A search for rapid pulsations among nine luminous Ap stars

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ABSTRACT
The rapidly oscillating Ap (roAp) stars are of importance for studying the atmospheric structure of stars where the process of chemical element diffusion is significant. We have performed a survey for rapid oscillations in a sample of nine luminous Ap stars, selected from their location in the colour–magnitude diagram as more evolved main-sequence Ap stars that are inside the instability strip for roAp stars. Until recently this region was devoid of stars with observed rapid pulsations. We used the Very Large Telescope UV–Visual Echelle Spectrograph to obtain high time resolution spectroscopy to make the first systematic spectroscopic search for rapid oscillations in this region of the roAp instability strip. We report nine null detections with upper limits for radial velocity amplitudes of 20–65 m s\(^{-1}\) and precisions of \(\sigma = 7–20\) m s\(^{-1}\) for combinations of Nd and Pr lines. Cross-correlations confirm these null results. At least six stars are magnetic and we provide magnetic field measurements for four of them, one of which three are newly discovered magnetic stars. It is found that four stars have magnetic fields smaller than \(\sim 2\) kG, which according to theoretical predictions might be insufficient for suppressing envelope convection around the magnetic poles for more evolved Ap stars. Suppression of convection is expected to be essential for the opacity mechanism acting in the hydrogen ionization zone to drive the high-overtone roAp pulsations efficiently. Our null results suggest that the more evolved roAp stars may require particularly strong magnetic fields to pulsate. Three of the studied stars do, however, have magnetic fields stronger than 5 kG.

Key words: stars: magnetic fields – stars: oscillations – stars: variables: other.

1 INTRODUCTION
Why do some stars oscillate while others do not? This question is particularly relevant for the class of rapidly oscillating Ap (roAp) stars for which the discovery of high-frequency oscillations came as a surprise (Kurtz 1982). The \(\delta\) Scuti pulsations of stars in this area of the colour–magnitude diagram (CMD) were not theoretically predicted to produce the observed high-frequency, high-overtone modes. Subsequently, considerable observational and theoretical efforts have been able to describe most pulsation properties of roAp stars through (i) the oblique pulsator model (Kurtz 1982), (ii) the probable driving mechanism of the pulsations (Balmforth et al. 2001) and (iii) their link with the magnetic fields present in Ap stars (see e.g. Cunha 2006; Saio 2005).

Ap stars are chemically peculiar stars that range from early-B to early-F spectral types with the majority having detectable magnetic fields with strengths of a few \(\times 10^2\) to a few \(\times 10^4\) G (Bychkov, Bychkova & Madej 2003, according to whom \(\sim 55\) per cent have mean longitudinal fields above 400 G). For the cool Ap stars (also called CP2 stars), abundance anomalies are typically visible in their spectra as abnormally strong absorption lines, particularly of rare earth elements (REEs). Candidate roAp stars can therefore be selected photometrically due to the influence of these spectral features on narrow-band photometric indices such as those of the Strömgren filter system (Martinez 1993, see also Section 2.1).

The high-overtone roAp oscillations are thought to be driven by the opacity mechanism acting in the partial hydrogen ionization zone (Dziembowski & Goode 1996; Balmforth et al. 2001; Cunha 2002; Saio 2005). The frequency range of the excited modes is related to the presence of strong magnetic fields in roAp stars that (i) directly stabilize the low-frequency, low-order \(\delta\) Scuti oscillations, excited by the \(\kappa\) mechanism acting in the He\(\iota\) partial ionization zone (Saio 2005), and (ii) indirectly enhance the driving of high-order oscillations by the \(\kappa\) mechanism acting in the partial hydrogen ionization zone.
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2.1 Selection

We selected nine stars based on Strömgren and $\beta$ indices from the Cape catalogue of cool Ap stars by Martinez (1993), and luminosities from Hipparcos parallaxes. For Strömgren photometry, the $c_1$ index is normally an indicator of luminosity while $m_1$ is an indicator of metallicity. The $\beta$ index is sensitive to temperatures for stars in the range A3–F2. Also $b - y$ indicates temperature, but is influenced by reddening. The relative indices $\delta c_1$ and $\delta m_1$ indicate how a given star deviates in $c_1$ and $m_1$ from ‘normal’ zero-age-main-sequence stars (see also Crawford 1979). A more negative value of $\delta m_1$ indicates stronger metallicity. For normal stars $\delta c_1$ is a luminosity indicator, while for Ap stars it is depressed by heavy line blocking and hence is not a reliable indicator of luminosity. A negative $\delta c_1$ is, in fact, indicative of strong peculiarity. However, because $c_1$ increases with luminosity, luminous Ap stars may have positive $\delta c_1$ which, without independent information on the luminosity, makes their chemical composition appear ‘normal’ in this index. A negative $\delta c_1$ has frequently been used for target selection in previous searches for roAp stars; as a consequence, luminous Ap stars have seldom been tested for pulsation. Our sample of nine roAp candidates was therefore hand-picked among Ap stars with Hipparcos
errors from the parallaxes. The only exception is HD 132322 which has a precise distance. No Lutz–Kelker correction (Lutz & Kelker 1973) was applied to the luminosities. The values for projected rotational velocities and magnetic fields in Table 2 are described further in Sections 3.1.1 and 3.1.2.

Fig. 1 shows the locations of these stars in a CMD superposed with evolutionary tracks by Christensen-Dalsgaard (1993) and locations indicated for stars that are predicted to be pulsationally stable or unstable (Cunha 2002). Luminosities are from distances based on Hipparcos measurements (ESA 1997) with considerable errors from the parallaxes indicated. Temperatures were estimated from the grids by Moon & Dworetsky (1985) based on $\beta$ photometry (Martinez 1993) alone.

### 2.2 Observations and data reduction

Our spectroscopic observations were obtained at the Very Large Telescope using UVES. The fast readout mode of 625 kpix s$^{-1}$ was used for reading out the two CCD mosaics on the red arm of UVES in the four-port low-gain mode. We observed our nine targets about 2 h each (see the observing log in Table 1) on the two nights of 2005 May 18–19 and 19–20 (JD 245 3509 and JD 245 3510), using exposure times of 40 s with 24–27 s readout and overhead times, giving a mean time resolution of 64 s. However, for the faintest
stars HD 110072 and HD 170565, exposure times were doubled to 80 s, which reduced the time resolution to 107 s. The total number of spectra per target ranges from 69 to 138. To ensure high count rates, an image slicer was used. The spectra were processed with the UVES pipeline and ESO MIDAS package to extract 1D spectra using nightly flat-field spectra and thorium–argon calibrations obtained at each telescope pointing. The spectra were extracted using the ‘average extraction’ option and the flat-fielded spectra from the two CCDs on the mosaic were rebinned to same step size in wavelength and combined in one spectrum. The rectification was performed in three steps. First, all spectra from the same night were normalized with a spline fit to a high-S/N spectrum of that night, only considering large-scale patterns, such as slopes. Next an undulating continuum pattern that followed the spectral orders was fitted with splines using averaged spectra of all spectra each night and then applied to eliminate the undulations in individual spectra. Finally, all spectra of the same series (i.e. of the same star) were rectified relative to a mean spectrum of that series. Removal of effects from cosmic rays and CCD blemishes in the spectra was made in two steps: cosmic rays were identified and removed by comparing each 2D CCD image with the previous and subsequent one, and the final, rectified 1D spectrum was corrected by a routine that identified and removed sharp emission features of non-stellar origin. For all spectra, the region $\lambda\lambda$ 6515–6535 Å suffers from spectrum-to-spectrum variability on the level of 10 per cent. A gap occurs in the region $\lambda\lambda$ 5963–6032 Å and is caused by the gap between the two CCD mosaic halves (referred to as ‘lower’ and ‘upper’).

For unknown reasons, our UVES reductions resulted in an increased noise in the spectra redwards of the gap, which varies from star to star but is particularly pronounced for HD 110072. This affects the accuracy of $v \sin i$, magnetic and RV measurements by increasing the noise for this spectral region, in some cases by 33 per cent. The effect is most clear when comparing the noise of cross-correlation results in the spectral regions bluer and redder than the gap (Table 5), or when comparing noise in co-added series of spectra of individual stars on both sides of the gap. The effect varies for individual stars and we suspect the origin of the problem to be found in the reduction of the spectra. During observations, it is more difficult to keep an object on the slicer when observing very close to zenith. This also affects the S/N and was indeed the case for HD 110072 and HD 131750 that were both observed at about 10° distance from zenith. However, as the performed RV analyses utilize regions on both sides of the gap, including the unaffected 1000 Å wide region below the gap, and do reach precisions comparable to those published in the literature for roAp stars, the current quality of the reductions suffice for the aims of this investigation.

The zero-point of the absolute wavelength calibration is of little importance for the differential RV analysis, but was found accurate to the level of 300 $\pm$ 200 ms$^{-1}$ based on the telluric line list by Griffin & Griffin (1973). This is as good as one may expect from RVs of telluric lines that depend on conditions in the Earth’s upper atmosphere. Barycentric velocity corrections were recorded in the FITS headers of the reduced spectra for the later analysis of the velocity fields, and not included in the wavelength calibration.

3 DATA ANALYSIS AND RESULTS

Our aim with this study was to search the spectra of nine roAp candidates for rapid oscillations and through simple estimates of physical properties to characterize the detected noAp or roAp stars. For this purpose, we used the cross-correlation technique and centre-of-gravity procedure to search for rapid pulsation using, respectively, Doppler shifts of whole wavelength regions and of individual and combined line profiles. Stellar properties were estimated with photometry and/or by comparison of observed spectra to synthetic line profiles.
For the purpose of spectral line identification, a synthetic comparison spectrum was produced with SYNTH (Piskunov 1992) using a Kurucz stellar atmosphere model for $T_{\text{eff}} = 8750$ K, turbulent velocity $2 \text{ km s}^{-1}$, $\log g = 4.0$ and slightly increased solar metal abundance $\log N(Z)/N(Z, \odot) = +0.5$. Atomic line data were taken from the Vienna Atomic Line Database (VALD, Kupka et al. 1999) for increased abundances mainly for the elements Nd, Pt, Sr, Cr, Eu, as given in Table A1. Other sources used for line data were the atomic data base NIST\(^1\) and the Database on Rare Earths at Mons University (DREAM\(^2\)) through its implementation in the VALD. This model’s temperature is less optimal for the coolest of the studied stars, but still appropriate for selecting lines for the RV analyses.

