Two new chemically peculiar stars with resolved, magnetically split lines

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Accepted 2007 March 5. Received 2007 February 13

ABSTRACT

We report the discovery of resolved, magnetically split lines in two chemically peculiar stars, the SrEuCr star HD 92499 and the Bp SiCr star HD 157751. From FEROS spectra, we have measured a mean magnetic field modulus of 8.5 kG for HD 92499 and a mean magnetic field modulus of 6.6 kG for HD 157751. Both stars have small projected rotational velocities: \( v \sin i = 3.0 \text{ km s}^{-1} \) and 8.5 km s\(^{-1}\), respectively. Our preliminary abundance analysis reveals an ionization imbalance of rare earths in HD 92499, indicating the abundance pattern typical of rapidly oscillating Ap stars. Cr and Fe are found to be strongly overabundant in HD 157751.

Key words: stars: abundances – stars: atmospheres – stars: chemically peculiar – stars: magnetic fields – stars: individual: HD 92499 – stars: individual: HD 157751.

1 INTRODUCTION

Between 2003 and 2006 we have been carrying out a systematic search for longitudinal magnetic fields in chemically peculiar stars whose magnetic fields have never been studied before (e.g. Hubrig et al. 2006, 2005a). The goal of this study was to statistically enlarge our data sample by including all southern stars for which the position in the Hertzsprung–Russell (H-R) diagram is known from accurate Hipparcos (ESA 1997) parallaxes \([\pi(\pi)/\pi < 0.2]\) and from photometric data in the Geneva and Strömgren systems, used to determine their effective temperatures. The longitudinal magnetic field determinations have been obtained with FORS 1 at the Very Large Telescope (VLT), which is a multimode instrument equipped with polarization analyzing optics comprising superachromatic half-wave and quarter-wave phase retarder plates, and a Wollaston prism with a beam divergence of 22 arcsec in standard resolution mode. We used the GRISM 600B and the GRISM 1200g to cover several hydrogen Balmer lines at spectral resolutions of \( R \sim 2000 \) for the GRISM 600B and \( R \sim 4000 \) for the GRISM 1200g. A few stars with detected strong longitudinal magnetic fields have been successively scheduled for the observations with high-resolution spectrographs.

In the course of such a study we had discovered a very slowly rotating extreme magnetic Ap star, HD 154708 (\( \equiv \text{CD} – 57^h 6753^m \)), which has the second highest value of a field modulus ever measured in Ap and Bp stars (Hubrig et al. 2005b). Up to now, the number of magnetic stars with a measured mean magnetic field modulus using magnetically resolved lines was 49. In this Letter we present our most recent discovery of two additional strongly magnetic, slowly rotating, chemically peculiar stars, the SrEuCr star HD 92499 (\( \equiv \text{CD} – 42^h 6407^m \)) and the Bp SiCr star HD 157751 (\( \equiv \text{CD} – 33^h 12069^m \)), for which the Zeeman pattern is resolved for several spectral lines.

2 OBSERVATIONS AND MAGNETIC FIELD MEASUREMENTS

The observations of HD 92499 and HD 157751 have been carried out with the echelle spectrograph FEROS at the 2.2-m telescope at La Silla. The spectrum of HD 92499 has been obtained on 2006 May 13 and the spectrum of HD 157751 on 2006 June 14. The signal-to-noise (S/N) ratio of the spectra is about 200–300 per pixel in the one-dimensional spectrum around 6150 Å. The wavelength coverage is 3530–9220 Å, and the nominal resolving power is 48 000. To our knowledge, these observations are the first carried out for both stars at high spectral resolution. Similar to the recently discovered cool low mass Ap star HD 154708, HD 92499 and HD 157751 have never been studied in detail and the SIMBAD data base offers merely a few references. As mentioned above, the only studies of both stars have been conducted with the purpose of longitudinal magnetic field determination with FORS 1 at the VLT. The longitudinal magnetic fields have been determined from the measurements of the circular polarization of opposite sign induced in the wings of each Balmer line by the Zeeman effect (see Hubrig et al. 2004b,a, for more details). Our measurements using all hydrogen Balmer lines from H\( \beta \) to the Balmer jump at a spectral resolution of \( R \sim 2000 \) revealed kG longitudinal magnetic fields for both stars: \( B_R \) of the order of \(-1.2 \text{ kG for HD 92499 and 4.0 kG for HD 157751} \) (Hubrig et al. 2006). In Figs 1 and 2 we present both the Stokes \( I \) and \( V \) spectra of these stars in the vicinity of the \( H_\beta \) line.

