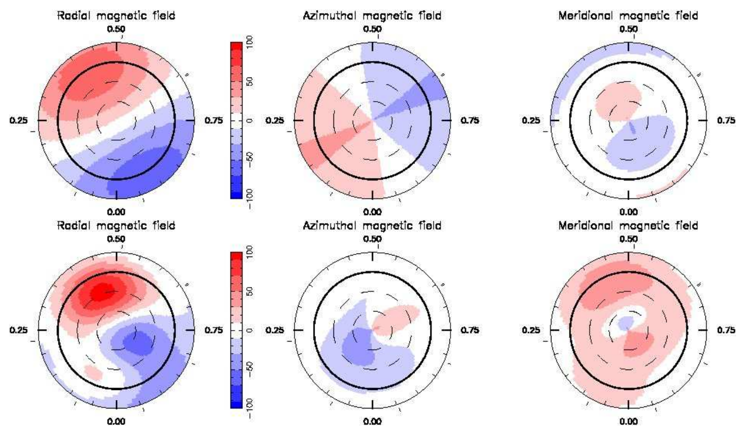

Fig. 4. Reconstructed magnetic topology of ζ Ori. The top figure assumes a dipolar field while the bottom figures assumes a more complex topology. For each topology, the three field components are displayed from left to right and the fluxes are labelled in G. The star is represented in flattened polar projection. The equator is represented by the bold circle and the parallels in dashed lines. The radial ticks depicted around each plot represent the phases of observations.

5 Conclusion

We made a complete spectropolarimetric analysis of the supergiant O9.7 star ζ Ori. We derived its stellar and wind parameters and highlighted the presence of a magnetic field. It is clear that this magnetic field has an impact on the wind of ζ Ori, through the spectral modulations we observed. The different characteristics of the field also ask the question of its origin; while a fossil field is generally admitted for massive stars, the field of ζ Ori would be likely dynamo generated.

New observations through several periods are necessary to confirm and expand our results, allowing a more precise determination of the rotation period and giving more constraints on the magnetic topology of ζ Ori. Moreover, this will bring informations on an hypothetic variation of the magnetic strength on a timescale of one year.

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