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3D atmospheric structure of the prototypical roAp star HD 24712 (HR1217)

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Abstract. The first analysis of the structure of the surface magnetic field of a rapidly oscillating Ap (roAp) star is presented. We obtain information about abundance distributions of a number of chemical elements on the surface of the prototypical roAp star HD 24712 and about magnetic field geometry. Inverting rotationally modulated spectra in Stokes parameters I and V obtained with the SOFIN spectropolarimeter attached to the NOT, we recover surface abundance structures of sixteen different chemical elements, including Mg, Ca, Sc, Ti, Cr, Fe, Co, Ni, Y, La, Ce, Pr, Nd, Gd, Tb, and Dy. Our analysis reveal a pure dipolar structure of the stellar magnetic field and surprising and unexpected correlations of the various elemental surface abundance structures to this field geometry. Stratification analysis at phases of both magnetic extrema enable us to obtain the vertical dimension in the atmosphere of HD 24712. High time resolved spectroscopic data and observations obtained with the MOST space photometer give us the possibility to compare (Lüftinger, 2007) our results to detailed pulsational analysis.

Key words: stars: chemically peculiar – stars: magnetic fields – methods: numerical – techniques: polarimetric – stars: individual: HD 24712

1. Introduction

To date very little is known about the origin and structure of magnetic fields in peculiar A (Ap) stars and their connection with surface abundance patches, pulsation, and stratification. Ap stars exhibit magnetic fields that appear to be highly ordered, very stable, and often very strong. Many of them also show dramatic line profile variations synchronized to stellar rotation, which is attributed to oblique magnetic and pulsation axes and to the presence of a non-uniform distribution of chemical elements on the stellar surface. The spectra of Ap stars also exhibit a remarkable variety of, often unidentified, spectral line features. Ryabchikova *et al.* (2004) find overabundances of up to a few dex for some iron peak and especially the rare earth elements (REE), while other chemical elements are found to be underabundant compared to the solar value. Rapidly oscillating Ap (roAp) stars, in addition, exhibit high-overtone, low-degree, non-radial *p*-mode pulsations with periods of 6 – 21 minutes. The modulation of the projected pulsation amplitudes with the visible magnetic field structure indicates a close connection between the magnetic field and the pulsation mechanism. HD 24712 (HR 1217, DO Eri), discovered to be a pulsator by Kurtz (1982), is the best studied roAp star exhibiting light (Wolff, Morrison 1973), spectrum and magnetic variations. We determined atmospheric parameters for this star of $T_{\rm eff}$= 7350 K and $\log g = 4.2$, and derived $v_{\rm e} \sin i$= 5.6 km s^{-1}.

2. Observations

Spectropolarimetric data of HD 24712 was obtained using the high resolution échelle spectrograph SOFIN attached to Nordic Optical Telescope (NOT, La Palma, Spain) with a nominal resolving power of ≈ 80 000. Rotational phases of HD 24712 were determined using to the ephemeris and rotation period obtained by Ryabchikova *et al.* (2005): HJD($\langle B_{\rm z}\rangle_{\rm max}$)=2 453 235.18(40)+12.45877(16) d.

Spectroscopic observations carried out during DDT (274.D-5011), that was granted with the UVES spectrograph ($R \approx 80\,000$) attached to the 8.2-m telescope UT2 (VLT, ESO, Chile) and a dearchived spectrum of the UVESPOP (www.sc.eso.org/santiago/uvespop/) data base were used to determine the vertical abundance profiles of Fe around positive magnetic extremum and the magnetic eqatorial phase.

3. Magnetic field geometry and abundances

The geometry of the magnetic field on the surface of HD 24712 was determined using seven different Fe I and five different Nd III lines suitable for magnetic Doppler imaging. The tilt i and the azimuth angle of the stellar rotational axis Θ, were used as derived by Bagnulo *et al.* (1995): $i = 137°$ and $\Theta = 4°$. We found a clear dipolar geometry (Fig. 1) as the best fit to the observed Stokes I and V line profiles in our magnetic Doppler imaging analysis and the resulting magnetic field strength varies between +2.2 kG and +4.4 kG. The surface abundances of Fe and Nd, which were mapped simultaneously with the magnetic field geometry, are presented in Fig. 2. Abundances of both elements are globally structured. Fe varies between −5.2 and −4.7 dex at its maximum, (slightly underabundant compared to the solar value of -4.59 dex) and Nd is extremely overabundant, varying between −8.0 and −7.0 dex (−10.59 dex solar). Both elements seem to be clearly anticorrelated: Fe is accumulated, where Nd is depleted, and minimum Fe abundance can be found where Nd shows its maximum abundance.

