An observational study of mixing in fast-rotating massive stars: description of the method and very first results

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Motivation

Collecting He and CNO abundances for a large sample of fast-rotating massive stars is crucial for addressing the efficiency of rotational mixing in these objects. This is becoming a pressing issue following the recent recognition based on observations by the 'VLT-FLAMES Survey of massive stars' that fast rotators can show no signs of deep mixing contrary to the predictions of models (Hunter et al. 2009; Brott et al. 2011).

The project

We plan to determine the abundances of the key elements indicators of mixing in a sample of fast-rotating, bright OB dwarfs in the solar neighbourhood. We present here the method and the very first results for two of the fastest rotating OB stars known (vsini of about 400 km s^{-1}): HD 93521 and ζ Oph. The results for HD 93521 have already been presented by Rauw et al. (2012). We focus here on our new study dedicated to ζ Oph.

The targets

These two stars share many similarities:

- They have the same spectral type (O9 V) and vsini within the errors (~390 km s^{-1}).
- They are non-radial pulsators (e.g., Kambe et al. 1997; Rauw et al. 2008).
- They are runaways. HD 93521 is located far above the Galactic plane and far away from any site of star formation. ζ Oph is believed to originate from a close massive binary in the Upper Scorpius association which experienced a supernova explosion about 1 Myr ago (the primary is now identified as the pulsar PSR B1929+10; Tetzlaff et al. 2010).

Determination of parameters

The atmospheric parameters and helium abundance by number, $y = N(\mathrm{He})/[N(\mathrm{H}) + N(\mathrm{He})]$, are estimated by finding the best match between a set of observed H and He line profiles and a grid of rotationally-broadened, synthetic profiles. They have been computed using the non-LTE line-formation code DETAIL/SURFACE and Kurucz models with a helium abundance twice solar. A microturbulence of 10 km s^{-1} was adopted.

An iterative scheme is used: Teff is taken as the value providing the best fit to the He I and He II features with the same weight given to these two ions, logg is determined by fitting the wings of the Balmer lines and y by fitting the He I lines.

Our analysis is based on our own or archival high-resolution spectra (ELODIE, FEROS or SOPHIE).

