Magnetic fields of Ap stars from full Stokes spectropolarimetric observations

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Abstract Current knowledge about stellar magnetic fields relies almost entirely on observations of circular polarization. Few objects have been observed in all four Stokes parameters. The magnetic Ap star HD 24712 (DO Eri, HR 1217) was recently observed in the Stokes $IQUV$ parameters with the HARPSpol instrument at the 3.6-m ESO telescope as part of our project at investigating Ap stars in all four Stokes parameters. The resulting spectra have dense phase coverage, resolving power $>10^5$, and S/N ratio of 300–600. These are the highest quality full Stokes observations obtained for any star other than the Sun.

We present preliminary results from magnetic Doppler imaging of HD 24712. This analysis is the first step towards obtaining detailed 3-D maps of magnetic fields and abundance structures for HD 24712 and for other Ap stars that we are currently observing with HARPSpol.

1. Introduction

Magnetic Ap stars are interesting objects that have been investigated in many ways. One objective of those investigations is the interplay between their magnetic fields and chemical spots. However, such studies as a rule only use observations of circular polarization, and in rare cases additional broad-band measurements of linear polarization. The latest spectropolarimetric investigations that have used observations in all four Stokes parameters show that these stars possess strong magnetic fields that are dipolar at large spatial scales, and with significant complexity at small scales [2]. Those investigations also show that magnetic Ap stars have inhomogeneous abundance distributions of many chemical elements [1]. Other analyses of spectroscopic and photometric pulsations [9, 7] show that some chemically peculiar stars have strong abundance gradients in their atmospheres.

Recent advances in observational techniques in spectropolarimetry are capable of bringing new insight towards the understanding of the magnetic Ap stars. The spectropolarimeter mode for the HARPS spectrograph [4] on the 3.6-m ESO telescope permits simultaneous observations in all four Stokes parameters, with spectral resolution greater than $10^5$. Unfortunately, current model atmospheres and imaging techniques, e.g., LLMODELS [8] and magnetic Doppler imaging (MDI) [5], although very powerful in themselves, have various
Figure 1. HARPSpol spectra of HD 24712 in the four Stokes parameters. The spectra plotted in black were obtained around phase zero during magnetic maximum; those plotted in red were obtained at the phase corresponding to magnetic minimum. The different Stokes profiles are offset vertically for clarity. The Stokes $Q$ and $U$ spectra are expanded by a factor of three compared to Stokes $V$ and $I$. Most lines exhibit strong intensity variations with phase, and show strong signatures in linear and circular polarization.

limitations which ultimately prevent us from exploiting the new advances in observational techniques. MDI codes do not incorporate vertical chemical stratification, while empirical stratified model atmospheres do not consider horizontal variations due to stellar surface structure.

We believe it is possible to relax those limitations to the current methods, and to perform simultaneous studies of 3-D chemical and magnetic structures using the highest quality observations in the four Stokes parameters. Such investigations can provide more insight into the relation between chemical spots and magnetic fields, and between horizontal and vertical structures, and will allow us to exploit the exceptional observations to the fullest extent.

2. Spectropolarimetric observations

We have commenced a new program to observe Ap stars in all four Stokes parameters with the HARPSpol spectropolarimeter on the 3.6-m ESO telescope. As our first target we have chosen HD 24712, which is one of the coolest Ap stars and shows both stratification of chemical elements and oblique rotator variations. This star was observed for sixteen nights during 2010–2011, when 43 observations of individual Stokes parameters were obtained. The resulting spectra have S/N ratios of 300–600 and a resolving power exceeding $10^5$. During two observing runs in 2012–2013 we also completed observations for two more objects, HD 125248 and HD 119419. Each now has 12 Stokes $IQUV$ observations with S/N ratios $\sim 200$. In Fig. 1 we present the observed spectra
of HD 24712 in the wavelength region $\lambda 4910–4960$ Å, in all four Stokes parameters. Many individual spectral lines show strong, complex signatures in linear and circular polarization. Many lines exhibit significant polarization signatures as parts of complex blends.