In the following section we describe the estimation of stellar physical parameters for the examined sample, the RV measurements and frequency analyses, and a performance test carried out on UVES data for two known roAp stars.

### 3.1 Analysis

The present study is a survey for variability, and therefore an analysis of abundances, temperatures, surface gravities and projected rotational velocities is outside the scope of this paper. Such an analysis must take the chemical element stratification, and possibly also temperature gradients, into account. We do, however, in Table 2 give estimates of $v \sin i$, effective temperatures and magnetic fields of the studied sample.

#### 3.1.1 Temperatures and rotational velocities

The spectra of Ap stars have flux distributions that are deformed by strongly peculiar elemental abundances. Calibrations based on Strömgren indices may therefore not provide reliable estimates of temperatures and surface gravity, $\log g$. The $\beta$ index, however, remains largely unaffected by this. Effective temperatures were thus estimated with the $c_0$, $\beta$ grids by Moon & Dworetsky (1985) using $\beta$ from Table 2 (from Martinez 1993). We allowed the value of $c_0$ to be free in these grids, fixed $\beta$ and assumed $3.5 \leq \log g \leq 4.0$. The resulting photometric temperatures are given in Table 2. An additional check on $T_{\text{eff}}$ was made by comparing synthetic line profiles to the observed spectra. This method is sensitive to normalization errors in the Hz region (Fig. 2, the above-mentioned undulations), and the core–wing anomaly in this line (Cowley et al. 2001) that prohibits fitting the atomic line profile with normal models. However, the average deviation of the photometric and spectroscopic temperatures is only 5 per cent, with the exception of HD 131750 which has a 17 per cent higher spectroscopic temperature. Moon & Dworetsky’s grids are furthermore ambiguous for $T_{\text{eff}} > 8500$ K and in those cases the spectroscopic temperatures of HD 132322 and HD 204367 were 8250–9250 K and 8000–8250 K, respectively. The synthetic line profiles were based on Kurucz atmospheres (Castelli & Kurucz 2003) and atomic line data from the VALD data base using increased REE abundances (identical for all models). The grid of models had $T_{\text{eff}} = 7000$–10500 K in steps of 500 K with $\log g = 3.5$, 4.0 and, in a few cases, 4.5. Best fits were obtained for $\log g = 3.5$–4.0, mainly to the lower side of this range. Better estimates of $T_{\text{eff}}$ require a detailed abundance analysis that takes stratification and magnetic fields into account, which will not be done here.

Projected rotation velocity estimates were made by measuring the Fe i lines $\lambda\,5434.52$ and 5576.08 Å that are rather insensitive to magnetic broadening. Synthetic models for $\log g = 3.5$ were compared to the spectra for a range of iron abundances and rotational broadening, using models corresponding in temperature to the individual stars. The macroturbulence was varied in the range 1–4 $\text{ km s}^{-1}$. When strong line blending hampered the measurements, additional iron lines were used to constrain the estimates. The derived velocities were then refined with synthetic models that took magnetic broadening into account (SYNTHMAG, Piskunov 1999). The analyses of several, typically 20–30 iron lines that determine the mean quadratic magnetic fields also give precise rotation velocities (Mathys & Hubrig 2006). These values are formally more precise than, but consistent with, the above estimates and are therefore given in Table 2, except for the case of HD 170565 where only the first estimate is given. It should be noted, though, that the values of the rotation velocities that are obtained as part of the analysis performed to determine the mean quadratic magnetic field are upper limits on the $v \sin i$, since they may actually include contributions from other line-broadening effects that are proportional to wavelength, such as microturbulence or macroturbulence. (Instrumental and thermal broadening are however dully isolated – see Mathys & Hubrig (2006) for details.) However, these contributions are mostly negligible, except in the slowest rotating stars.

#### 3.1.2 Magnetic fields

Known roAp stars have strong magnetic fields (Kurtz et al. 2006a), and we therefore searched for magnetically resolved or broadened lines in the spectra of the roAp candidates. Many Ap stars have fields that are measurable only with polarimetry. It takes a strong field, typically exceeding $\sim 1.5 \text{ kG}$, combined with a slow projected rotation rate ($\text{smaller than } v \sin i \sim 10 \text{ km s}^{-1}$) to produce magnetically resolved lines by the Zeeman effect (Mathys et al. 1997).

In the simplest cases of spectral lines corresponding to doublet or triplet Zeeman patterns, simple formulae can be applied to determine in a virtually approximation-free manner the mean magnetic field modulus $B$ from measurement of the wavelength separation of the resolved Zeeman components (Mathys 1989). $B$ is the average of the modulus of the magnetic vector, over the visible stellar hemisphere, weighted by the local line intensity. For a triplet pattern, its value (in G) is obtained from the wavelength separation between the central π component and either of the σ components, $\Delta \lambda$, by application of the formula

$$B = \Delta \lambda / (4.67 \times 10^{-13} \lambda_c^3 \, g_{\text{eff}}),$$

(3)

where $\lambda_c$ is the central wavelength of the line and $g_{\text{eff}}$ is the effective Landé factor of the transition. Both $\Delta \lambda$ and $\lambda_c$ are expressed in Å. For a doublet pattern, the relation between the field modulus and the wavelength separation of the split components (each of which is the superposition of a π and a σ component) is

$$B = \Delta \lambda / (9.34 \times 10^{-13} \lambda_c^3 \, g_{\text{eff}}).$$

(4)

Note that equation (4) also describes the relation between $B$ and the wavelength separation of the red and blue σ components of a triplet.

Mainly due to smearing by rotational broadening, only one of the studied stars (HD 208217) has clearly resolved lines from magnetic splitting that can be used with equation (3) or (4) to estimate the field strength directly. In another star, HD 107107, magnetic splitting and rotational broadening are comparable for the lines with the highest magnetic sensitivity, so that it is possible to obtain an estimate of

\(^{1}\)http://physics.nist.gov.

\(^{2}\)http://w3.umh.ac.be/~astro/dream.shtml.
the surface magnetic field by fitting synthetic profiles to these lines. This estimate, which we shall denote by \(\langle B_{\text{synth}} \rangle\), should be of the same order of magnitude as the mean magnetic field modulus, but it is not entirely equivalent to the latter. (In particular, \(\langle B_{\text{synth}} \rangle\) is model dependent, while \(\langle B \rangle\) is not.)

For the other stars we estimated the surface magnetic field from consideration of the magnetic broadening and intensification of magnetically sensitive lines. By assuming that a line’s full width at half-maximum (FWHM) increases linearly with the separation of its (unresolved) Zeeman-split components, we used equation (4) to obtain an estimate \(\langle B_{\text{FWHM}} \rangle\) of the magnetic field by comparing lines with different effective Landé factors (see also Preston 1971). The assumption is justified as long as the magnetic splitting of the analysed lines is small compared to their overall width (in particular, due to rotational broadening); then, \(\langle B_{\text{FWHM}} \rangle\) should typically be comparable to \(\langle B \rangle\) or \(\langle B_0 \rangle\) (see below).

Other estimates of the magnetic fields were obtained by comparing the observed spectra to magnetically resolved or broadened line profiles to determine \(\langle B_{\text{synth}} \rangle\). These models were synthesized with SYNTHMAG for a temperature grid of \(T_{\text{eff}} = 7500, 8000\) and 8500 K. For this comparison, Cr and Fe lines with low Landé factors were used to fix abundances and the rotation rate of the models prior to applying them to magnetically resolved or broadened lines. Instrumental broadening of 0.05 Å was adopted while the macroturbulence was fixed for each star within the range 1–4 km s\(^{-1}\). This approach worked well for magnetically broadened lines because both the equivalent width and the FWHM are affected by magnetic broadening; when absorption in a line is intrinsically spread over a larger wavelength range, the absorption becomes more effective, increasing the equivalent width (magnetic intensification). Again, the quantity that is derived should be comparable to the mean magnetic field modulus, but in general is not exactly equal to it.

Finally, the values of the mean quadratic magnetic field, \(\langle B_\theta^2 \rangle = (\langle B_\theta^2 \rangle + \langle B_z^2 \rangle)^{1/2}/2\), were derived through application of the method described in Mathys & Hubrig (2006). Here \(\langle B_\theta^2 \rangle\) is the mean square magnetic field modulus (the average over the stellar disc of the square of the modulus of the field vector, weighted by the local emergent line intensity), while \(\langle B_z^2 \rangle\) is the mean square longitudinal field (the average over the stellar disc of the square of the line-of-sight component of the magnetic vector, weighted by the local emergent line intensity). The analysis was based on consideration of samples of reasonably unblended lines of Fe i and Fe ii; the number of analysed lines varies from star to star and ranges from 14 to 33. This approach could not be successfully applied to HD 170565, for which the number of usable diagnostic lines (9) proved insufficient to untangle the contributions of the magnetic field (probably fairly strong), non-negligible rotation and a possibly inhomogeneous distribution of iron on the stellar surface. The mean quadratic magnetic field is typically a few per cent greater than the mean magnetic field modulus.