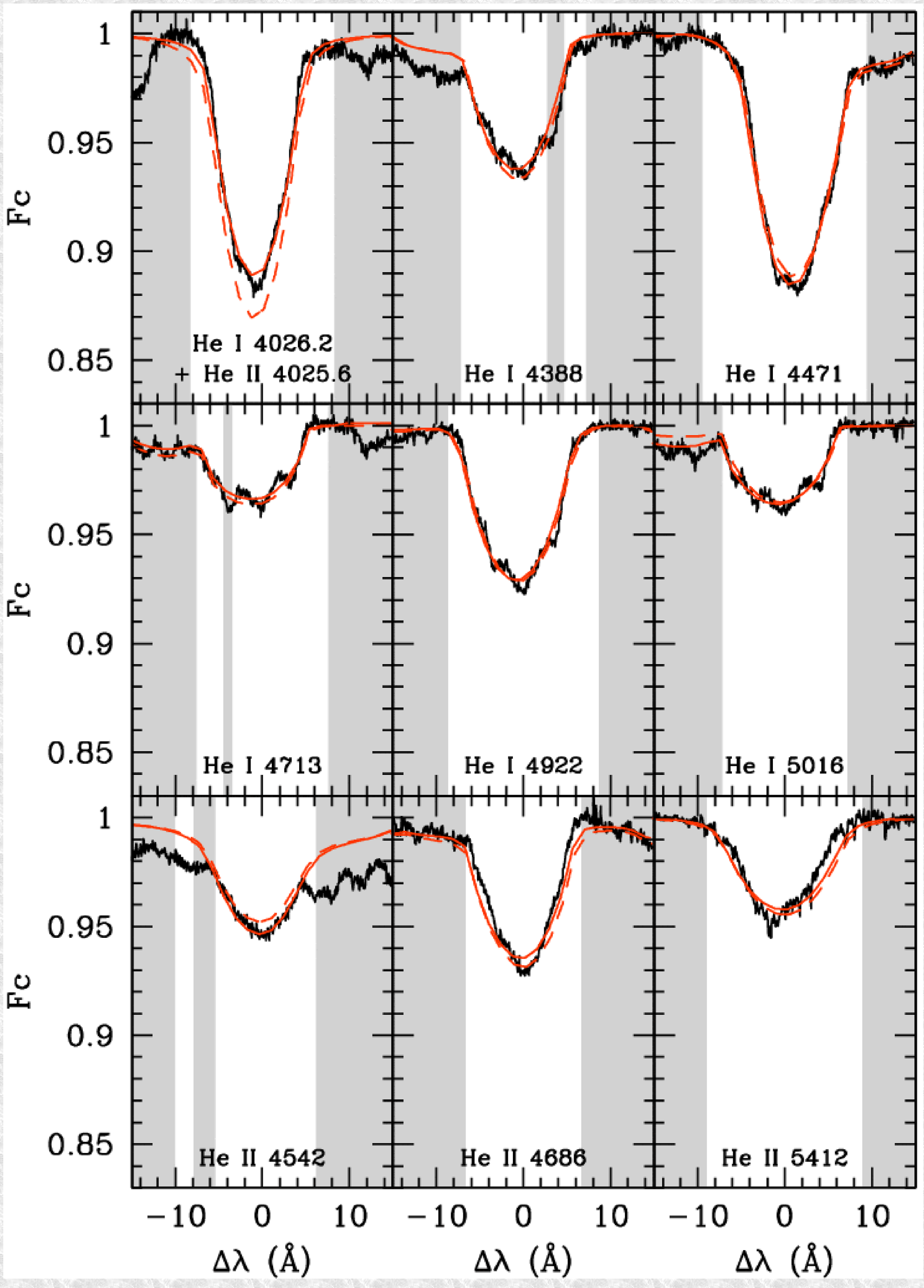

Fig.1 – Comparison for ζ Oph between the FEROS (black) and best-fitting He synthetic line profiles (solid red). The dashed, red lines show the line profiles computed for the final, mean parameters. The light grey-shaded areas delineate the regions where the quality of the fit has been evaluated.

Determination of CNO abundances

Once the parameters are determined, the CNO abundances are derived by fitting synthetic profiles to three spectral domains containing lines of at most two of these species and for which the contribution of other elements can be neglected.

