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HD 97394: a magnetic Ap star with high cerium overabundance⋆

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ABSTRACT

We report a spectroscopic analysis of the chemically peculiar Ap star HD 97394. The stellar spectrum is rich in lines of rare earth elements with large overabundances, especially cerium, gadolinium and europium. Enhancement of the abundances of these rare earths shows this star to be one of the most peculiar stars. Very large overabundances were found for lines of Ce III and Eu III. Abundances obtained from second ionization lines of Nd, Ce and Eu are about 2 dex higher than for those of the first ionization. From partially split Zeeman components of the Fe II 6149.258 Å line and from synthetic modelling, a global magnetic field of 3.1 kG was measured. We tested for pulsation of the star with high time resolution spectroscopy obtained with the ESO Very Large Telescope. We place an upper limit to any pulsation amplitude of 30–40 m s^{-1} for individual lines of rare earth elements, of 10–20 m s^{-1} for the combination of several lines, and of 6–10 m s^{-1} for cross-correlation over large spectral bands.

Key words: stars: atmospheres – stars: chemically peculiar – stars: individual: HD 97394 – stars: magnetic field.

1 INTRODUCTION

Chemically peculiar (CP or Ap/Bp) stars are main-sequence stars with significant overabundances of some chemical elements, in particular rare earths, in comparison with solar abundances. The hypothesis of atomic diffusion as an explanation for this phenomenon (Michaud 1970) is widely accepted. There are other important properties in many CP stars, such as photometric and spectral variability, strong global magnetic fields and relatively low rotation velocities. Rotation periods of these stars detected from photometric or magnetic variability have a range from several days to tens of years. Observed magnetic fields in CP stars reach 30 kG (Freyhammer et al. 2008; Elkin et al. 2010) in cool SrCrEu stars and 34 kG in hotter Si-type stars (Babcock 1960).

In a high spectral resolution survey of cool CP stars, based mostly on the list of photometric observations by Martinez (1993), nearly 350 Ap stars have been observed with the FEROS spectrograph on the ESO 2.2-m telescope. The majority show overabundances of rare earth elements. Some of the observed stars show extraordinarily rich spectra, even when compared with other peculiar stars. The analysis of one of these stars, HD 97394, is described in this paper. Examples of the abundance enhancements for HD 97394 are clearly visible in Fig. 1 where a small spectral region is shown in comparison with two other well-known cool Ap stars. One of them (HD 101065, Przybylski's star) stood out for several decades as a unique member of the Ap star class on account of the extreme peculiarity and high line density of its spectrum. While other stars showing similar characteristics have been identified in recent years (see e.g. Hubrig et al. 2002), they still represent a small minority among Ap stars.

Strömgren photometric indices (Martinez 1993) and fundamental parameters of the star, $T_{\rm eff} = 7600$ K and $\log g = 4.2$ (cgs), indicate that HD 97394 is a main-sequence star situated in the Hertzsprung–Russell (HR) diagram where the instability strip crosses the main sequence. For many Ap stars in this region, rapid oscillations have been detected, thus HD 97394 is a suitable candidate to test for pulsation.

2 OBSERVATIONS AND DATA REDUCTION

The unusual nature of HD 97394 was first recognized on a high-resolution spectrum obtained in 2007 February (a 660-s exposure starting at MJD = 54138.3357) with the FEROS echelle spectrograph at the La Silla 2.2-m telescope of the European Southern Observatory (ESO). The spectrum reveals a large number of spectral lines, even for a peculiar star. Since the star shows an extraordinarily rich spectrum and physical parameters corresponding to the rapidly oscillating Ap (roAp) stars, it was included in a list for further observations with the ESO Very Large Telescope (VLT). High time resolution spectroscopic observations were carried out with the VLT using the Ultraviolet and Visual Echelle Spectrograph (UVES) installed at Unit Telescope 2 (UT2). For HD 97394, 55 spectra were obtained on 2008 February 27 with exposure times of 40 s and

