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First results on the multi-element Doppler imaging of the CP star HD 3980

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Abstract. We present the first results of an ongoing analysis of the inhomogeneous elemental surface distribution in the lithium-rich magnetic Ap star HD 3980. To derive surface maps for Fe, Pr, Li, Gd and Cr the Doppler imaging inversion code INVERS12 was applied. For this work high resolution time-series observations obtained with the VLT Ultraviolet and Visual Echelle Spectrograph (UVES) were used.

Key words: stars: chemically peculiar – stars: abundances – stars: individual: HD 3980

1. Introduction

HD 3980 is a cool Sr-Cr-Eu Ap star (Bidelman, Macconnell 1973) with a spotted lithium surface distribution (e.g. Drake *et al.*, 2004; Drake *et al.*, 2005). The star shows variations of spectral line profiles and brightness, with a rotation period close to 4 days (Maitzen *et al.*, 1980).

2. Observations

In this work we analyzed observations obtained at the ESO-VLT with UVES (074.D-0392, 076.D-0535). Nearly 20 high resolution spectra $R = 110\,000$ correspond to 8 phases, which are sampled over the rotation period (see Fig. 3). The results of our Doppler imaging analysis of lines in the region from 6100 Å - 6800 Å are presented below.

3. Fundamental parameters and abundances

By applying the calibration of Moon and Dworetsky (1985) to Strömgren photometry (Hauck, Mermilliod 1998) using TempLogG^{TNG} (Kaiser, 2006), the fundamental atmospheric parameters $T_{\rm eff} = 8340$ K and $\log g = 4.3$ were determined. An initial scaled solar model was calculated with ATLAS9 (Kurucz, 1993). Synthetic spectra were computed with Synth3 (Kochukhov, 2007) and linelists extracted from the VALD database (Piskunov *et al.*, 1995; Kupka *et al.*, 1999).

Equivalent widths were measured to improve the atmospheric parameters iteratively and derive element abundances. The resulting parameters are:

- $T_{\rm eff} = 8500 \pm 250\,{\rm K}$
- $\log g = 4.0 \pm 0.1$ and
- $v_{\rm mic} = 1.0 \pm 0.3\,{\rm km\,s^{-1}}$.

No microturbulence is expected in the atmosphere of HD 3980, because the magnetic field is likely to suppress convective motion. Hence, the formally derived value of $1\,{\rm km\,s^{-1}}$ probably reflects magnetic intensification. The $v \sin i$ of $22.3 \pm 1\,{\rm km\,s^{-1}}$ was determined by fitting iron lines possessing a low Landé factor.

These final values were used to calculate an individual model atmosphere with the LLmodels code (Shulyak *et al.*, 2004) and new synthetic spectra for further analysis.

By fitting observed line profiles with synthetic spectra, previously determined abundances were refined. Additional elements which could only be found in line blends were then analyzed. Fig. 1 shows abundances of several elements relative to the solar values (Asplund *et al.*, 2005).

Maitzen *et al.* (1980) determined a period of 3.9516 ± 0.0003 from Strömgren v photometry. The light curve shows a double wave pattern with an amplitude of 0.13 mag. Catalano *et al.* (1998) confirmed the period with near infrared measurements. For $\log L/L_\odot$ several values are already given in the literature: 1.249 ± 0.032 (Drake *et al.*, 2004), 1.296 ± 0.052 (Hubrig *et al.*, 2007) and 1.244 ± 0.035 (Kochukhov, Bagnulo 2006), which agree well within the error bars. A $\log L/L_\odot = 1.24 \pm 0.04$ was adopted for calculating the inclination angle of the rotation axis to the line of sight.

With these values a radius of $1.93 \pm 0.13\ R_\odot$ and hence an inclination angle of $65 \pm 12^\circ$ could be derived. Maitzen *et al.* (1980) found the magnetic field to vary with a 4-day period and an amplitude of the order of 2 kG, which agrees very well with the measurements of Hubrig *et al.* (2006).

4. Doppler imaging

Inhomogeneous abundance distributions on the stellar surface can be detected as line profile variations due to stellar rotation and the Doppler effect. The Doppler imaging technique uses the information contained in the time series of spectra and inverts them into elemental surface distributions.

The Doppler imaging code INVERS12 developed by N. Piskunov and refined by O. Kochukhov (Kochukhov *et al.*, 2004) fits line profiles iteratively. The code also allows one to investigate the abundance structures of different elements in blends and different wavelength intervals simultaneously (see e.g. Fig. 3, Gd–Fe).