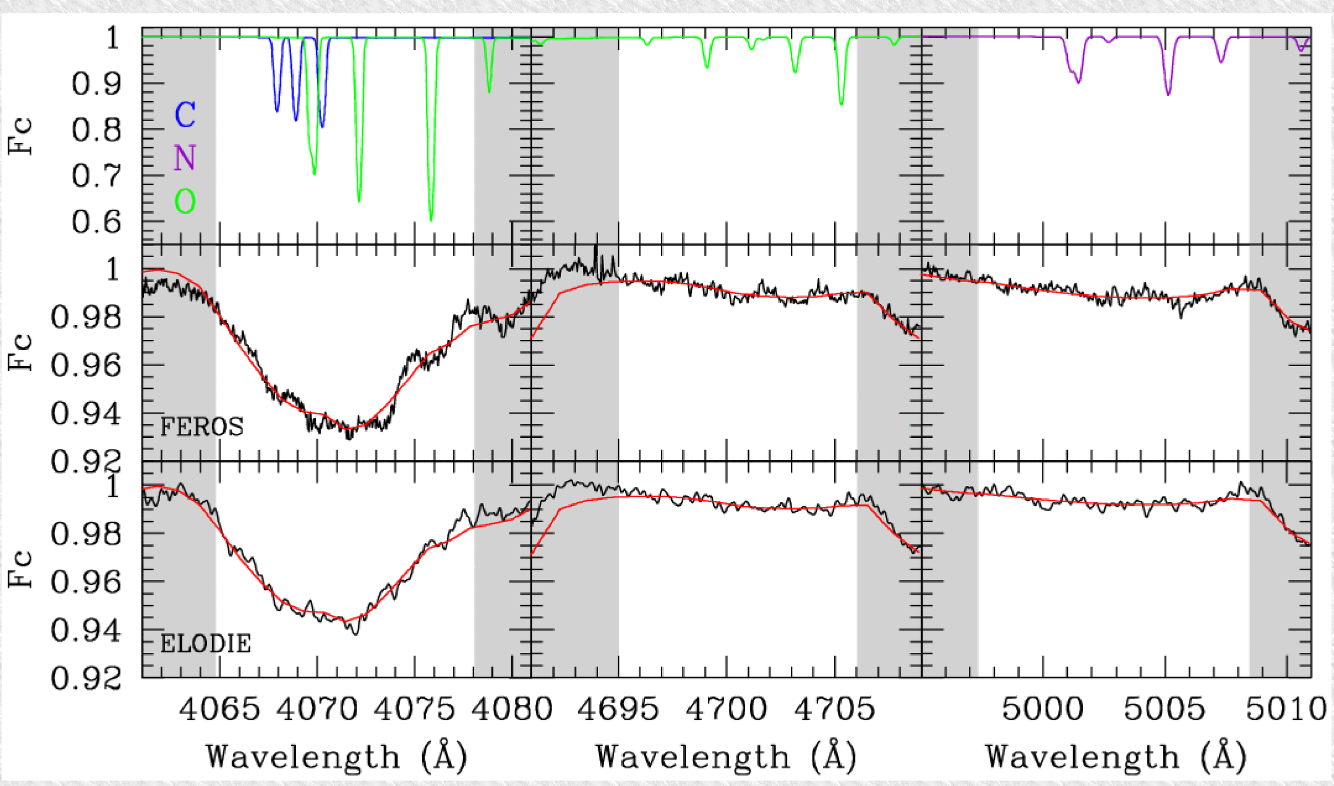

Fig.2 – Comparison for ζ Oph between the observed (black) and best-fitting synthetic metal line profiles (red). The light grey-shaded areas delineate the regions where the quality of the fit has been evaluated. The top panels show the (non-rotationally broadened) synthetic profiles computed for the final parameters and abundances.

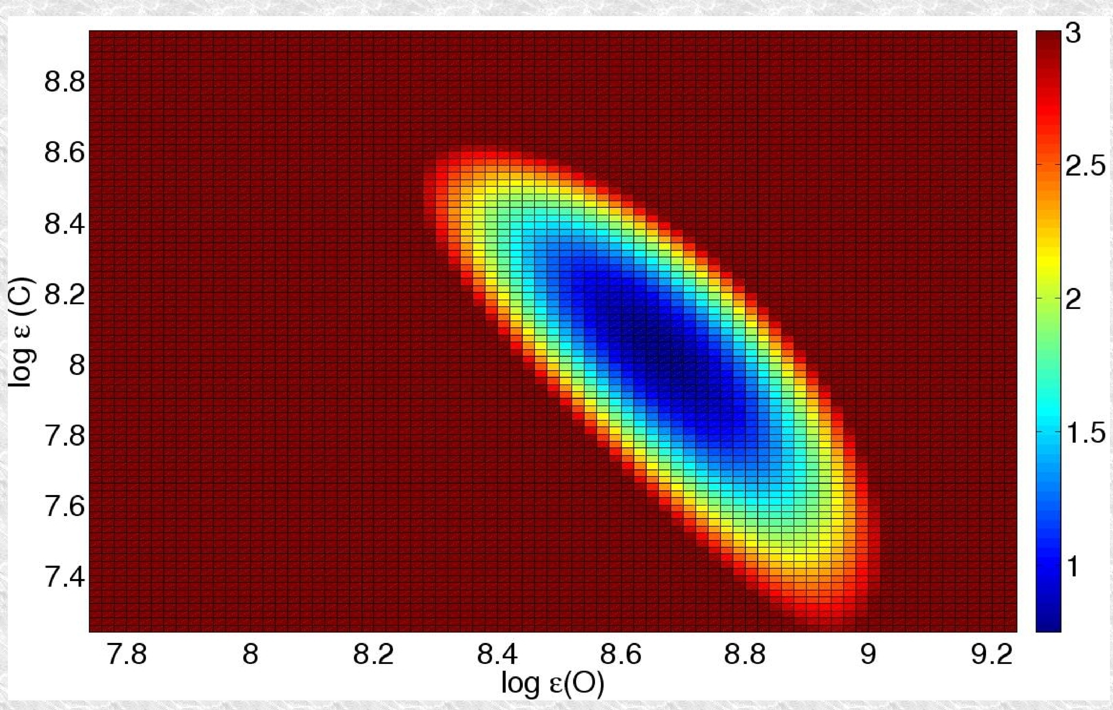

Fig.3 – Variation of the fit quality in the region 4065-4078 Å for different combinations of the C and O abundances (colour coded as a function of the reduced χ^2) in the case of the FEROS spectrum of ζ Oph.

Validation

Three narrow-lined, O9-B0.2 dwarfs were analysed to validate the procedures developed to derive the atmospheric parameters and abundances: 10 Lac, HD 57682, and τ Sco. These stars had their parameters and abundances derived from standard, curve-of-growth techniques (Rauw et al. 2012, and references therein). Within the errors, the values derived from spectral synthesis (either using the observed spectrum or that broadened to the same vsini as the main targets) match the reference ones inferred from the classical analysis.