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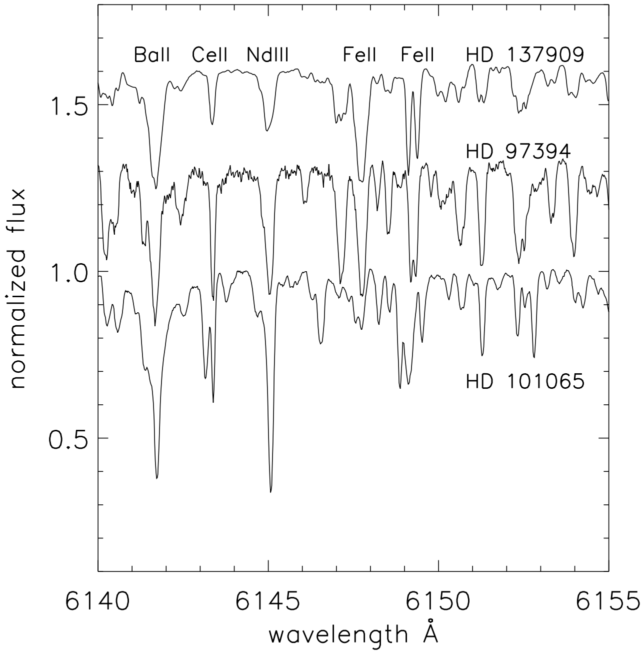

Figure 1. A section of the observed spectrum of HD 97394 in comparison with two well-known peculiar rapidly oscillating Ap stars, HD 101065 (Przybylski's star) and HD 137909 (β CrB). The spectra are shifted along the *y*-axis for visibility. Strong lines of some chemical elements are noted.

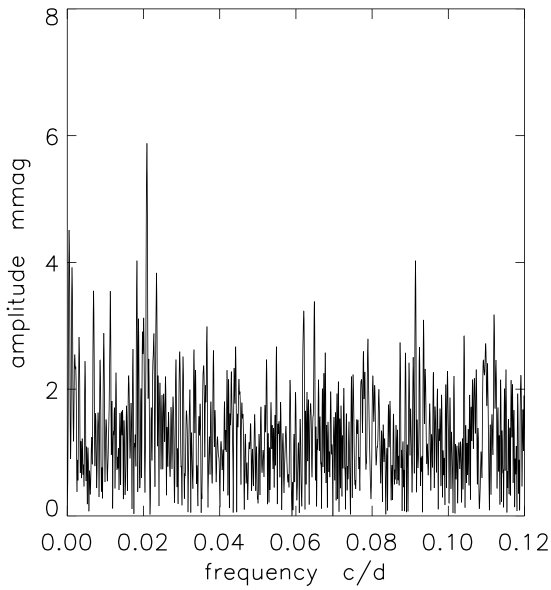

Figure 2. An amplitude spectrum of ASAS photometry of HD 97394. The highest peak corresponds to a period of 47.90 d.

readout plus overhead times of ~21 s, corresponding to a time resolution of ~61 s.

The spectral region covered is in the range λλ 4970–7010 Å, with a small gap near 6000 Å caused by the space between the two CCDs. The average spectral resolution is about $R = 10^5$. The CCD frames were processed using the UVES pipeline to extract and merge the echelle orders to 1D spectra that were normalized to the continuum. The UVES spectra were co-added and this average spectrum was used for an abundance analysis.

3 ANALYSIS OF THE OBSERVATIONAL DATA

3.1 Stellar parameters

A star with such an unusual spectrum is an interesting target. We therefore performed an analysis of the chemical abundances for some elements that were identified in the spectrum. For line identification and chemical analysis, synthetic spectra were calculated. The source of the spectral line list was the Vienna Atomic Line Database (VALD, Kupka et al. 1999), which also includes lines of rare earth elements from the DREAM data base (Biémont, Palmeri & Quinet 1999). Model atmospheres were taken from the NEMO (Vienna New Model Grid of Stellar Atmospheres) data base (Heiter et al. 2002).