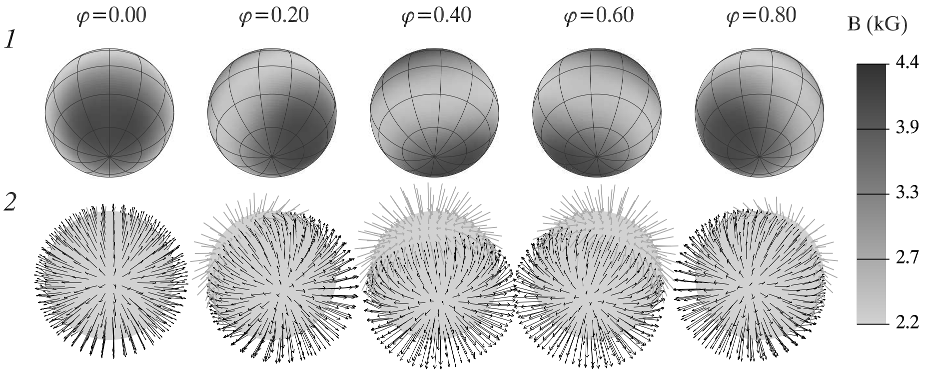

Figure 1. First mapping of the distribution of magnetic field strength (1) and field orientation (2) on the surface of a roAp star. The results reveal a pure dipolar magnetic field geometry with a polar field strength varying between 2.2 kG and 4.4 kG. Above: distribution of the field strength, below: orientation of the magnetic vectors (grey field vectors are pointing inside the stellar surface while black arrows are pointing outwards).

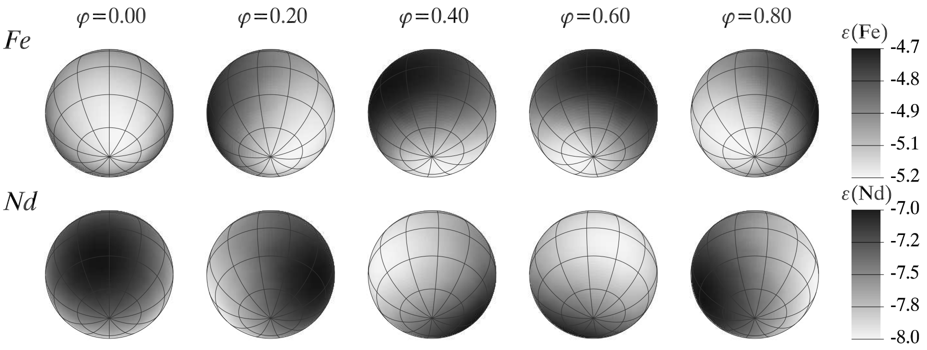

Figure 2. Abundance distribution of Fe and Nd III on the surface of HD 24712. The upper panel presents the surface map of Fe abundance while in the lower panel the distribution of Nd III can be found. The maps were derived using Stokes I and V spectra.

Comparing the abundances of these two elements to the derived magnetic field geometry presented in Fig. 1, we find that the Fe abundance enhancement region is associated with the area where the magnetic equatorial region dominates the visible hemisphere (around $\phi \simeq 0.5$), whereas the Nd map shows its area of maximum abundance during the phase where the positive magnetic pole is visible. Contradicting common expectations both elements are not accumulated

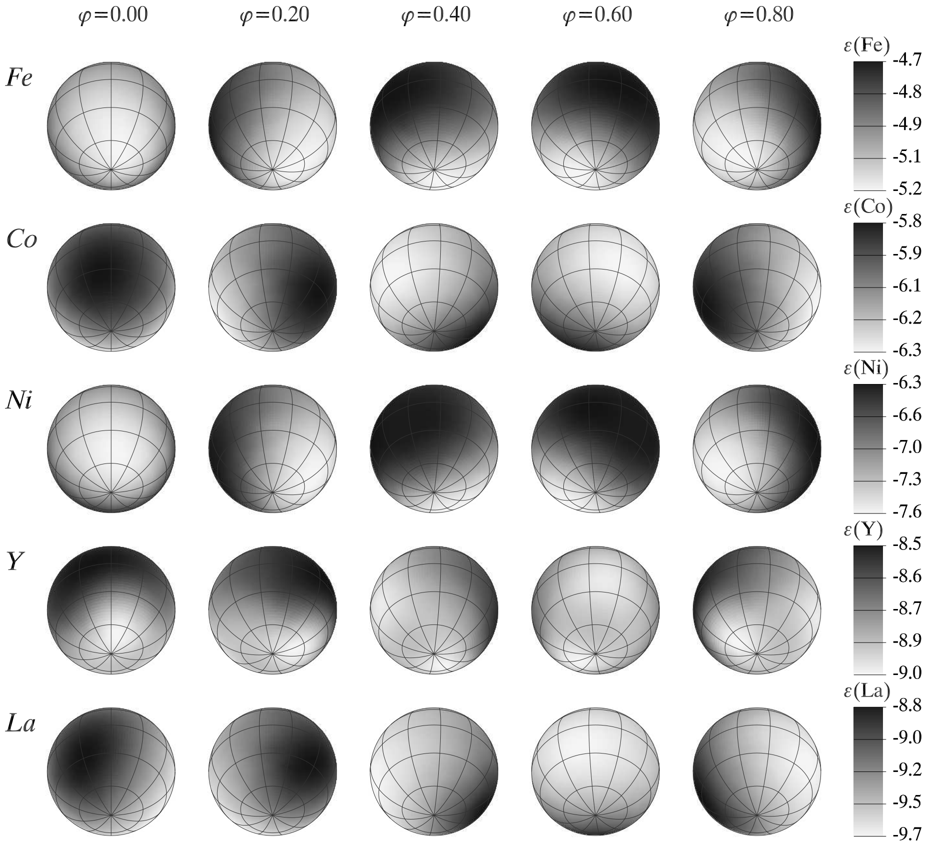

Figure 3. Abundance distributions of Fe, Co, Ni, Y and La on the surface of HD 24712.