An initial analysis of the full Stokes vector spectropolarimetric data for HD 24712 has been published by Rusomarov et al. [6]; we computed mean line profiles using least-squares deconvolution, and determined magnetic observables from low-order moments of these profiles. We measured the mean longitudinal magnetic field, $\langle B_z \rangle$, with a precision of 5–10 G, and obtained precise net linear polarization measurements. By combining $\langle B_z \rangle$ and the net linear polarization measurements we determined the parameters of the dipolar magnetic field topology. By combining available $\langle B_z \rangle$ measurements we improved the rotational period. The analysis of all $\langle B_z \rangle$ measurements showed no evidence of a significant gradient in the radial magnetic field.

3. Magnetic Doppler Imaging

We present here our preliminary results from the magnetic Doppler imaging of HD 24712. We used the MDI code INVERS10, first introduced by Piskunov & Kochukhov [5], which performs simultaneous and self-consistent reconstruction of the magnetic and chemical maps of a stellar surface using spectra in all four Stokes parameters. The inversion procedure employs synthetic spectra that are calculated by treating in detail the polarized radiative transfer in the atmosphere of the star. The code is written in Fortran and is optimized for running on massively parallel computers using MPI libraries.

To carry out the inversion procedure, we need to supply a model atmosphere and a number of input parameters as well as the observed profiles and line data. We chose an LLMODELS model atmosphere for the stellar parameters presented in [6]. The abundances of the most important elements (Fe-peak elements and REEs) in the model atmosphere were set to the values that correspond to the mean spectrum. Among the (constant) parameters that we need to supply to INVERS10 are the inclination of the stellar axis, $i$, and the obliquity angle, $\beta$. We adopted the values for these parameters derived by Rusomarov et al. [6] for the case of a dipolar magnetic field topology.

In the present paper we are not intending a complete inversion that uses as many lines as possible, so we chose the unblended Nd III $\lambda 5851.54$ Å line, which shows very strong signatures of linear and circular polarization. We set an additional constraint in INVERS10 that keeps the geometry of the magnetic field dipolar. That is needed because HD 24712 shows a mostly positive magnetic pole to the observer.
Figure 2. Abundance distribution maps of Nd on the surface of HD24712, and maps showing a distribution of the magnetic field strength (a), radial component (b), and field orientation (c).

The inversion results of our MDI analysis are illustrated in Fig. 2, which shows that the abundance distribution maps of Nd, and the maps of the magnetic field, are not too far from the results of Lüftinger et al. [3]. Neodymium is distributed in a patch around the visible magnetic pole. Figure 3 compares observations and model profiles for the Nd III line. At this stage one can make an interesting comparison between our results from just one line and the results by Lüftinger et al. [3], who deduced the magnetic field distribution and abundance maps of various elements using only Stokes I and V spectra, also under the assumption of dipole field geometry. When we compare the profiles of Nd III λ5851.54 Å calculated according to their results, we see that Stokes I and V profiles describe our observations quite successfully. However, the Stokes Q and U profiles do not match in amplitude, although they match in morphology. That may be expected since Lüftinger et al. did not incorporate linear polarization data in any way. In any case, our preliminary MDI results show no evidence of significant deviations from dipolar field geometry which have been apparent in other MDI four-Stokes parameter studies of Ap stars [2, 1].

We plan to perform a more detailed MDI analysis of HD 24712 that is based
Figure 3. Observed (dots) and calculated (thick lines) Stokes profiles for HD 24712. The thin lines plot the Stokes profiles calculated according to the Nd abundance maps and magnetic field distribution derived by Lüftinger et al. (2010). Phases increase downwards. The bars at the bottom of each panel show the vertical (5%) and horizontal (0.5 Å) scale.
on lines of more chemical elements. We also plan to obtain detailed maps of the magnetic field and horizontal and vertical abundance structures for other Ap stars as well as for HD 24712.

References