Basic parameters for HD 97394 were determined from photometric and spectroscopic data. Strömgren photometry (Martinez 1993) and the calibration by Moon & Dworetsky (1985) give for HD 97394 an effective temperature of $T_{\rm eff} = 8000$ K and with $\log g = 4.3$. From Geneva photometry[1] (Mermilliod, Mermilliod & Hauck 1997) we obtained an effective temperature of $T_{\rm eff} = 7700$ K using the calibration by Hauck & North (1993). Balmer lines for cool A stars are sensitive to effective temperature and can be used to improve the value obtained from photometry. Synthetic spectra for the Hα region were calculated with the SYNTH code (Piskunov 1992) using NEMO models with effective temperature ranging from 7000 to 9000 K. Then synthetic profiles of Hα were compared with the observed spectrum for a best fit, which gave $T_{\rm eff} = 7600$ K. The Balmer lines are not very sensitive to gravity for this temperature region; we adopted a model with $\log g = 4.2$, which is close to that obtained from photometry. Using the narrow line of Fe I at 5434.524 Å which is magnetically insensitive, we estimated $v \sin i = 3.5 \pm 0.5$ km s^{-1}.

From All Sky Automatic Survey (ASAS) photometry (Pojmanski 2002) we searched for the rotation period of the star. Time series analysis of ASAS data was carried out with ESO-MIDAS and with the PERIOD04 package (Lenz & Breger 2005). An amplitude spectrum is shown in Fig. 2; the highest peak corresponds to a frequency of $0.020\,879 \pm 0.000\,03$ c d^{-1}. If this peak is caused by rotational variation, then the rotation period is 47.90 ± 0.07 d. For an estimated radius of the order of 1.7 R$_\odot$, this suggests $v_{\rm eq} = 2$ km s^{-1} and an equator-on view of the star from the measured $v \sin i$. There would be better agreement with $v_{\rm eq} = 3.2$ km s^{-1} for a more evolved star with a radius close to 3 R$_\odot$. Such an interpretation is not secure, hence further observations are needed to test it. A study of the longitudinal magnetic field variations over this suggested rotational period could provide this test, but it requires a significant amount of time with spectropolarimetric observations at a large telescope. ASAS provided two large observing sets of this star and both have a peak close to that shown.

3.2 Magnetic field

In our UVES spectrum the Fe II 6149.258 Å line shows a partially spit Zeeman doublet structure suitable for magnetic field measurement. FEROS observations have lower resolution, so this splitting is not visible for them, although magnetic broadening of lines with large Landé factors is still detectable. Direct measurements of Fe II 6149.258 Å splitting by fitting Gaussians yield a magnetic field

[1] http://obswww.unige.ch/gcpd/gcpd.html

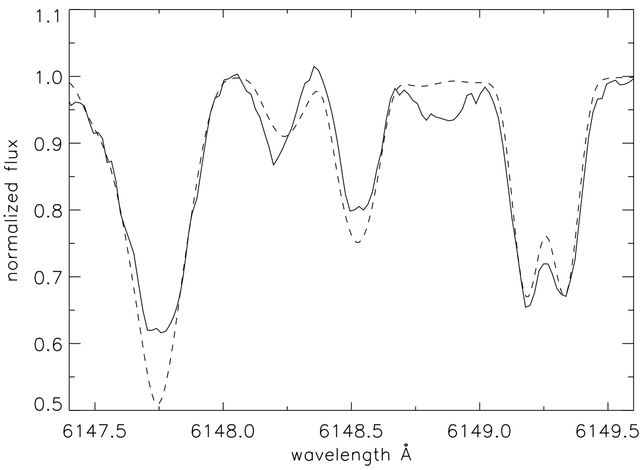

Figure 3. Observed (solid line) and synthetic (dashed line) spectra of a region including the lines of Fe II at 6147.741 Å and 6149.258 Å. The calculations of the synthetic spectra were done for a magnetic field of 3.1 kG.

modulus of $\langle B \rangle = 2.75$ kG, although the profile fits better to the synthetic spectrum for a slightly higher magnetic field of 3.1 kG as shown in Fig. 3. The Cr II 5116.049 Å line reveals a Zeeman triplet structure. The distance between centres of the Zeeman components gives a magnetic field of $\langle B \rangle = 3.0$ kG. However, the splitting is also partial and the line is blended with a Ce II line. Several other lines with large Landé factors also show partial Zeeman triplets, doublets or magnetic broadening. Most of the lines fit well a synthetic profile calculated for a magnetic field of 3.1 kG. We therefore adopt this field as an average for the star with an estimated error of 0.2 kG. Zeeman splitting and magnetic broadening show the magnetic nature of HD 97394, thus the magnetic field must be taken into account in the spectral analysis.