The visual inspection of high-resolution FEROS spectra disclosed that in both stars spectral lines are strongly affected by the magnetic field. Several spectral line profiles observed in HD 92499 are fully

*Based on observations obtained at the European Southern Observatory, La Silla, Chile [ESO programme 077.D-0477(A)].
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Figure 1. Stokes I and V/I spectra of the Ap star HD 92499 in the vicinity of the H/β line.

Figure 2. Stokes I and V/I spectra of the Ap star HD 157751 in the vicinity of the H/β line.

resolved whereas for HD 157751 the magnetic splitting is less noticeable due to the non-negligible rotational Doppler effect. From the observed magnetically split lines we determined the mean magnetic field modulus (the average over the visible stellar hemisphere of the modulus of the magnetic vector, weighted by the local line intensity) which is related to the wavelength separation of the Zeeman components through the relation

\[
\langle B \rangle = \Delta \lambda / \left( 9.34 \times 10^{-13} \lambda^2 \right),
\]

where \( \lambda \) is the central wavelength of the line (in a Zeeman triplet this corresponds to the position of the \( \pi \)-component), \( \Delta \lambda \) is the wavelength separation between the centroids of the \( \sigma \)-components and \( g_{\text{eff}} \) is the effective Landé factor. To calculate \( \Delta \lambda \), the wavelengths of the centers of gravity of the split doublet and triplet components have been determined by fitting a Gaussian simultaneously to each of them (if the lines are not fully split) or by direct integration of the whole component profile (if the splitting is large). When the lines were blended, a multiple fit of three or four Gaussians has been performed. This procedure is well-established over the years and has been used in previous studies of magnetic stars with resolved magnetically split lines (e.g. Mathys et al. 1997). In this manner we obtained the mean magnetic field modulus \( \langle B \rangle = 8.5 \pm 0.2 \text{ kG} \) for HD 92499 and \( \langle B \rangle = 6.6 \pm 0.5 \text{ kG} \) for HD 157751. The accuracy of our measurements essentially depends on the magnitude of the Zeeman splitting, the presence of blends and the complexity of the profiles.

Strongly magnetic stars with measured mean magnetic fields from magnetically resolved lines are of special interest because they provide the best opportunity to study the effect of the magnetic field on the stellar atmospheres. Very frequently, abundances of many elements are non-uniformly distributed over the stellar surface and they are also vertically stratified. To get more insight in the peculiar nature of HD 92499 and HD 157751, we tried to determine the abundances of a few elements.

To calculate the effective temperature \( T_{\text{eff}} \) and \( \log g \) we used \( u v w \beta \) and Geneva photometry listed in the General Catalogue of Photometric Data (Mermilliod, Mermilliod & Hauck 1997). Further, we made use of the software package TEMPLOGG (Roger 1995; Stütz et al. 2002) which offers the possibility to automatically correct for the reddening, to obtain \( T_{\text{eff}} = 7000 \text{K} \), \( \log g = 4.15 \) for HD 92499 and \( T_{\text{eff}} = 11380 \text{K} \), \( \log g = 4.44 \) for HD 157751. The calculations of abundances for a few lines – mainly for Fe and Cr lines – were made with an evolved version of the WIDTH9 code (Kurucz 2005). This code takes into account the extra broadening induced by the magnetic field and gives a good first estimate which can later be refined by more detailed analyses using spectral synthesis. Iteratively, the dependence of the average Fe abundance on the excitation potentials of the measured lines was minimized to derive a more accurate value of \( T_{\text{eff}} \).