For three stars, we also indicate in Table 2 values of the mean longitudinal magnetic field \(\langle B_\theta \rangle\) and the magnetic field modulus \(\langle B \rangle\) from the literature. \(\langle B_\theta \rangle\) is the average over the stellar disc of the component of the magnetic vector along the line of sight, weighted by the local emergent line intensity. This field moment strongly depends on the geometry of the observation, and contrary to e.g. \(\langle B \rangle\) or \(\langle B_0 \rangle\), it typically varies considerably during a stellar rotation cycle. Accordingly, it is not well suited to characterize the strength of the magnetic field in a star, other than to give (through its absolute value) a generally very conservative lower limit of the latter. But significant measurements of \(\langle B_\theta \rangle\) at least provide definitive evidence that a star is magnetic.

### 3.1.3 Radial velocity shifts

Precise RV shifts were measured for several spectral lines with the centre-of-gravity method and by fitting with Gaussian profiles. We used the local continuum in the selected subregions of measured lines, which gave consistent amplitudes for both methods in tests on UVES spectra for known roAp stars (see below). The centre-of-gravity method was preferred due to its stability and better ability to deal with blended line profiles. For strong and isolated lines, the two methods were comparable. Table 3 gives the most important spectral lines used, but the actual selection of lines depended on line blending and composition for each stellar case.

Additionally, line shifts were determined by cross-correlating the spectra with averaged spectra of each series. The maxima of the correlation functions were determined with a spline fit, which was found more reliable and stable than with Gaussian or fourth-order polynomial functions. The cross-correlation regions were chosen to be free of static features: \(\lambda\lambda 5150–5800, 6035–6273, 6350–6700\) and 6510–6570 Å. However, to check for non-stellar periodicities, we also used two regions dominated by telluric or the interstellar lines of Na D: \(\lambda\lambda 5888–5898\) and 6873–6899 Å. Because the UVES pipeline produces merged spectra in the linear wavelength scale only, we re-binned the selected regions of the spectra to log wavelength which is more appropriate (Tonry & Davis 1979) when determining velocity shifts using large wavelength regions. For each region, the size of the bins was optimized according to pixel size and local spectral resolution.

Because of the stratification of Ap star atmospheres, high-order mode pulsation amplitude and phase may change from element to element. Therefore the amplitudes of cross-correlation velocities cannot be directly compared to measurements of individual lines. Nevertheless, cross-correlation is efficient for detecting pulsations by using long wavelength regions with numerous lines to obtain high S/N.

Table 3. List of laboratory wavelengths of the most important lines used in the RV measurements based on the centre-of-gravity method. Note that due to broadening and abundance differences among the roAp candidates, not all lines could be used for all stars, and in some cases line blending made it necessary to include close lines in the measurements. Laboratory wavelengths have been taken from NIST, DREAM and VALD. For comparison with the stellar lines a few telluric lines were used (\(\lambda\lambda 5919.2, 5946.0, 5949.2, 6278.9\) and 6889.9 Å).

| Line   | Wavelength (Å) |
|--------|----------------|
| H i    | 6562.852       |
| Li i   | 6707.761       |
| Na i   | 5895.924, 5889.951 |
| Ca i   | 6122.217, 6162.173 |
| Cr ii  | 5280.054, 5310.687 |
| Fe i   | 5434.524, 6136.614, 6137.694 |
| Fe ii  | 5061.718, 5284.109 |
| Ba ii  | 5853.675, 6141.713 |
| Ce ii  | 5077.854, 5117.946, 5147.565, 5459.193, 5468.371, 5613.694, 5680.261, 5711.437, 5858.546 |
| Pr ii  | 5220.108, 5605.642, 6114.381 |
| Pr iii | 5208.507, 5284.693, 5299.993, 5844.408, 5956.043, 6053.003, 6090.010, 6160.233, 6195.619, 6866.793 |
| Nd ii  | 5319.811, 5356.967, 5361.467, 5620.594, 6425.779, 6650.178 |
| Nd iii | 5085.001, 5203.902, 5286.764, 5825.857, 5845.068, 6145.072, 6327.244, 6505.326 |
| Eu ii  | 6437.680, 6645.064 |
| Gd ii  | 5860.727       |
IDL tools for line and cross-correlation measurements and analyses were developed and tested on UVES spectra of the known roAp stars 33 Lib and HD 154708, published by Kurtz et al. (2005) and Kurtz et al. (2006b), respectively. For 33 Lib, we confirm two frequencies, 2.015 and 1.769 mHz (Fig. 3), which are in excellent agreement with the published frequencies, amplitudes and noise levels for lines of Eu II and Hα. Similarly, we find amplitudes of 32 ± 5 ms^{-1} for Ca I and Ti II lines and 130 ± 13 m s^{-1} for Ba II. A telluric line (6888.96 Å) shows only noise with a highest amplitude of 9 ± 3 ms^{-1}. We also made cross-correlation measurements of the above-mentioned wavelength regions and recovered the 2.015 mHz frequency with amplitudes in the range 20 ± 2 to 50 ± 5 m s^{-1}. All cross-correlation and line measurements gave similar significance S/N = 10, although at very different amplitudes (see also Fig. 3).

The second test, the new roAp star HD 154708, was even stronger as this star pulsates with amplitudes that are among the smallest known for roAp stars. Kurtz et al. (2006b) needed to combine RV measurements for several lines of this star in order to detect its rapid oscillation. We confirm that no individual line (including Hα) shows signal on or above the 4σ level. Yet, as seen in Fig. 4, we directly recover the known 2.088 mHz mode with cross-correlations in the lower region of the spectra, λλ 5150–5800 Å, with S/N = 6.2, and a marginal detection (110 ± 32 m s^{-1}) using the single line Pr III 5299.99 Å.

### 3.1.4 Frequency analysis

Frequency analyses were performed using a discrete Fourier transform programme (Kurtz 1985) and the PERIOD04 (Lenz & Breger 2005) programme. Linear trends in the individual ∼2h RV series were fitted and removed with linear least-squares fitting. The noise σ in the amplitude spectra (see Tables 4 and 5) is determined from least-squares fitting of harmonics to the data following Deeming (1975). Because the barycentric velocity correction is approximately linear for each series of spectra, and rather small (the correction varies from 44 to 150 m s^{-1} h^{-1} for the nine stars), it was eliminated with other drifts by a linear fit before the frequency analysis. With the 0.3 arcsec slit and seeing conditions of 0.9–1.4 arcsec, the centring error for UVES is 50–100 m s^{-1} according to Bouchy et al. (2004). Furthermore, a 1-mbar change in pressure may induce drifts of 90 m s^{-1}. During each of our observing nights, the pressure changed 1.5–2.0 mbar. We therefore expect instrumental drifts of up to 280 m s^{-1} per night, depending on seeing and pressure, and less during a 2-h series on a star. The drift during a series of spectra may be non-linear (which is what we actually see in some cases). We noted that comparison lines or regions with non-stellar constant lines occasionally exhibit drifts that are not seen for other regions of the same spectra (such as in Fig. A10, panel ‘Tell’). This difference may be because the strong and sharp telluric lines result in higher sensitivity, and they are influenced by fast wind speeds in the high layers of the Earth’s atmosphere where telluric lines are formed.
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Figure 3. Amplitude spectra for the known roAp star 33 Lib. Top: the 2.015 mHz frequency for the Eu II 6645.06 Å line. Bottom: cross-correlation (see text) for the region $\lambda\lambda$ 5150–5800 Å. The frequencies 2.015 mHz, its harmonic 4.030 and 1.769 mHz are recovered. Note different ordinate scales.

The null results are presented on a star-by-star basis in Sections 3.2–3.10. We emphasize the statistical fact that when calculating about 50 amplitude spectra for each of nine candidate roAp stars, the chance for a spurious peak to reach the $4\sigma$ level increases. Furthermore, the analyses show several combined amplitude spectra with single, prominent peaks reaching 3–4\sigma. However, the reality of such peaks is that they often originate from shallow and blended lines. Our criteria for detecting rapid oscillations are therefore as follows. (i) A peak of four times the noise (see Breger et al. 1993; Kuschnig et al. 1997) in an amplitude spectrum, (ii) confirmation in an amplitude spectrum for either a line, or combination of lines, of a different ionization or element, or cross-correlation region and (iii) only frequencies above 0.4 mHz (42 min) are considered. The latter is because we have less control over drifts on these time-scales in the wavelength calibration (i.e. we did not observe simultaneous reference spectra). Lower frequencies are not typical for known roAp stars and may be due to e.g. stellar rotation and surface spots. As an upper limit of the studied frequency range we use 6 mHz. The sampling frequency is either 9.5 or 15.6 mHz, and the Nyquist frequency is half of that but still above the frequencies in known roAp stars.

In the following sections, we comment case by case on the individual stars in our sample.

3.2 HD 107107

With a magnitude of $V = 8.734$, this star is one of the faintest in our sample. Martinez (1993) obtained 1.89-h photometry during a single night and excluded periodic variability above 0.3 and 0.7 mmag for frequencies higher than 1.0 and 0.4 mHz, respectively. Based on his $\beta$ photometry (Table 2) the corresponding temperature from the grids by Moon & Dworetsky (1985) is 8300 K. The Hipparcos mission obtained 100 useful measurements; an amplitude spectrum of those has a noise level of 3.1 mmag and excludes peaks above 9 mmag. The distribution of Hipparcos data is, however, not well suited for detecting rapid oscillations, but may instead show rotation periods of spotted stars. The Michigan Spectral Catalogue (Houk & Cowley 1975) classifies the star as Ap CrEuSr. No spectroscopy has been previously published for HD 107107.

Our observations of this star comprise 111 UVES spectra obtained over a time-span of 1.94 h with 63-s time resolution. The spectra are rotationally broadened to $v \sin i = 10.5 $ km s$^{-1}$ (Table 2) and have single and strong REE lines. The star is very peculiar with strong Nd III and Pr III lines, probably with a large ratio between abundances of singly and doubly ionized REEs. The latter could indicate ionization disequilibria of REEs, a common feature among known roAp stars (Ryabchikova et al. 2004). The Na D $\lambda\lambda$ 5889.95 and 5895.92 Å lines each have a stellar and two interstellar components that are sharper, stronger and red-shifted with respect to the stellar one.