3.3 Atmospheric abundances

Chemical abundances of HD 97394 were determined with the SYNTHMAG code of Piskunov (1999) since the star has a strong magnetic field. SYNTHMAG calculates synthetic spectra taking into account the Zeeman structure of spectral lines in the presence of a magnetic field. Synthetic spectra were computed for a model atmosphere with parameters $T_{\rm eff} = 7600$ K and $\log g = 4.2$ and for a magnetic field of 3.1 kG. For a small number of important spectral lines there were no Landé factors in the VALD data base. In these cases we initially used an average Landé factor $z = 1.14$ evaluated from several thousand lines extracted from VALD. If the line did not fit well with that value, we empirically varied the Landé factor for better fitting.

The abundances were adjusted by repeating the synthetic calculations until an acceptable fit was obtained with the observed spectrum. Table 1 gives the determined abundances with estimated uncertainties. For comparison, abundances for β CrB (Kurtz, Elkin & Mathys 2007) and for the Sun (Asplund, Grevesse & Sauval 2005) are also presented.

For HD 97394 we obtained an almost solar abundance of Fe while Cr is enhanced by 2 dex and Sc and Ti are enhanced by 1 dex compared to the Sun. After being debated for several decades, the presence of lithium in a number of (cool) Ap stars has now been convincingly established (Polosukhina et al. 1999, 2010; Kochukhov 2008). In the spectrum of HD 97394 we found a line in the region of the Li I doublet at 6707.761 and 6707.912 Å that is partly blended with a stronger Ce II line 6708.099 Å. There were no Landé factors for these lines in the VALD data base so we used the LS-coupling approximation for each of the involved terms. This leads to the following values of the effective Landé factor: 1.167 for the 6707.761 Å line, and 1.333 for the 6707.912 Å line. The synthetic spectrum fitted the observed lines well with an overabundance of lithium of 2.3 dex. This is admittedly a first approximation, since a more exact abundance determination would have required the partial Paschen–Back effect to be included in the synthesis of the Li doublet. However, for the purpose of the present work, this additional complication is not justified.

Table 1. Chemical abundances for HD 97394 obtained from an average UVES spectrum with a signal-to-noise ratio of about 300. The errors quoted are internal standard deviations for the set of lines measured; for single lines errors have been estimated from the line fitting. Column 3 gives the number of lines used in each case. The unresolved lithium doublet near 6708 Å is given as one line. The abundances for β CrB (HD 137909) are mostly taken from Kurtz et al. (2007); the abundances of Li I, Ba II, Ce III and Eu III for β CrB are new calculations. The corresponding solar abundances are from Asplund et al. (2005).