The best fit to the observed spectrum of HD 92499 has been achieved for \( T_{\text{eff}} = 7200 \pm 200 \text{K} \) and \( \log g = 4.15 \pm 0.15 \). For HD 157751, we obtained \( T_{\text{eff}} = 11300 \pm 300 \text{K} \) and \( \log g = 4.4 \pm 0.2 \). Our estimates of the projected velocity \( v \sin i \) using several Fe and Cr lines with small Landé factors resulted in \( v \sin i = 3.0 \pm 0.5 \text{ km s}^{-1} \) for HD 92499 and \( v \sin i = 8.5 \pm 1.0 \text{ km s}^{-1} \) for HD 157751. Atomic line data were taken from Vienna Atomic Line Database (VALD; Kupka et al. 1999). Iteratively, the derived Fe and Cr abundances were then used to calculate a model with individual abundances using the LLMODELS code (Shulyak et al. 2004). Atmospheric parameters and abundances of Fe II and Cr II model calculations are presented in Table 1.

Employing the calculated model for HD 92499, we have determined abundances for a few rare earth elements using strong unblended lines. Europium, praseodymium and neodymium have

| HD 92499 | HD 157751 |
|----------|----------|
| \( T_{\text{eff}} \) [K] | 7200 ± 200 | 11300 ± 300 |
| \( \log g \) | 4.15 ± 0.15 | 4.4 ± 0.2 |
| \( v \sin i \) [km s\(^{-1}\)] | 3 ± 0.5 | 8.5 ± 1.0 |
| \( \langle B \rangle \) [kG] | 8.5 ± 0.2 | 6.6 ± 0.5 |
| \( \log (N_{\text{Fe II}}/N_{\text{tot}}) \) | −4.28 | −3.25 |
| \( \log (N_{\text{Cr II}}/N_{\text{tot}}) \) | −5.40 | −3.31 |
been found to be strongly overabundant, as is typical for most magnetic chemically peculiar stars. The computed respective relative abundances are: \( \log \left( \frac{N_{\text{Eu II}}}{N_{\text{tot}}} \right) = -9.41 \), \( \log \left( \frac{N_{\text{Nd II}}}{N_{\text{tot}}} \right) = -8.15 \), \( \log \left( \frac{N_{\text{Nd III}}}{N_{\text{tot}}} \right) = -7.29 \), \( \log \left( \frac{N_{\text{Pr II}}}{N_{\text{tot}}} \right) = -9.31 \) and \( \log \left( \frac{N_{\text{Pr III}}}{N_{\text{tot}}} \right) = -8.13 \), with estimated uncertainties of 0.3 dex.

Interestingly, we find the obvious imbalance of Nd and Pr abundances from different ions, also called ‘rare-earth-anomaly’. The abundances derived from the first and second ions differ by \( \sim 0.86 \) dex for Nd and by \( \sim 1.18 \) dex for Pr. Such an anomaly is usually explained by vertical abundance stratification of the elements in the stellar atmosphere and is known to be a typical feature of the abundance pattern of the rapidly oscillating Ap (roAp) stars (Ryabchikova et al. 2004). It is generally accepted that the vertical abundance stratification is a consequence of atomic diffusion, i.e. radiative levitation and gravitational settling.

The observed FEROS spectra and line identification according to VALD in various spectral regions containing magnetically split lines are presented for both stars in Figs 3–6.