RV shifts of 47 stellar lines were measured (Table 4) using the full line profiles where line blending permitted it. The core of $H\alpha$ is constant to 65 m s$^{-1}$ ($\sigma = 20 $ m s$^{-1}$) and other lines also exhibit no detectable variability in the considered frequency range (0.4–6.0 mHz). Table 4 and Fig. A3 show selected results of the atomic lines measured in the frequency analysis. As indicated in the table, RV series for different lines of same species were combined following Kurtz et al. (2006a) to reduce the noise. Combining all line measurements, including different species, we reach $\sigma = 8 $ m s$^{-1}$ and a maximum amplitude of 34 m s$^{-1}$. One peak at 1.8 mHz (panel ‘HD 107107 all’) is just above the 4$\sigma$ detection limit, but originates...
Table 4. Frequency analyses from combination of individual line shifts determined for multiple lines of different species with the centre-of-gravity method. The highest amplitude in each stacked amplitude spectrum is given as $A_{\text{max}}$. $'n'$ indicates number of measurements, typically number of lines or components in case of double structures. Linear shifts have been fitted and removed separately from each time-series. See Table 3 for a listing of the lines typically used. Low-frequency peaks (0.4 mHz or below) were excluded from the noise estimates and not considered for significance. ‘Nd,Pr’ indicates combined RV series for all possible Nd and Pr lines.

Table 5. Frequency analyses from cross-correlations. Low-frequency peaks (0.4 mHz or below) were excluded from the noise estimates and not considered for significance. These six regions essentially cover the spectrum bluer than the 6000-Å gap, two regions redder than the gap and avoiding the weak telluric line region at λλ 6275–6320 Å, the Hα region, the region with the Na D doublet and a comparison region dominated by telluric lines.

from weak and blended Nd III lines. Yet, this ion has some of the highest amplitudes in roAp stars and is excellent for detecting rapid pulsations. However, this peak cannot be confirmed by lines of other elements, so following the criteria in Section 3.1.4 we rather label it a possible detection that needs confirmation. Other lines (such as Eu II) show peaks near the detection limit, but again the frequency analysis is not confirmed elsewhere. This demonstrates the difficulty in reliable detection of signal at this noise level. Selected results of the cross-correlation analysis, presented in Table 5 and Fig. 5, strengthen this null result. For the five stellar wavelength regions defined in Section 3.1.3, the noise in the cross-correlation RV shifts is around 4 m s$^{-1}$ without significant peaks above 15 m s$^{-1}$. This is comparable to the result for the stable telluric line region (λλ 6873–6899 Å).

Some Cr II and Fe II lines are magnetically broadened or partially resolved and the mean quadratic field determined for 27 iron lines is $\langle B \rangle = 5.2 \pm 0.4$ kG. Using measured FWHM of 25 Fe lines, we derive (Fig. 6) a field strength of 3.4 ± 0.6 kG (1σ error). Due to the combination of marginally resolved lines, rotational broadening and line blending, the use of apparently double lines gave less consistent results that, however, support existence of a strong magnetic field. SYNTHMAG synthetic profiles for different magnetic field strengths were computed and compared to CrII 5116.049, CrII 5318.382, CrII 5247.566 and Fe II 6149.25 Å. The best fit was obtained for a magnetic field strength of $\langle B_{\text{synth}} \rangle = 4.5 \pm 0.5$ kG (estimated error). The magnetic field modulus was further estimated directly to be $\langle B \rangle = 5.6 \pm 2.3$ kG from separations of the partially resolved components of five Cr II, Cr II and Fe II double lines using Gaussian fitting.

HD 107107 is, therefore, a chemically peculiar A star that is pulsationally stable above 39 m s$^{-1}$ (σ = 12 m s$^{-1}$) for all Nd and Pr lines combined, and 9 m s$^{-1}$ (σ = 3 m s$^{-1}$) for cross-correlations. The star is a new magnetic star, with marginally resolved Zeeman-split lines and a field of $\langle B_q \rangle = 5.2 \pm 0.4$ kG.

### 3.3 HD 110072

This is the faintest star in our sample. Martinez (1993) excluded photometric variability above about 1.4 and 0.8 mmag for frequencies above 0.4 and 0.9 mHz, respectively, based on 67 min of photometry on a single night. The Hipparcos data show no significant peaks above 22 mmag at shorter frequencies. Houk & Cowley (1975) correctly note that HD 110072 is type Ap SrCr rather than K0 (SAO Staff 1966, classification source: M. W. Mayall).
We collected 69 spectra with UVES in 2.06 h with a time resolution of 107 s. The spectra are sharp lined: the estimated $v \sin i$ is only $3.3 \pm 0.5$ km s$^{-1}$ and many strong REE lines are visible, e.g. Pr, Nd, Y, Eu II and Ce II. Also Cr II, Fe II, Ni II, Co I and Al II are strong. In addition to a stellar component, the Na D lines each have three sharper and bluer (with respect to the stellar component) interstellar components of comparable strengths. The average spectrum is very similar to those of two known roAp stars 33 Lib and HD 176232 (Fig. A1). These have temperatures of $T_{\text{eff}} = 7550 \pm 150$ and $7550 \pm 100$ K, respectively (Ryabchikova et al. 2004), which is supported by the indistinguishable shapes of the H$\alpha$ wings of 33 Lib and HD 110072 ($T_{\text{eff}} = 7300$ K). All three stars have similar peculiarities for REEs, and Ba II, Si I and Ca I are considerably weaker in HD 110072.

The H$\alpha$ profile is strongly asymmetric (see Fig. 2) with a dip $\sim 70$ km s$^{-1}$ blueward of the H$\alpha$ core. This dip is only 3–4 per cent below the H$\alpha$ wing, but about 40 per cent broader (FWHM) than the H$\alpha$ core. We re-observed the star 2 yr later with FEROS at the ESO 2.2-m telescope and found this feature to have disappeared. This indicates that HD 110072 is a binary with a secondary star that may be less luminous than the primary. The broadness of the core of the secondary’s H$\alpha$ line can either be due to faster rotation ($\sim 50$ km s$^{-1}$) or a later spectral type (H$\alpha$ weakens towards G0). At other wavelengths, the UVES and FEROS spectra are largely identical and no secondary spectrum is seen (see also Fig. A1). However, a few lines appear only in the recent FEROS spectrum (resolution $R = 48000$) such as at locations of Sc 6151.20 Å, O 6156.77 Å, Sm 6157.53 Å, Nd 6549.52 Å and Fe II 6552.33 Å. These lines have a broadening similar to the primary’s spectrum. We suspect they originate from this star and their appearance is a result of viewing different aspects of a magnetic field and/or spotted chemical surface distribution combined with line blending.

RV shifts were measured for 49 stellar lines (Table 4) and show no detectable signal. The blended H$\alpha$ core is stable to 135 m s$^{-1}$ but the noise of $\sigma = 52$ m s$^{-1}$ in this RV series is considerable, caused by fewer spectra and lower S/N than obtained for the other roAp candidates. Highest significance ($3.9\sigma$) is seen for the combined Fe II lines at 1.86 mHz, but iron is known in other roAp stars to have low amplitudes, and there is no support for this frequency from other lines. Combining all 49 lines (Fig. A4) reduces the noise to 8 m s$^{-1}$, excluding peaks above 25 m s$^{-1}$. The cross-correlations in Table 5, with examples in Fig. 7, result in flat amplitude spectra above 0.45 mHz. A $4\sigma$ peak at 0.45 mHz is caused by non-linear drifts. The telluric line region is stable to 17 m s$^{-1}$.

The mean quadratic field determined for 33 iron lines is $\langle B_\alpha \rangle = 1.5 \pm 0.6$ kG. Comparison of 14 Cr and Fe lines with SYNTH-MAG models indicates broadening by a magnetic field of 1–3 kG, in particular for lines such as Cr II 5246, Cr II 5247, Fe I 5324 and Fe II 6149.25 Å. Measurements of FWHM of 27 iron lines with IRAF’s onedspec.splot task give (Fig. 8) a mean magnetic field modulus of $\langle B_{\text{FWHM}} \rangle = 1.5 \pm 0.3$ kG (1σ error).

HD 110072, the coolest star in our sample, with $T_{\text{eff}} = 7300$ K, is thus a sharp-lined, double-lined binary with strongly peculiar lines of, e.g. Nd, Pr and Eu. It is a new magnetic star with a field of $\langle B_\alpha \rangle = 1.5 \pm 0.6$ kG and has spectral features very similar to the roAp stars 33 Lib and HD 176232. It is therefore intriguing that the star is pulsationally stable to 42 m s$^{-1}$ ($\sigma = 10$ m s$^{-1}$) for all Nd and Pr lines combined, and 12 m s$^{-1}$ ($\sigma = 3$ m s$^{-1}$) for cross-correlations. The slow rotation of HD 110072, its peculiar abundances and the rare combination of a magnetic field and its binary status makes it an important case for studying stellar evolution and diffusion processes.

### 3.4 HD 131750

For this star, the classification of Houk & Cowley (1975) is Ap CrEuSr. Martinez (1993) observed it 1–2 h on each of three nights. The first night showed a clear peak around 8.5 mHz (which is outside the range we consider), but the other nights showed no variability above 0.6 mmag for $f > 0.6$ mHz. Strohmeier, Fischer & Ott (1966) listed an unconfirmed 0.35 mag variability from...
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Figure 7. Amplitude spectra from cross-correlation for the HD 110072 spectra. Top: for the wavelength region \(\lambda\lambda\) 5150–5800 Å; bottom: for the wavelength region \(\lambda\lambda\) 6350–6700 Å.

Figure 8. Magnetic broadening measurements of 27 Fe lines in HD 110072 plotting the measured Gaussian FWHM (\(\Delta \lambda\)) versus the product of laboratory wavelength squared and Landé factor (\(\lambda^2 g_{\text{eff}}\)). A significant relation (\(r = 0.70\)), fitted with a least-squares linear fit, is indicated with a line.

photographic plates (no period given). Hipparcos data do not support this.