Ion	$\log N/N_{\rm tot}$ HD 97394	$N_{\rm lines}$	$\log N/N_{\rm tot}$ HD 137909	$\log N/{\rm H}$ Sun
Li I	−8.60 ± 0.10	1	−8.8	−10.95
Si II	−4.65 ± 0.20	2		−4.49
Ca I	−5.65 ± 0.21	2	−5.5	−5.69
Sc II	−7.86 ± 0.10	5	−8.3	−8.95
Ti II	−6.01 ± 0.11	10	−6.7	−7.10
Cr I	−4.45 ± 0.15	2	−5.0	−6.36
Cr II	−4.35 ± 0.15	15	−4.9	−6.36
Mn I	−5.40 ± 0.20	1	−5.5	−6.61
Fe I	−4.48 ± 0.11	17	−4.2	−4.55
Fe II	−4.33 ± 0.17	3	−4.1	−4.55
Y II	−9.00 ± 0.10	2		−9.79
Ba II	−9.10 ± 0.20	2	−9.1	−9.83
La II	−9.53 ± 0.05	3	−9.1	−10.87
Ce II	−6.99 ± 0.15	52	−7.6	−10.42
Ce III	−5.08 ± 0.23	5	−5.7	−10.42
Pr III	−9.10 ± 0.19	4	−9.3	−11.29
Nd II	−10.10 ± 0.25	3	−10.0	−10.55
Nd III	−8.12 ± 0.38	5	−8.5	−10.55
Eu II	−7.30 ± 0.18	4	−8.2	−11.48
Eu III	−5.40 ± 0.20	3	−6.1	−11.48
Gd II	−7.10 ± 0.13	14	−7.7	−10.88

Rare earth abundances are impressively high for certain elements. The first ionization ions Ce II, Eu II and Gd II show between 3 and 4 dex overabundances. To fit Ce III and Eu III lines with synthetic profiles required much higher abundances than were obtained for Ce II and Eu II. For the lines of the second ionization stage Ce III and Eu III we found enhancements as large as 5 dex. Example of line fits for Ce II, Ce III and Gd II are presented in Fig. 4.

The lines of Eu II and the line of Eu III at 6666.347 Å show wide wings that are better fitted with a 0.5 kG increase in the magnetic field strength, or with an increase of 3–5 km s^{-1} in the macroturbulent velocity. This suggests that these lines may form in spots that are close to the magnetic poles.

Lines of Nd III and Pr III are enhanced by around 2 dex above solar values. Lines of Nd II when present are very weak. One of the strongest lines of Nd II at 5319.810 Å is just a blend in the wing of a stronger Ce II line. The abundances obtained for Nd II lines are close to normal, but uncertain. Nevertheless, they clearly show large differences with abundances determined from Nd III lines.

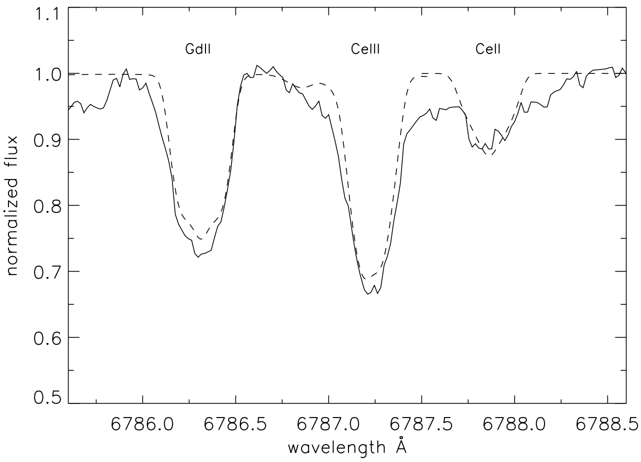

Figure 4. Observed (solid line) and synthetic (dashed line) profiles for lines of Gd II at 6786.313 Å, Ce III at 6787.236 Å and Ce II at 6787.863 Å as examples of the fitting. In calculations for cerium different abundances were used, with log $N/N_{\rm tot} = -4.8$ for Ce III and log $N/N_{\rm tot} = -6.7$ for Ce II lines. These are higher than the average abundances in Table 1.

Lines of Gd II are strong and show large overabundances. We also identified in our spectra several lines of Gd III from the NIST data base and from Callahan (1962). Line parameters for Gd III are not available for calculation of synthetic profiles to estimate abundances for this ion. Biémont, Kohnen & Quinet (2002) provide parameters for Gd III lines, but only for the ultraviolet spectral region.

Higher abundances obtained for second ionization ions may be explained by vertical stratification where lines form in different layers in the atmosphere (Ryabchikova et al. 2000). Rare earth element lines form in upper atmospheric layers where, in addition to stratification, non-local thermodynamic equilibrium (NLTE) effects may be present as discussed by Mashonkina, Ryabchikova & Ryabtsev (2005).