or depleted on *both* magnetic poles *or* around the magnetic equator, but follow *either* the region of the positive magnetic phase *or* the magnetic equatorial region. The additional 14 chemical elements we mapped, including Mg, Ca, Sc, Ti, Cr, Co, Ni, Y, La, Ce, Pr, Gd, Tb and Dy, exhibit comparable behaviour. As space is limited here, we can only present a selection of surface abundances (Fig. 3) and refer the reader to Lüftinger (2007) for a detailed description.

4. Stratification of Fe with changing aspects of the magnetic field

For the first time *abundance stratification* with changing aspects of the magnetic field could be determined for a star. We derived the vertical abundance gradients of Fe using DDAFit, a procedure developed by Kochukhov (2007). A

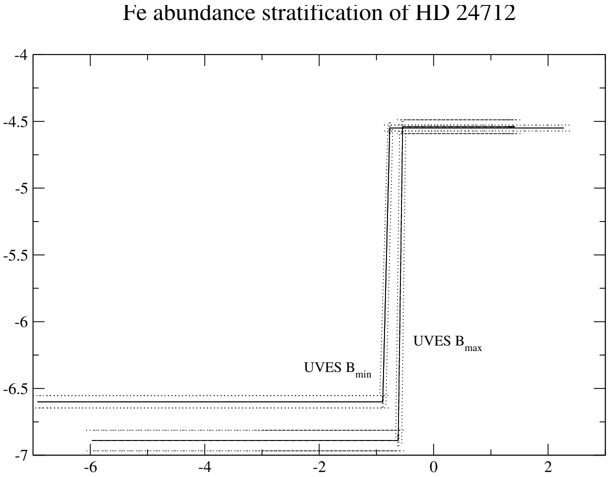

Figure 4. The vertical abundance gradient of Fe within the atmosphere of HD 24712.

one step model was used to determine the vertical abundance profiles. Chemical abundance in the upper atmosphere, the abundance in deeper layers and the vertical position of the abundance step were optimized simultaneously by least squares fitting. The stratification profiles, as presented in Fig. 4, represent a change in Fe abundance from -6.60 ± 0.046 dex in higher atmospheric layers to -4.55 ± 0.022 below $log\tau_{5000} = -0.7$ around the phase where the magnetic equatorial region is visible (left profile). The analysis around the phase where the positive magnetic pole dominates the visible stellar hemisphere (right profile) places the abundance jump in slightly deeper atmospheric layers, around $log\tau_{5000} = -0.5$.

5. Discussion

Observational data in several polarization stages and modelling their shapes via magnetic Doppler imaging enabled us to derive, for the first time, the magnetic field geometry and abundance distributions of numerous elements inhomogeneously distributed over the surface of a roAp star. We obtain a pure dipolar magnetic field structure and elemental abundance patterns that are correlated to this geometry in a surprising way: instead of abundance enhancement or depletion regions on *both* magnetic poles or around the magnetic equator, we observe huge regions of abundance inhomogeneities around *either* the phase where the magnetic equatorial region dominates the visible stellar surface *or* where the positive magnetic pole is visible. In addition, these enhancement or depletion regions for various chemical elements are shifted in longitude relative to each other. This behaviour most likely gives us information how the magnetic field influences the chemical diffusion of the various species within the stellar atmosphere. We tried to correlate our results with simple atomic parameters (like spin orientation, atomic weight, or excitation potential), but did not find any clear evidence for a direct connection. This raises the speculation, as the effect clearly is present, that in stellar interiors penetrated by a magnetic field, there is a more complex interplay of the various atomic characteristics influencing mutual chemical diffusion. This 'chemically stratified tail' of each spot gives hints for diffusion models that try to explain how the magnetic field controls atmospheric diffusion. High-resolution spectroscopic data enabled us to trace the changing vertical structure of Fe within the atmosphere of HD 24712 also with changing aspects of the magnetic field - either the field strength, or, more likely - the magnetic field geometry. So far, we can only speculate, whether these changes in magnetic field strength and orientation are associated with a jump in temperature structure, where higher temperatures would lead to an abundance jump in, e.g., deeper atmospheric layers, or vice versa.

Observations obtained by the MOST space mission (Matthews *et al.*, 2004) and our high time resolved spectroscopic data give us the possibility to compare our results (Lüftinger, 2007) to detailed pulsational analysis (Ryabchikova *et al.*, 2007) revealing additional vertical atmospheric structure.

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The UVESPOP data base, http://www.sc.eso.org/santiago/uvespop/