Our 111 spectra, obtained in 1.98 h with a time resolution 64 s, show HD 131750 to be rotating with \(v \sin i = 25.3\) km s\(^{-1}\) with strong lines of Nd, Eu and Pr. The Na D doublet is strong with multiple sharp interstellar components. RV shifts of 40 stellar lines were measured (Table 4). The noise in the RV measurements is relatively high due to the rotation rate. The core of Hz is stable to 72 m s\(^{-1}\) (\(\sigma = 21\) m s\(^{-1}\)), while all measured lines combined (Fig. A5) reveal no rapid pulsation above 39 m s\(^{-1}\) (\(\sigma = 8\) m s\(^{-1}\)). The cross-correlations provide an upper limit of 9–15 m s\(^{-1}\) to the averaged RV shifts of the measured regions. Flat amplitude spectra of two of these regions are given in Fig. 9. The Na D region has a significant peak at 0.45 mHz caused by non-linear instrumental drifts in the data. Elsewhere, the amplitude spectra are flat, devoid of significant peaks.

Some of the stellar line profiles have flat ‘squared’ cores, such as Cr II 5613.18 and Fe II 5854.19, and others have apparently split cores such as Fe II 5457.73, Cr II 5472.60 and Fe I 5862.35. Magnetically resolved lines require a Zeeman splitting at least comparable to rotational broadening, in this case around \(\langle B \rangle = 8\) kG. The mean quadratic field was derived to \(\langle B^2 \rangle^{1/2} = 5.3 \pm 3.3\) kG by using nine iron lines. It is our impression that the upper limit on any magnetic field modulus (at this rotation phase) is 8 kG.

HD 131750 is thus an Ap star with strong REEs, no rapid oscillations above 58 m s\(^{-1}\) (\(\sigma = 18\) m s\(^{-1}\)) amplitude for all Nd and Pr lines combined, and 9 m s\(^{-1}\) (\(\sigma = 3\) m s\(^{-1}\)) for cross-correlations. The rotation rate \(v \sin i = 25.3\) km s\(^{-1}\) results in considerable line blending and the star may have a magnetic field of a few kG.

3.5 HD 132322

Houk & Cowley (1975) classify this star as ‘Ap SrCrEu, A1’ and note that Sr is extremely strong. Photometric Strömgren indices also indicate strong peculiarity. Martinez (1993) examined the star during a single night and excluded rapid photometric variability above 0.4 mmag for the frequency range 0.4–10 mHz. Levato et al. (1996) obtained two spectra of the star and found \(v \sin i = 85\) km s\(^{-1}\),
a somewhat high value for an Ap star. Additionally, Hubrig et al. (2006) discovered a mean longitudinal magnetic field of $357 \pm 51\, \mu G$.

HD 132322, $V = 7.357$ mag, is the second brightest star in our sample and the individual spectra have S/N well above 100. A total of 111 spectra were obtained in 2.03 h, providing a 66-s time resolution. The spectra appear to show splitting of all lines, such as Ba, Fe and Cr lines, and also of all REEs, such as Nd and Eu II. Surprisingly, even lines with small Landé factors are double (Fig. 10) which would indicate a spotted surface distribution rather than splitting of lines by a magnetic field. It is, however, improbable that all elements, in particular Fe, are split due to a spotted surface. In the course of the 2 h of observations, we do not find any systematic change in the RV difference of the components, nor in their centre of gravity. The estimated rotational broadening is $v \sin i = 25–35\, \text{km s}^{-1}$, based on the full double profiles, and $v \sin i = 34.3 \pm 1.8\, \text{km s}^{-1}$ from the quadratic magnetic field analysis, which together with the peculiarity results in considerable blending. Lines of Pr are not very strong but may also be double. The otherwise useful lines of Ce II are absent. For some roAp stars this ion has the highest pulsation amplitude, such as for $\beta$ CrB (Kurtz, Elkin & Mathys 2007). The Na D doublet is strong with a broad and a sharp (interstellar) component.

RV shifts measured for 34 stellar lines put an upper limit of $6–15\, \text{m s}^{-1}$ for $B_{\text{D}}$ of $300\, \text{km s}^{-1}$ and $B = 0\, \mu G$ is superposed (thin line) with its dominant atomic lines indicated.

Figure 10. Double-lined structures in the magnetically insensitive line Fe I 5434.52 in the averaged spectrum of HD 132322 (thick line). A synthetic model for $v \sin i = 30\, \text{km s}^{-1}$ and $B = 0\, \mu G$ is superposed (thin line) with its dominant atomic lines indicated.

Figure 11. Amplitude spectra from cross-correlation for the HD 132322 spectra. Top: for the wavelength region $\lambda \lambda 5150–5800\, \text{Å}$; bottom: for the wavelength region $\lambda \lambda 6550–6700\, \text{Å}$.

the other. This pattern is similar for lines of REEs, Cr and Fe (cf. Figs A2 and 10). A comparison of the H$\alpha$ profile to a synthetic spectrum, shifted in wavelength corresponding to the separation in the double structures, firmly excludes a secondary spectrum of a star of comparable brightness as it would have introduced a strong asymmetry. New high-resolution spectra are required to understand these double structures.

HD 132322 is a magnetic Ap star with projected rotation velocity $v \sin i = 34\, \text{km s}^{-1}$. All lines, even those of REEs, are double except for H$\alpha$. This can partly, but not fully, be explained by abundance spots or a secondary spectrum. Pulsations are excluded down to $37\, \text{m s}^{-1}$ ($\sigma = 13\, \text{m s}^{-1}$) for all Nd and Pr lines combined, and 6 m s$^{-1}$ ($\sigma = 2\, \text{m s}^{-1}$) for cross-correlations.

3.6 HD 151301

The star is classified Ap SrCrEu by Houk & Cowley (1975). Martinez (1993) observed it on six nights for 0.9–1.4 h each, and excluded pulsations down to 0.5–0.8 mmag for frequencies above 0.5 MHz.

We obtained 111 UVES spectra in 1.95 h at a time resolution of 63 s. The lines of REEs are strong (Nd, Pr, Eu) and many are double (see also Fig. 2) indicating abundance spots. The Na D lines have a stellar component and a sharp, strong interstellar line at longer wavelength. The photometric temperature is $T_{\text{eff}} = 8000\, \text{K}$ and the spectroscopy provides an upper limit $T_{\text{eff}} = 9000\, \text{K}$ for $\log g = 3.5$. With the astrometric luminosity of the star, this agrees with HD 151301 being more than halfway through its main-sequence lifetime.
RV shifts of 39 stellar lines were measured (Table 4). Lines of Pr II, Ce II and Nd II are weak with considerable scatter in their RV series. When combining all 39 lines, we find an upper limit on rapid pulsation of 18 m s$^{-1}$ ($\sigma = 6$ m s$^{-1}$), while the core of Hα is stable to 54 m s$^{-1}$ ($\sigma = 19$ m s$^{-1}$). Each double component of the two strongest Eu II lines was measured and the combined amplitude spectrum (Panel ‘Eu II’, Fig. A7) shows a significant (4.2σ) peak at 2.22 mHz. It is equally significant for the individual Eu II lines and when combining three available Eu II lines. No other line or combination of lines confirm this peak, including a few weak lines of La II and Ce II added to the analysis. Even cross-correlation of the whole Eu II profiles did not recover the 2.22 mHz frequency and it is therefore considered a probable, but unconfirmed detection. The spectrum of HD 151301 is rich in lines, and the cross-correlations reach a low noise level (Table 4), in particular in the bluer spectrum below the 6000 Å gap (1.4 m s$^{-1}$, Fig. 12). The spectrum region above the 6000 Å gap results in considerably larger noise (8–10 m s$^{-1}$) but also excludes significant rapid pulsations.

The rotational broadening is $\nu \sin i = 13.7 \pm 1.1$ km s$^{-1}$. Some Fe I and Fe II lines show additional broadening or asymmetric profiles. An upper limit of the mean quadratic field is found to $|B_0| \leq 2.4$ kG, using 18 Fe lines. SYNTHMAG fitting to Cr II 5313.56, Fe I 6137.69 and Fe I 5266.55 rejects magnetic fields stronger than 2 kG. However, from linewidth measurements of magnetic broadening of 13 Fe lines, a weak, possibly insignificant relation ($r = 0.50$) indicates $\langle B_{\text{RWM}} \rangle = 1.2 \pm 0.60$ kG.

HD 151301 is a strongly chemically peculiar star possibly having a magnetic field of up to 2 kG. The surface distribution of REEs is spotted. No pulsations are seen down to amplitudes of 24 m s$^{-1}$ ($\sigma = 8$ m s$^{-1}$) for all Nd and Pr lines combined, and 5.4 m s$^{-1}$ ($\sigma = 1.4$ m s$^{-1}$) for cross-correlations.

### 3.7 HD 170565

Martinez (1993) observed this star on five nights. In general, no pulsations are seen down to 0.7 mmag for frequencies above 0.5 mHz. However, the last two nights show two peaks around 1.7 and 2.6 mHz at 3–4 times the noise. The first of these is also present on the first and most intensively observed night. Kudryavtsev et al. (2006) detected a magnetic field in this star with a mean longitudinal field of $1.76 \pm 0.17$ kG.