3.4 A search for pulsations

The roAp stars comprise a subclass of Ap stars that show photometric and radial velocity variability with periods from 5.6 to 21 min. Their effective temperatures range approximately from 6500 to 8200 K. The parameters of HD 97394 are typical for roAp stars, thus we searched for pulsations in this star. While photometric observations by Martinez & Kurtz (1994) did not reveal rapid variability, the high-quality time-resolved spectroscopy we obtained is in many cases more sensitive to pulsations than ground-based photometry (e.g. Kurtz et al. 2007).

To search for rapid radial velocity variability we cross-correlated sections of the individual spectra using ESO-MIDAS software. We also measured the central positions for profiles of individual spectral lines by the centre-of-gravity method. Frequency analyses of radial velocities were performed using time series analysis of ESO-MIDAS.

Cross-correlations were done for different spectral bands mostly in the range 5150–5800 Å to avoid hot pixels, strong interstellar sodium lines and some telluric lines. No clear pulsation signal was found with amplitudes in excess of 5–10 m s^{-1} for different spectral ranges and different templates. We tried to measure pulsations for individual spectral lines that were identified by comparison with synthetic spectra calculated with the SYNTH code. The pulsation amplitudes in roAp stars normally are much higher in lines belonging to rare earth elements and smaller or undetectable in spectral lines of other elements. We did not find pulsation from lines of rare earth elements, including Nd III, Pr III, Eu II and Ce II, which usually show pulsation in roAp stars. For most individual lines the noise level is too high to detect low-amplitude pulsation in such a short observing run. Some examples of the obtained amplitude spectra are shown in Fig. 5.

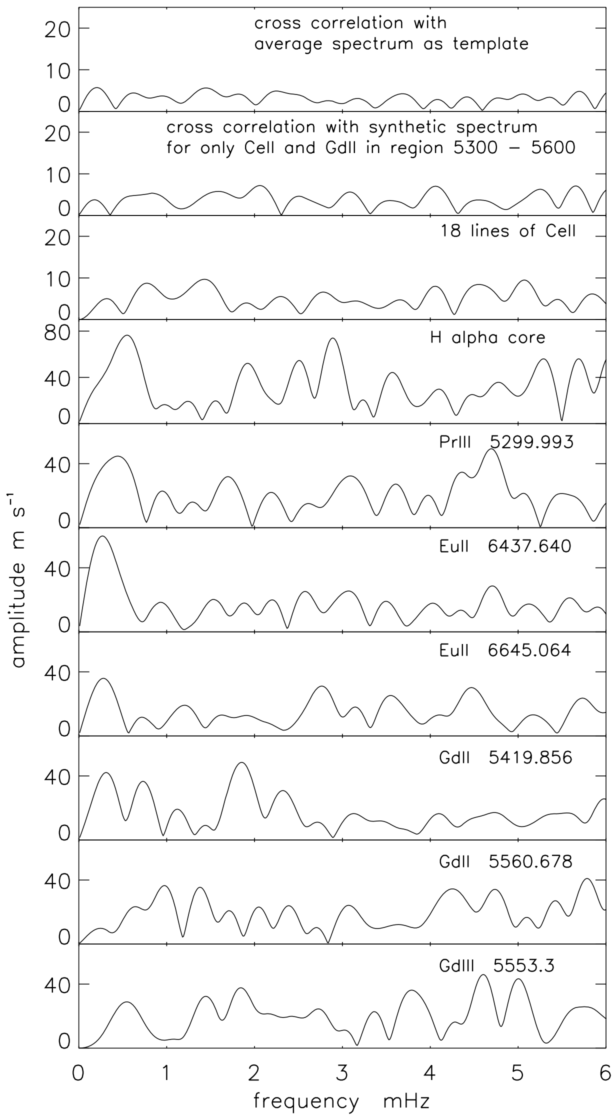

Figure 5. Amplitude spectra calculated for HD 97394 using different methods. Cross-correlations over spectral regions from 5150–5450 Å (top panel) where an average spectrum was used as a template; cross-correlations over spectral regions from 5300–5600 Å (second panel) with a synthetic template calculated only for lines of Ce II and Gd II. The next panels in this figure give results for a combination of 18 lines of Ce II, for the core of the Hα line, and for several individual lines. No pulsation signal was detected at the levels shown.