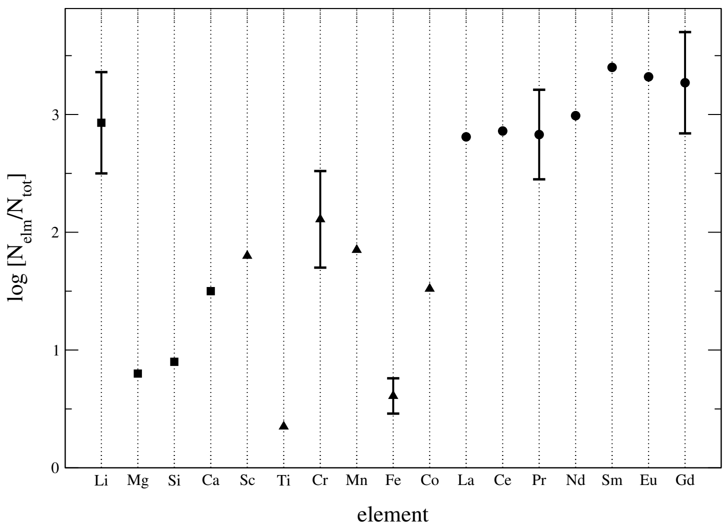

Figure 1. Element abundances of HD 3980 relative to the sun. Error bars are attached to already investigated elements, and correspond to variations during the rotation period, as can be seen in section 4. For the elements without error bars variations of the same order of magnitude are expected, but not yet determined by Doppler imaging. The squares represent the light elements, triangles iron peak elements and circles rare earth elements.

So far we have determined chemical surface compositions for Fe, Li, Pr, Gd and Cr, as illustrated in Fig. 2. All elements show strong overabundances in spots located at the rotational equator. In particular the REE (Pr and Gd) and Li show spots of enhanced composition around phases 0.4 and 0.9. The Li map gives a very similar structure to the surface distribution of Li for HD 83368 (Kochukhov *et al.*, 2004), where the spots coincide with the magnetic poles. HD 83368 has an inclination of 87° between rotation axis and magnetic field axis, which might also apply to HD 3980, judging from the similar geometry of the Li spots. The extrema of the magnetic field curve of HD 3980 coincide with the spots of Li and the REE, assuming a dipolar configuration.

As it can be seen in Fig. 3, the fits of the combination of the Gd - Fe blend at 6380 Å and Fe at 6230 Å are not perfect, but the general variability pattern is reproduced. Further analyses will lead to more accurate results. The next steps will include the investigation of more lines to improve the determined abundance patterns. In addition we will perform Doppler imaging for further elements.