We obtained 85 spectra of the star in 2.50 h with a time resolution of 106 s. The star is highly peculiar and has $v \sin i = 18$ m s$^{-1}$. There are many strong REE lines, such as those of Eu II, Ce II and Nd that are all double, indicating abundance spots. Pr II is less strong, but also double. As a result line blending is considerable. RV shifts of 41 stellar lines were measured and reject pulsations down to 32 m s$^{-1}$ ($\sigma = 8$ m s$^{-1}$) when combining all lines (Fig. A8 and Table 4). The core of Hα shows stability to 75 m s$^{-1}$ ($\sigma = 24$ m s$^{-1}$). There are no confirmed significant peaks in periodograms for any combination of RV series. Cross-correlations show stability down to 10–30 m s$^{-1}$ (Table 5 and Fig. 13). Only the $\lambda 6350$–$6700$ Å region shows a significant (4.2σ) peak at 2.59 mHz (the same as the second ‘transient’ photometric period). No other line measurements or cross-correlations support this unconfirmed detection. Cr is double or broadened while Fe is broadened in several cases. Magnetic measurements were tried with three methods: mean quadratic field measurements, SYNTHMAG fitting to four Cr and Fe lines, and from widths of 22 Fe lines. However, due to the rotation, line blending and a possible inhomogeneous stellar surface distribution of iron, it is not possible to constrain the known magnetic field with these data.

This star is a known magnetic star which is consistent with the present data. It is a chemically peculiar Ap star with a spotted surface distribution of Cr and REEs, and is pulsationally stable down to 32 m s$^{-1}$ ($\sigma = 10$ m s$^{-1}$) for all Nd and Pr lines combined, and 10 m s$^{-1}$ ($\sigma = 5$ m s$^{-1}$) for cross-correlations.

### 3.8 HD 197417

The classification for this object is Ap CrEu(Sr) (Houk & Cowley 1975), and the star has been investigated earlier due to its chemical peculiarities and photometric variability associated with its rotation period. Martinez (1993) observed the star on two nights. The corresponding amplitude spectra are flat and place an upper limit of 0.6 mmag on photometric variability. Floquet et al. (1984) studied this star and found a photometric rotation period of 4.551 ± 0.002 d. With spectra obtained at 12 Å mm$^{-1}$ dispersion, they used Balmer and Ca II lines to determine $T_{\text{eff}} = 9500$ K and $\log g = 4.0$, and from Mg II 4481 Å they measured $\nu \sin i = 23$ km s$^{-1}$. A strong variability was noted in the intensity and profile of Ca II 3922 Å and by assuming an oblique rotator geometry and a spotted surface distribution of elements, they proposed an inclination of $i = 64^\circ$ (angle of the stellar rotation axis to the line of sight) and that Ca II, Eu II and Sr II in particular seemed located in a common spot. From 156 Hipparcos measurements we do not find this period significant, but cannot reject it based on the noisier Hipparcos data alone. Based on four spectra, Levato et al. (1996) listed the star as probably single (25 per cent chance for random velocity distribution). Paunzen, Stitz & Maitzen (2005) list the star as a confirmed chemically peculiar star with $\Delta a = 0.054$ and $(b - y)_0 = 0.032$. 

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**Figure 12.** Amplitude spectra from cross-correlation for the HD 151301 spectra. Top: for the wavelength region $\lambda \lambda 5150$–$5800$ Å; bottom: for the wavelength region $\lambda \lambda 6350$–$6700$ Å.
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HD 197417 has the second highest $\delta c_1$ $(0.015)$ of our sample, and the 125 UVES spectra, obtained in 2.20 h at 63-s time resolution, show weak lines of REEs; Pr II, Pr III and, e.g. Nd III 6530.32, 6145.07 and 6327.24 Å are almost absent (2–4 per cent below the continuum). Both Eu II 6437.68 and 6645.06 Å lines are weak (less than 5 per cent below the continuum). Some REE lines are partially split, e.g. Pr III 6866.80, Eu II 6437.64 and Eu II 6645.06 Å, which may indicate that the stellar surface is spotted. This may in combination with the rotation $v \sin i = 25.5$ km s$^{-1}$ partly explain the weak REE lines of this Ap star. Lines of Co I, Fe II and La II are strong, while a weak Ca I supports the high photometric temperature, $T_{\text{eff}} = 8400$ K. Ce II is absent. The Na D lines have a stellar component and a sharper interstellar component at longer wavelengths.

RV shifts of 33 stellar lines were measured (Table 4 and Fig. A9). The noise is considerable due to the low peculiarities and line blending due to rotational broadening, but the RV series for the core of H$\alpha$ alone, or all 33 lines combined, exclude rapid pulsation to 48 m s$^{-1}$ ($\sigma = 13$). Cross-correlations result in flat amplitude spectra down to 5–10 m s$^{-1}$ (see e.g. Fig. 14). Magnetically sensitive lines, such as Cr II 5116.04, Fe II 6149.25 and Fe I 6232.64 Å, are not magnetically resolved. Comparison of eight Fe and Cr lines with magnetically broadened SYNTHMAG profiles, and also an attempt to measure the mean quadratic field using 20 lines, exclude magnetic fields above $\sim 2$ kG. Due to considerable line blending, smaller fields cannot be quantified without polarimetric measurements.

HD 197417 does not appear to have strong REE abundances in the wavelength regions we cover. This may, however, be an effect from a spotted surface distribution of REEs and rotational broadening. The existence of an inhomogeneous surface distribution of REEs is supported by the star’s known (rotational) photometric period and the many double REE lines. A spotted surface on Ap stars can often be related to presence of a magnetic field, for which we in this case put an upper limit at 2 kG. The star is stable to 65 m s$^{-1}$ ($\sigma = 20$ m s$^{-1}$) for all Nd and Pr lines combined, and 5 m s$^{-1}$ ($\sigma = 2$ m s$^{-1}$) for cross-correlations. The significant rotation $v \sin i = 25.5$ km s$^{-1}$ does, combined with blending from the many double lines, limit the lines available for analysis.

3.9 HD 204367

The Michigan Spectral Catalogue lists the star as A(p SrEuCr) and notes that it is either a weak Ap star, or a normal star of spectral type A0IV/Vs. Supposedly due to this, Martinez (1993) did not make any time-series photometry of this object. The star has the highest $\delta c_1$ $(0.020$ mag) and $c_0$ index in our sample. Because HD 204367 is one of the least evolved of the studied stars (Fig. 1), the high indices rather indicate a less peculiar spectrum rather than a higher luminosity. Manfroid, Burnet & Renson (1998) obtained 21 measurements (one per night) in the Geneva photometric system of this Ap candidate and found no variability (mmag level) over a 23-night run. With 90 Hipparcos measurements, we find the star stable to 6.5 mmag for periods longer than a day.

We obtained 111 spectra of this moderate rotator ($v \sin i = 10.8$ km s$^{-1}$) in 1.96 h at a time resolution of 64 s. The spectra revealed the least chemically peculiar star in this study, with considerably fewer lines and longer continuum windows than any of the other stars. Lines of Nd, Pr, Ce and Cr are either absent or much weaker than in the other studied stars. The absorption of Eu II is in
all cases less than 2 per cent below the continuum and only a few REE lines could be used in the velocity analysis. Lines of Ni, Si, S, Na, Ba and Zn are strong.

RV shifts of 38 stellar lines were measured. The noise is considerable, but when combining all lines (Fig. A10), we can exclude rapid pulsation with amplitudes above 56 m s\(^{-1}\) (\(\sigma = 12\) m s\(^{-1}\)), and 46 m s\(^{-1}\) (\(\sigma = 14\) m s\(^{-1}\)) for the H\(\alpha\) line core alone (Table 4). There are no significant peaks in the periodograms. Cross-correlations produce similar ‘flat’ amplitude spectra (Table 5 and Fig. 15).

An upper limit of the mean quadratic field is found with 27 Fe lines to \(\langle B_q \rangle \leq 1.4\) kG, while SYNTHMAG models compared to 16 Cr and Fe lines gave an upper limit of \(\langle B_{\text{synth}} \rangle \leq 1\) kG. Further, line width measurements of 33 iron lines showed a weak relation (Fig. 16) that would indicate a rather weak field of 0.77 \(\pm 0.24\) kG (1\(\sigma\) error). This fit is, however, barely significant as a significance test only gave \(t = 2.9\) while \(t > 3.0\) is required. Polarimetry is therefore needed for verification.

This star shows no detectable periodic variability down to 72 m s\(^{-1}\) (\(\sigma = 25\) m s\(^{-1}\)) for all Nd and Pr lines combined, and 5 m s\(^{-1}\) (\(\sigma = 2\) m s\(^{-1}\)) for cross-correlations. Rotation is slow (\(v \sin i = 10.8\) km s\(^{-1}\)), the spectrum is nearly devoid of REEs, and the star may have a small magnetic field of \(\sim 0.8\) kG.

### 3.10 HD 208217

This known magnetic and peculiar star, classified as Ap SrEuCr, A1 (Houk & Cowley 1975) has been previously examined in several studies. Martinez (1993) spent nearly 13 h on the star on eight separate nights. With \(\delta c_1 = -0.19\) it is strongly peculiar. The high-speed photometry excludes periodicities above 0.4 mmag (frequencies above 0.8 mHz) and 0.8 mmag (frequencies above 0.5 mHz). With spectroscopic observations, Mathys et al. (1997) detected a mean magnetic field modulus varying with a semi-amplitude of nearly 1000 G about a mean value of 7958 G (\(\sigma = 588\) G) over a rotation period of 8.44475 d (Manfroid & Mathys 1997). For this period, the epoch of our spectroscopic observations occurs near a negative extremum of the longitudinal field (Mathys, unpublished observations). For roAp stars, maximum pulsation amplitude occurs when one of the stellar magnetic poles come into sight. In this case the negative magnetic pole, and our chances for detecting roAp pulsations should therefore be optimal. Mathys et al. furthermore found the star to be a single-lined binary with a most likely orbital period of at least 2 yr.

With a typical S/N of 150 per spectrum, this set of 138 UVES spectra obtained in 2.52 h with a 66-s time resolution has the highest quality of this study. The spectra show strong lines of Nd, Pr and Eu II, while Ca I is weak which could indicate a higher temperature than the \(T_{\text{eff}} = 7700\) K from photometry, but the wings of H\(\alpha\) agree well with models for \(T_{\text{eff}}\) in the range 7500–8000 K. Lines of REEs such as Nd II 6549.52 are mostly single; Eu II 6437.64 Å is double while the single Eu II 6437.64 appears broadened. The lines of Ce II are absent.