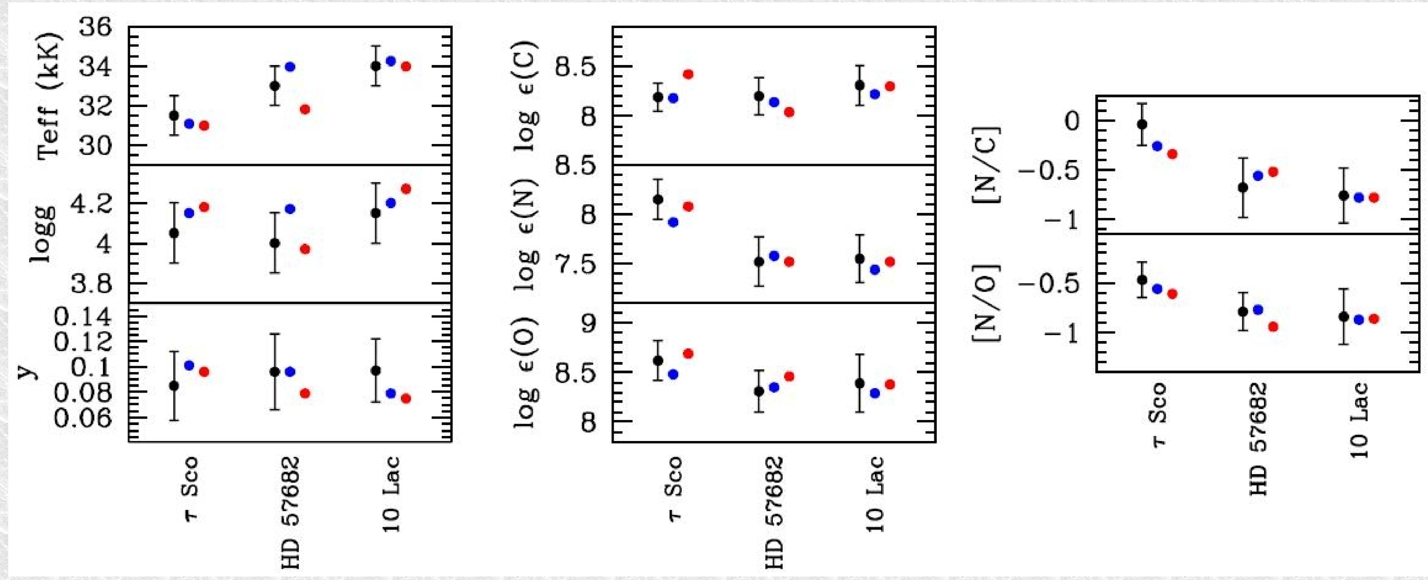

Fig.4 – Comparison for the reference stars between the parameters and abundances derived using classical techniques (black) and with spectral synthesis (blue). The red points show the results of the synthesis applied to the spectra broadened by the same vsini as the main targets (390 km s^{-1}).

Main results

	T_{eff} [K]	log g	y	log ε(C)	log ε(N)	log ε(O)	[N/C]	[N/O]
HD 93521								
sph. symm.	30 918±850	3.67±0.17	0.178±0.027	7.56±0.19	7.97±0.23	8.24±0.25	+0.41±0.24	–0.27±0.17
non sph. symm.	—	—	—	7.62±0.19	8.00±0.23	8.28±0.25	+0.38±0.24	–0.27±0.17
ζ Oph								
sph. symm.	32 087±850	3.78±0.17	0.147±0.027	8.09±0.19	7.88±0.23	8.40±0.25	–0.21±0.24	–0.53±0.17

Table 1 – Summary of the results. The row 'non sph. symm.' shows the results when taking the oblateness of HD 93521 into account (see Rauw et al. 2012). The errors have been estimated based on the differences for the standard stars between the values found and the reference ones, the results obtained using different spectra, and the systematic errors related to the normalisation and the choice of the microturbulence.

These stars follow within the errors the predictions for CNO-cycled material dredged up to the surface. HD 93521 is substantially nitrogen enriched, but this is less the case for ζ Oph. If previously part of a binary system where mass transfer has taken place, it is conceivable that Roche-lobe overflow has considerably spun up ζ Oph, but that little material from the mass donor has been accreted (e.g., Langer et al. 2008). The two stars also show evidence for enhanced helium.