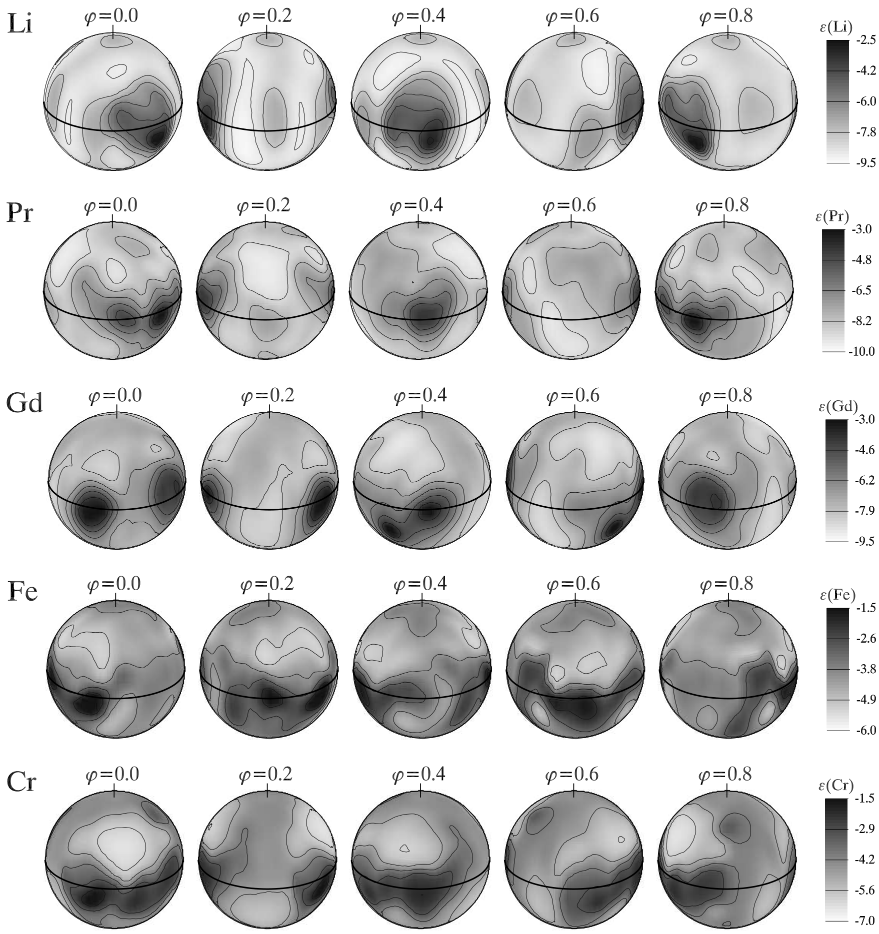

Figure 2. Surface abundance distributions of Li, Pr, Gd, Fe and Cr. Darker areas correspond to higher elemental concentrations. The star is displayed at five equidistant rotation phases at an inclination angle $i = 65^\circ$. The thick solid line denotes the location of the rotational equator, while the contours, comprising areas of equal abundance, are plotted with a 1.0 dex step.

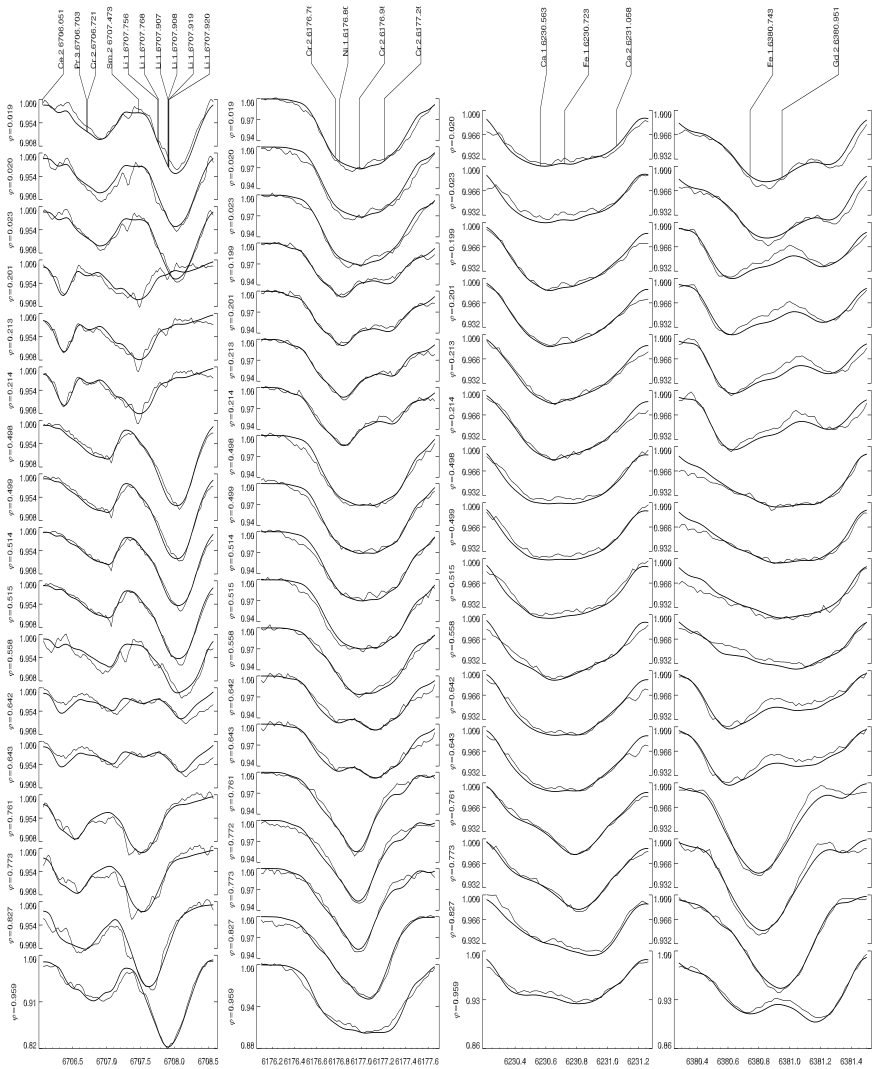

Figure 3. Comparison of observed and computed variations of Pr III 6706.7Å, Li I 6708.8Å (first column), Cr II 6176.9Å (second column), Fe II 6230.7Å (third column) and Fe I 6380.7Å with Gd II 6380.9Å. The vertical shift of the spectra denotes their different rotation phases. The Gd-Fe blend at 6380 Å was calculated simultaneously with Fe II 6230 Å. The blend with Pr and Li was used to determine the distributions for both elements. Other ions, for example Ce II contribute marginally to the blends. They were considered to be constant over the rotation period in these calculations.

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