RV shifts of 52 lines were measured (Table 4) and show for all lines combined no rapid oscillations above 14 m s\(^{-1}\) (\(\sigma = 4\) m s\(^{-1}\)). The core of H\(\alpha\) is stable to 40 m s\(^{-1}\) (\(\sigma = 13\) m s\(^{-1}\)). However, lines of Pr III and Eu II show peaks of 3.9 and 4.9\(\sigma\), respectively, but for different frequencies and are rejected. The cross-correlations produce flat amplitude spectra (Fig. 17) reaching the lowest noise level in this study: the integrated RV noise is only 1.4–2.8 m s\(^{-1}\) and no peaks appear above 3\(\sigma\). Lines of REEs are in general, single; however, Eu II 6437.64 is broadened while Eu II 6437.64 is double. Also Fe II 6149.25 and Fe II 6432.68 Å are double, and iron lines are generally broadened, consistently with the strong magnetic field known for this star. The rotation is slow (\(v \sin i = 10.8\) km s\(^{-1}\)), but the spectrum is distorted by the magnetic field and blends from the abundant peculiar elements, so line identification and analysis is complicated. Using 16 Fe lines, the mean quadratic field is found to \(\langle B_q \rangle = 8.0 \pm 0.5\) kG. With SYNTHMAG fitting of 17 lines of different Landé factors (see examples in Fig. 18) the field strength is found to be \(\langle B_{\text{synth}} \rangle = 7.5 \pm 0.5\) kG, while the Zeeman splitting of Fe II 6149.25 and Cr II 5318 Å gives a magnetic field modulus of \(8.0 \pm 0.3\) kG.

Summarizing, this star has strongly peculiar REE abundances, a (known) strong magnetic field of \(\langle B_q \rangle = 8.0 \pm 0.5\) kG and is stable.
A search for pulsations in luminous Ap stars

4 DISCUSSION

The class of roAp stars is notoriously difficult to supplement with new members, as demonstrated by several photometric and spectroscopic studies before this one. But motivated by the recent discovery of the luminous roAp star HD 116114 (Elkin et al. 2005b), we have spectroscopically tested a sample of nine luminous Ap stars for rapid pulsations. Using lines known to show pulsations in roAp stars, we reach typical upper amplitude limits in RV of 40–75 m s\(^{-1}\) (\(\sigma = 13–24\) m s\(^{-1}\)) for the line core of H\(_\alpha\), 20–65 m s\(^{-1}\) (\(\sigma = 7–20\) m s\(^{-1}\)) when combining all measured Nd and Pr lines, and 20–40 m s\(^{-1}\) (\(\sigma = 7–11\) m s\(^{-1}\)) when combining all measured lines. With cross-correlations, using large wavelength regions, we typically reach upper amplitude limits of 4–10 m s\(^{-1}\) (\(\sigma = 1–4\) m s\(^{-1}\)). In spite of a clear theoretical prediction (Cunha 2002) and empirical evidence for roAp pulsations in this part of the HR diagram, we end up with nine null results, or noAp stars. A number of questions are therefore pertinent to discuss.

4.1 How well does our test sample resemble known roAp stars?

All studied stars have strong REE lines, except for HD 204367 and possibly also HD 197417. They have the core–wing anomaly typical for roAp stars, and Hipparcos luminosities with our temperature estimates place them inside the predicted roAp instability strip. General appear to have spotted surface distributions of REEs (such as HD 170565, HD 151301, HD 132322 and perhaps also HD 197417) which is typically associated with the strong magnetic fields common in known roAp stars. Indeed most of the stars are magnetic, and cover a range in magnetic field strengths of 0.4–8.0 kG, comparable to that of known roAp stars (Kurtz et al. 2006b). In the case of the sharp-lined HD 110072, we compared its spectrum in detail with those of two known roAp stars, and found remarkable similarities for the REEs. However, HD 110072 and HD 208217 are double-lined and single-lined binaries, respectively, which might indirectly influence their stability to high-frequency pulsations by reducing the magnetic field intensity (see Cunha 2002, and references therein). Still, the orbits are probably too wide in both cases for tidal interaction to occur and HD 208217 has a known strong magnetic field (\(\langle B \rangle = 8\) kG). The known roAp stars have cases of wide binaries, such as \(\beta\) CrB (spectroscopic binary), HR 3831, \(\alpha\) Cir, \(\gamma\) Equ and HD 99563 (visual binaries). In these regards, the studied sample has the characteristics of roAp stars.
4.2 Could pulsations have been overlooked?

Kurtz et al. (2006b) published RV amplitudes for the Hα cores of 16 roAp stars. Of these, only three have amplitudes below 75 m s$^{-1}$ (HD 116114, HD 154708 and HD 166473, of which two have amplitudes above 3σ), while the rest range from 148–2528 m s$^{-1}$. Further, RV series for Pr and Nd line measurements in UVES spectra of these 16 roAp stars (Kurtz et al., partly unpublished), show that about 75 per cent of the measured and significant (3σ) amplitudes are within the range 350–1600 m s$^{-1}$. Five of these stars have very small Nd and Pr amplitudes (60–90 m s$^{-1}$): HD 166473, HD 116114, β CrB, 33 Lib and HD 154708. In such difficult cases, other lines or combinations of several lines makes detection of pulsations possible. We successfully tested our procedures on the two latter roAp stars in Section 3.1.3, and also used combinations of several lines, including of different elements. More of the other 19 known roAp stars have low amplitudes, such as 10 Aql, but our tests and analyses show that we reach these amplitude levels and should have detected such rapid pulsations if present in the studied sample.

A complication for our analyses is typical $v \sin i \sim 10–30$ km s$^{-1}$ combined with double lines due to either spots on the stellar surface and/or magnetic splitting, which results in considerable line blending and makes line identification and analysis more difficult. However, our RV analysis was based partly on cross-correlations that are more robust than line measurements (as shown by our tests for two roAp stars) and this method similarly results in flat amplitude spectra that exclude rapid oscillations to relatively small roAp-amplitude levels. It also seems improbable that, e.g. unfavourable viewing angles of the global pulsations or short mode lifetimes could explain a momentary lapse of detectable pulsation amplitudes simultaneously in all nine stars. In fact, we know independently that HD 208217 was observed near its magnetic negative extremum where roAp pulsations are expected to have maximum amplitudes. Future surveys like this one may benefit from being repeated at different rotation phases. We also note that the near-normal REE abundances of HD 197417 and HD 204367 reduce the probability that they are roAp stars, given the strong peculiarity of all known roAp stars.

4.3 Do these stars really not pulsate?

In pulsators such as roAp stars oscillations are intrinsically unstable. Their excitation depends on the balance between the driving and damping of the oscillations over each pulsation cycle. In roAp stars this balance is thought to be particularly delicate. On one hand, the amount of energy input through the opacity mechanism acting on the hydrogen ionization region depends strongly on the interaction between the magnetic field and envelope convection, being maximal in the regions where envelope convection is suppressed (Balmforth et al. 2001; Cunha 2002). On the other hand, the direct effect of the magnetic field on pulsations can introduce significant energy losses, through slow Alfvén waves in the interior and through acoustic waves in the atmosphere, both resulting from mode conversion in the magnetic boundary layer (Cunha & Gough 2000; Saio 2005). Due to this delicate balance, it is not too surprising that roAp and noAp stars occupy the same locus in the HR diagram. Despite the developments in theoretical studies of linear non-adiabatic pulsations in models of roAp stars, we still lack a theoretical study that takes into account all these phenomena simultaneously and, thus, cannot firmly predict the conditions under which pulsations should be expected in roAp stars. In fact, both studies of Cunha (2002) and Saio (2005) considered the extreme case in which envelope convection is fully suppressed. Moreover, the first of these studies did not consider the direct effect of the magnetic field on pulsations and neglected the energy losses as a result of mode conversion, and the second study, while considering mode conversion, assumed the waves are fully reflected at the surface, hence neglecting energy losses through acoustic running waves in the atmosphere.

As discussed by Cunha (2002), the condition for suppression of envelope convection, which seems necessary to make the high-frequency modes unstable, is in principle harder to fulfill in evolved stars due to the increase with age of the absolute value of the buoyancy frequency in the region where hydrogen is ionized. Hence, it is likely that in evolved stars oscillations are excited only if the magnetic field is relatively strong. Unfortunately, the complexity of the interaction between magnetic field and convection makes it impossible to derive a global convective stability criterion, even if local criteria for convective stability may be established (Gough & Tayler 1966; Moss & Tayler 1969) (see also Théado et al. 2005, for an extensive discussion on this subject). Thus, the magnetic intensity needed to suppress convection at a given age, for a given mass, is very hard to establish. The more evolved roAp star HD 116114, in which a relatively low-frequency oscillation was found well in agreement with theoretical predictions, has a magnetic field modulus of ≈6 kG. In contrast with this, most stars in our sample have estimated mean magnetic field moduli around or below 2 kG. The clear exceptions are HD 107107, HD 131750 and HD 208217. Of these three, the latter is clearly an important test case to check the theoretical predictions. It has the strongest confirmed magnetic field in our sample and is strongly peculiar. However, we observed HD 208217 when one of its magnetic poles was almost visible, so pulsation should have been near its maximum amplitude.

From the observational point of view, one way to investigate the conditions under which roAp star oscillations are excited, and thus test theoretical models, is by identifying systematic differences between roAp and noAp stars. This study would have been able to detect pulsations in all the known roAp stars, and any missed rapid pulsations must have amplitudes lower than these. Hence we conclude that based on the obtained data, most stars in our sample are indeed noAp stars, and also excellent roAp candidates. Despite this conclusion, it is premature to state that we can confirm the evidence that noAp stars are in average more luminous and more evolved than roAp stars, as indicated by earlier studies based on photometric surveys for pulsations in roAp candidates (North et al. 1997; Handler & Paunzen 1999; Hubrig et al. 2000). To conclude that, we would also need to search for rapid pulsations in a control group of less evolved roAp stars with lower luminosity and compare the frequency of null results in the two cases. Such a survey has been started and results are expected in the near future. The next step is to analyse the noAp stellar atmospheres in detail, taking temperature gradients and the abundance stratification into account.