### 3 DISCUSSION

Strong magnetic stars with low \( v \sin i \) values, for which the magnetic splitting of the spectral lines is evident in high-resolution spectra in unpolarized light, present an excellent opportunity to derive stronger constraints on the geometry of their magnetic fields from the observations of the variability of the magnetic field modulus and the longitudinal magnetic field over the rotation cycle. Further information about the magnetic field geometry can be obtained from the study of the field moments measured in the circular polarization profiles and in line profiles observed in unpolarized light, as has been done by Landstreet & Mathys (2000). Additional observations of these two stars are needed to allow one to determine their rotational periods and the magnetic field geometry and to carry out a multi-element abundance analysis.

Our preliminary abundance analysis of the FEROS spectra of HD 92499 and HD 157751 reveals the overabundance of Cr in both stars, the overabundance of Fe in HD 157751 and a nearly solar abundance of Fe in HD 92499. The discovery of ionization anomalies of Nd and Pr in HD 92499 indicates the abundance pattern typical of roAp stars. Because of the location of HD 92499 in the same region of parameter space in which rapidly oscillating Ap (roAp) stars have been detected, this star was searched photometrically for pulsations by Martinez & Kurtz (1994) with no detected oscillations. However, we recall the recent paper by Kurtz et al. (2006) reporting the discovery of the presence of a single frequency of \( \nu = 2.088 \) mHz \( (P = 8.0 \) min\) with very low amplitudes in the range 30–60 m s\(^{-1}\) from a high-precision radial velocity study of HD 154708. No oscillations had previously been detected in this star in photometric studies. We conclude that a time-resolved high-resolution spectroscopic study of radial velocity is called for to confirm or withdraw the presumption that HD 92499 could be a low-amplitude roAp star for which photometry would not detect oscillations.
ACKNOWLEDGMENT

This work was supported by the Austrian Science Fund (FWF-PP17890).

REFERENCES

ESA, 1997, ESA SP-1200, The Hipparcos and Tycho Catalogues. ESA Publications Division, Noordwijk
Hubrig S., Kurtz D. W., Bagnulo S., Szeifert T., Schöller M., Mathys G., Dziembowski W. A., 2004a, A&A, 415, 661
Hubrig S., Szeifert T., Schöller M., Mathys G., Kurtz D. W., 2004b, A&A, 415, 685
Hubrig S., North P., Szeifert T., 2005a, in Adamson A., Aspin C., Davis C. J., Fujiyoshi T., eds, ASP Conf. Ser. Vol. 343, Astronomical Polarimetry: Current Status and Future Directions. Astron. Soc. Pac., San Francisco, p. 374
Hubrig S. et al., 2005b, A&A, 440, 37
Hubrig S., North P., Schöller M., Mathys G., 2006, Astron. Nachr., 327, 289
Kupka F., Piskunov N. E., Ryabchikova T. A., Stempels H. C., Weiss W. W., 1999, A&AS, 138, 119
Kurtz D. W., Elkin V. G., Cunha M. S., Mathys G., Hubrig S., Wolff B., Savanov I., 2006, MNRAS, 372, 286
Kurucz R. L., 2005, Mem. Soc. Astron. Italiana Supp., 8, 14
Landstreet J. D., Mathys G., 2000, A&A, 359, 213
Martinez P., Kurtz D. W., 1994, MNRAS, 271, 129
Mathys G., Hubrig S., Landstreet J. D., Lanz T., Manfroid J., 1997, A&AS, 123, 353
Mermilliod J. C., Mermilliod M., Hauck B., 1997, A&AS, 124, 349
Rogers N. Y., 1995, Comm. Asteroseismology, 78, 1
Ryabchikova T., Nesvacil N., Weiss W. W., Kochukhov O., Stütz Ch., 2004, A&A, 423, 705
Shulyak D., Tsymbal V., Ryabchikova T., Stütz Ch., Weiss W. W., 2004, A&A, 428, 993
Stütz C., Nendwich J., Rogers N. Y., 2002, TempLogG.v2, http://ams.astro.univie.ac.at/templogg/

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