No pulsations were detected in the star with upper limits to the amplitude of 30–40 m s^{-1} for single lines and 10–20 m s^{-1} when several lines were combined. The observing time of one hour is not sufficient to detect low-amplitude (below 30 m s^{-1}) pulsation for individual lines for the spectra with signal-to-noise ratio about 100 which we have for this star. Pulsation with amplitudes below our detection level is still possible and may be detected with a longer data set with better signal-to-noise ratio.

4 DISCUSSION AND CONCLUSION

Abundances in Ap stars vary widely from one star to another (e.g. Adelman 1973a; Cowley & Henry 1979). Adelman (1973b) found that cerium shows enhancement in cool Ap stars. However, on average for the 21 stars he studied the overabundances of other rare earth elements such as Pr, Nd, Sm, Eu and Gd was much higher than for cerium. The high Ce abundance of HD 97394 distinguishes it from those 21 stars. For a wider temperature range of Ap stars, Cowley (1976) noted that cerium may be one of characteristic signatures of peculiar stars – not because of the line strengths of Ce, but for the numbers of lines of the element. To describe the rare earth element behaviour, Cowley (1980) suggested two empirical groups. In the first, more common group, cerium is strongest while abundances of other lanthanides are lower. In the second group cerium is one of the weakest of the lanthanides, while europium dominates.

The high overabundance of cerium in HD 97394 is not unique. In at least 15 other stars from our FEROS and UVES samples, cerium lines are strong. In HD 52847, their strengths are similar to those observed in HD 97394; in the remaining stars, they are mostly weaker. High abundances of cerium were also found in the Ap star HD 18610 by Ryabchikova et al. (2004). For these three stars no rapid photometric variability was found by Martinez & Kurtz (1994). Another example of a star with significant cerium lines and no detected pulsation is HD 965 (Kurtz, Dolez & Chevreton 2003; Elkin et al. 2005).

Yet, strong cerium lines are also present in stars that show rapid variability, such as HD 101065, the first roAp star found, which has one of the highest photometric pulsation amplitudes of the class. While this star is well known for the extreme peculiarities of its spectrum, HD 97394 has even higher abundances of Ce II, Ce III and Eu II. By contrast, the abundances of La, Pr and Nd are higher in HD 101065, and both stars show similar abundances of Gd. The abundances of Fe and Cr are lower in HD 101065 (Shulyak et al. 2010).

In another well known roAp star, 10 Aql, the cerium lines are rather weak but show one of the highest pulsation amplitudes among the studied elements in this star (Elkin, Kurtz & Mathys 2008). The strong Ce II lines of the low pulsation amplitude roAp star β CrB have on average the second largest amplitude of rapid radial velocity variations observed in the lines of rare earth elements (Kurtz et al. 2007). Cerium is also one of the most overabundant rare earths in this star. Comparison with HD 97394 appears in Table 1. Both stars show similar overabundances, within the errors, for Fe, Li, Ca, Ba, Nd and Pr, while the abundances of Sc, Ti, Cr, La, Ce and Eu are further enhanced by 0.4–0.9 dex in HD 97394.

One of the characteristic properties of Ap stars is their spectral and photometric variability with rotation period. We observed HD 97394 in only two epochs with 375 d between them. The spectra for the two epochs are similar. Lines in the UVES spectra are a little stronger, but considering the lower resolution of the FEROS spectra this may not be significant. Lines of cerium are weaker for the first observations with FEROS. This suggests spectral variability with rotation, but more observations are needed to confirm this.

The CP magnetic star HD 97394 is an interesting object with a very rich spectrum. The overabundances of certain rare earth elements are very high and we can claim that this is one of the most peculiar stars. HD 97394 is one more important example of the large variety of Ap stars and an intriguing target for further observations.

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