New spectra are needed of HD 132322 to clarify the origin of its double-lined structures, and of HD 110072 to verify its secondary spectrum and to test for the ‘spurious’ absorption lines in the recent FEROS spectrum. Polariometry of HD 110072 and HD 204367 is needed to confirm the detected magnetic fields.

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REFERENCES

Amado P. J., Moya A., Suárez J. C., Martín-Ruiz S., Garrido R., Rodríguez E., Catala C., Goupil M. J., 2004, MNRAS, 352, L11
Ashoka B. N. et al., 2000, Bull. Astron. Soc. India, 28, 251
Bebac H. W., 1958, Apl. 128, 228
Balmforth N. J., Cunha M. S., Dolez N., Gough D. O., Vauccluse S., 2001, MNRAS, 323, 362
Bouchy F., Lovis C., Mayor M., Pepe F., Queloz D., Udry S., Melo C., Santos N., 2004, in Beaulieu J., Leccavelier Des Etangs A., Terquem C., eds, ASP Conf. Ser. Vol. 321, Extrasolar Planets: Today and Tomorrow, Astron. Soc. Pac., San Francisco, p. 15
Breger M. et al., 1993, A&A, 271, 482
Burstein D., Heiles C., 1982, AJ, 87, 1165
Bystchik V. D., Bystchikova L. V., Madjej 2003, A&A, 407, 631
Castelli F., Kurucz R. L., 2003, in Piskunov N., Weiss W. W., Gray D. F., Burstein D., Heiles C., 1982, AJ, 87, 1165
Castelli F., Kurucz R. L., 2003, in Piskunov N., Weiss W. W., Gray D. F., Burstein D., Heiles C., 1982, AJ, 87, 1165
Castelli F., Kurucz R. L., 2003, in Piskunov N., Weiss W. W., Gray D. F., Burstein D., Heiles C., 1982, AJ, 87, 1165
Christensen-Dalsgaard J., Grevesse N., 1983, in Baglin A., Weiss W. W., eds, ASP Conf. Ser. Vol. 40, Proc. IAU Symp. 210, Modelling of Stellar Atmospheres. Astron. Soc. Pac., San Francisco, p. 20
Hubrig S., North P., Schöller M., Mathys G., 2006, Astron. Nachr., 327, 289
Hubrig S. et al., 2005, A&A, 440, L37
Hubrig S., North P., Schöller M., Mathys G., 2006, Astron. Nachr., 327, 289
Hubrig S., North P., Schöller M., Mathys G., 2006, Astron. Nachr., 327, 289
Hubrig S., North P., Schöller M., Mathys G., 2006, Astron. Nachr., 327, 289
Hubrig S., North P., Schöller M., Mathys G., 2006, Astron. Nachr., 327, 289
Kupka F., Piskunov N., Ryabchikov T. A. et al., 1999, A&AS, 138, 99 (http://www.astro.uu.se/~vald/)
Kuschnig R., Weiss W. W., Gruber R., Bely P. Y., Jenkins H., 1997, A&A, 328, 544
Kuschnig R., Weiss W. W., Gruber R., Bely P. Y., Jenkins H., 1997, A&A, 328, 544
Lanz P., Breger M., 2005, Commun. Asteroseismol., 146, 53
Levato H., Malaroda S., Morrell N., Solivella G., Grosso M., 1996, A&AS, 118, L231
Lutz T. E., Kelker D. H., 1973, PASP, 85, 573
Manfroid J., Mathys G., 1997, A&A, 320, 497
Manfroid J., Burnet M., Renson P., 1998, A&AS, 127, 201
Martínez P., 1993, PhD thesis, Univ. Cape Town
Martínez P., Kurtz D. W., 1994, MNRAS, 271, 129
Mathys G., 1989, Fundam. Cosm. Phys., 13, 143
Mathys G., Hubrig S., 2006, A&A, 453, 699
Mathys G., Hubrig S., Landstreet J. D., Lanz T., Manfroid J., 1997, A&AS, 123, 353
Moon T. T., Dworetsky M. M., 1985, MNRAS, 217, 305
Mosley D. L., Taylor R. J., 1969, MNRAS, 145, 217
Nelson M. J., Kreidl T. J., 1993, AJ, 105, 1903
North P., Jaschek C., Hauck B., Figueras F., Torra J., Kunzli M., 1997, ESA SP-402, Hipparcos-Venice 97. ESA Publications Division, Noordwijk, p. 239
Paunzen E., St¨utz Ch., Maitzen H. M., 2005, A&A, 441, 631
Piskunov N. E., 1992, in Glagolevsky Yu. V., Romanjuk I. I., eds, Stellar Magnetizm. Nauka, St Petersburg, p. 92
Piskunov N. E., 1999, in Nagendra K. N., Stenflo J. O., eds, Atmosph. Space. Soc. Library, Vol. 243, Polarization. Kluwer, Dordrecht, p. 515
Preston G. W., 1971, ApJ, 164, 305
Ryabchikova T., Nesvacil N., Weiss W. W., Kochukhov O., Stutz C., 2004, A&A, 423, 705
Ryabchikova T. et al., 2007, A&A, 462, 1103
Saio H., 2005, MNRAS, 360, 1022
Smithsonian Astrophysical Observatory Star Catalog J2000
Strohmeier W., Fischer H., Ott H., 1966, IBVS, 120, 1
Théado S., Vaucluse S., Cunha M. S., 2005, A&A, 443, 627
Tiwari S. K., Chaubey S. U., Pandey C. P., 2007, IBVS, 5787, 1
Tonry J., Davis M., 1979, AJ, 84, 1511
Weiss W. W., Ryabchikova T. A., Hubrig S., Lueftinger T. R., Savanov I. S., Manfroid J., 2002, in Szabados L., Kurtz D., eds, ASP Conf. Ser. Vol. 203, Proc. IAU Collq. 176, The Impact of Large-Scale Surveys on Pulsating Star Research. Astron. Soc. Pac., San Francisco, p. 487

APPENDIX A: SUPPLEMENTARY MATERIAL

A1 Additional tables

Table A1. Abundances in log N/H for our model spectrum used for line identification. Effective temperature T_eff = 8750 K and surface gravity is log g = 4.0.

| Element | Value |
|---------|-------|
| H       | 0.91 N |
| C       | -3.48 N |
| Na      | -5.71 Mg |
| S       | -4.83 Cl |
| Sc      | -8.94 Ti |
| Fe      | -3.57 Co |
| Ga      | -9.16 Ge |
| Kr      | -8.11 Rb |
| Nb      | -9.62 Mo |
| Pd      | -9.35 Ag |
| Sn      | -10.59 Ir |
| Sr      | -9.67 Se |
| Y       | -9.14 Y |
| Zr      | -9.58 Zn |
| Nd      | -10.24 Nd |
| Pm      | -11.04 Pr |
| Ba      | -8.91 Lu |
| Ce      | -9.04 Eu |
| Dy      | -9.34 Ho |
| Er      | -9.74 Hf |
| Tb      | -9.82 Th |
| Dy      | -9.92 Tb |
| Ho      | -10.01 Tm |
| Er      | -10.44 Eu |
| Tm      | -10.79 Ce |
| Yb      | -10.92 La |
| Lu      | -10.95 Pr |
| Ac      | -10.96 Nd |
| Er      | -11.18 Tb |
| Tm      | -11.30 Dy |
| Ho      | -11.57 Er |
| Tb      | -11.77 Sm |
| Dy      | -12.02 Eu |
| Ho      | -12.25 Ce |
| Er      | -12.40 Pr |
| Tb      | -12.56 Nd |
| Tm      | -12.75 Sm |
| Ho      | -12.90 Er |
| Tb      | -13.06 Sm |
| Tm      | -13.18 Eu |
| Ho      | -13.31 Nd |
| Tb      | -13.43 Ce |
| Tm      | -13.55 Pr |
| Ho      | -13.69 Nd |
| Tb      | -13.80 Sm |
| Tm      | -13.92 Eu |
| Ho      | -14.03 Nd |

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A2 Amplitude spectra for combined line measurements

These figures show star-by-star amplitude spectra calculated for combined RV series for elements as indicated by top labels: ‘all’ indicates all available lines, ‘NdPr’ all lines for neodymium and praseodymium. For centre-of-gravity line measurements. Note that for double lines, both components were measured separately and included. Compare with Table 4.
Figure A2. Comparison of the profiles of all examined Ap stars. To increase the readability, the individual spectra have been offset in flux, and appear with increasing temperature upwards. The selected region shows examples of double lines due to magnetic splitting, such as HD 208217, or spots on the surface of the stars. The spectrum of HD 110072 was smoothed over every two pixels.
Figure A3. Amplitude spectra for HD 107107. Panel labels indicate the element lines(s) in the combined RV series. Top left-hand panel is the window function for a 3 mHz signal. Panels ‘all’ and ‘Tell’ are, respectively, for all available lines combined and for all telluric lines combined.
Figure A4. Same as Fig. A3 but for HD 110072. The Nyquist frequency is 4.6 mHz.
Figure A5. Same as Fig. A3 but for HD 131750.
Figure A6. Same as Fig. A3 but for HD 132322. The Nyquist frequency is 4.7 mHz.
Figure A7. Same as Fig. A3 but for HD 151301.
Figure A8. Same as Fig. A3 but for HD 170565. The Nyquist frequency is 4.7 mHz.
Figure A9. Same as Fig. A3 but for HD 197417.
Figure A10. Same as Fig. A3 but for HD 204367.
Figure A11. Same as Fig. A3 but for HD 208217.

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