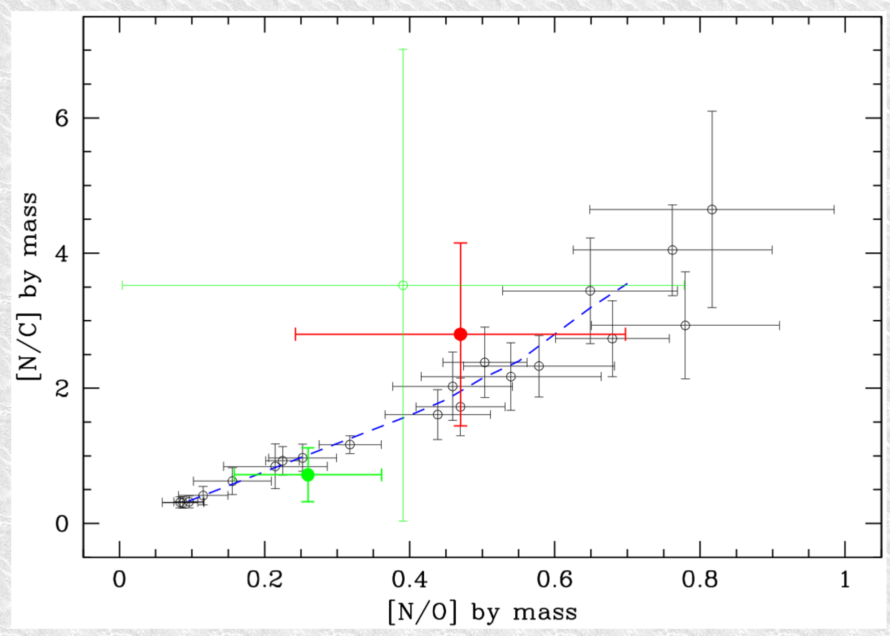

Fig.5 – Dependence between the [N/C] and [N/O] abundance ratios (by mass). Open black circles: B stars from Przybilla et al. (2010), red filled circle: HD 93521, green filled circle: ζ Oph (the open circle shows the results of Villamariz & Herrero 2005). The dashed line shows the predictions of Geneva models (Przybilla et al. 2010).

Based on a set of Geneva models, we estimate evolutionary ages of the order of 6 Myrs. The star ζ Oph is believed to have been ejected from Upper Scorpius. Its age is consistent with that often reported in the literature for this association (~5 Myrs; e.g., Preibisch et al. 2002).

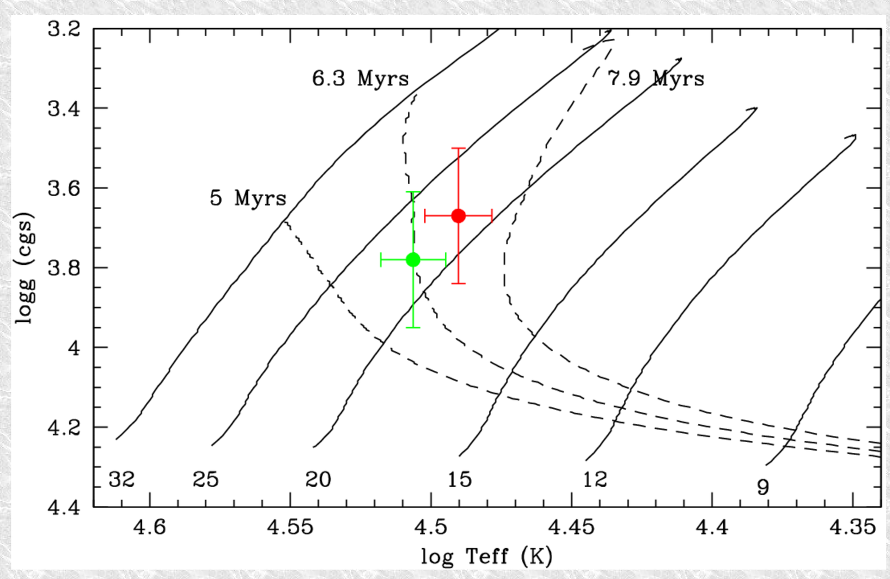

Fig.6 – Position of the two targets in the (logg-logTeff) plane (red: HD 93521, green: ζ Oph). Geneva evolutionary tracks for stars initially rotating at 40% of the critical velocity and for initial masses ranging from 9 to 32 solar masses are overplotted (Ekström et al. 2012). Isochrones for 5, 6.3, and 7.9 Myrs are also indicated (dashed lines).

Further work and perspectives

- Apply the analysis of ζ Oph to archival HARPS and UVES spectra in order to better assess the uncertainties related to the data and the reduction procedures (especially normalisation).
- Analyse ζ Oph taking the oblateness of the star into account. Our previous investigation for HD 93521 suggests that it is unlikely to significantly affect our conclusions (Table 1).
- Compare our abundance results with the predictions of theoretical models.
- Observation time has been granted at the Hamburg Robotic Telescope (HRT) to monitor in spectroscopic mode a number of fast-rotating OB dwarfs. These data will be used to derive both their chemical composition and their binary status.

References

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