A search for rapid pulsations in the magnetic cool chemically peculiar star HD 3980

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\textbf{ABSTRACT}

The Ap star HD 3980 appears to be a promising roAp candidate based on its fundamental parameters, leading us to search for rapid pulsations with the VLT UV-Visual Echelle Spectrograph (UVES). A precise \textit{Hipparcos} parallax and estimated temperature of 8100 K place HD 3980 in the middle of the theoretical instability strip for rapidly oscillating Ap stars, about halfway through its main sequence evolution stage. The star has a strong, variable magnetic field, as is typical of the cool magnetic Ap stars. Dipole model parameters were determined from VLT observations using FORS1. From Doppler shift measurements for individual spectral lines of rare earth elements and the H\textalpha little core, we find no pulsations above 20–30 m s\textsuperscript{-1}. This result is corroborated by inspection of lines of several other chemical elements, as well as with cross-correlation for long spectral regions with the average spectrum as a template. Abundances of chemical elements were determined and show larger than solar abundances of rare earth elements. Further, ionisation disequilibria for the first two ionised states of Nd and Pr are detected. We also find that the star has a strong overabundance of manganese, which is typical for much hotter HgMn and other Bp stars. Line profile variability with the rotation period was detected for the majority of chemical species.

\textbf{Key words:} Stars: oscillations – stars: variables – stars: individual (HD 3980) – stars: magnetic.

\section{INTRODUCTION}

After the discovery of low amplitude pulsation for the bright and well-studied cool, magnetic chemically peculiar A (Ap) star \beta Crab \cite{Hatzes&Mkrtichian2004, Kurtz2007}, the question arose whether all cool Ap stars (with effective temperatures below $T_{\text{eff}} \sim 8200$ K) are rapid oscillators. This still unanswered question could be a pivotal point for theoretical modelling and understanding of the driving mechanism in rapidly oscillating (roAp) stars. Several searches for rapid oscillations in Ap stars have been made. Elkin, Kurtz, & Mathys \cite{Elkin2008} found that 24 known roAp stars that exhibit pulsations photometrically also show rapid radial velocity variations for the corresponding pulsation periods. However, several Ap stars with photometric indices typical for known roAp stars were tested photometrically for pulsations by \citet{Martinez&Kurtz1994} and found to be stable to high precision; these stars are called non-oscillating Ap stars, or noAp stars.

About a decade later, \citet{Elkin2005b} used fast UVES spectroscopy to discover low amplitude radial velocity pulsation for one of these stars, the former noAp star HD 116114. \citet{Lorenz2005} reported a new photometric null result for the star, but noted a low amplitude pulsation peak in the amplitude spectrum of their data slightly above the noise level for the same frequency. Spectroscopy therefore is superior to photometry as a tool for detection of rapid low amplitude pulsation, and we expect that more Ap stars previously identified as non-oscillating (noAp) may exhibit rapid radial velocity variations.

One such promising example is HD 965, which has physical parameters corresponding to those of known roAp stars. The fast photometry by \citet{Kurtz2003} and high time resolution spectroscopy by \cite{Elkin2005b}, however, found no rapid variability. Both of these studies mentioned the known roAp problem of amplitude modulation with the rotation phase as a possible explanation for the null result and proposed to re-observe the star at a different rotation phase when one of the magnetic poles is at a more favourable aspect.

\begin{flushleft}
\textsuperscript{*} Based on observations collected at the European Southern Observatory, Paranal, Chile, as part of programme 077.D-0150(A) and part of programmes 074.D-0392(A) and 076.D-0535(A) in the ESO Archive.
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As seen in, e.g., the astrometric HR-diagram by Hubrig et al. (2003, their figure 2) for roAp and noAp stars, the apparent roAp stars occupy essentially the same regions as the roAp stars. However, the noAp stars appear to be systematically more evolved than the roAp stars (North et al. 1992; Handler & Paunzen 1998; Hubrig et al. 2000). Nevertheless, the theoretical roAp instability strip (Cunha 2002) also predicts rapid pulsations for the more evolved Ap stars (near the terminal age the main sequence). HD 116114 (Elkin et al. 2005b) was indeed detected in this region of the HR-diagram, oscillating with the predicted frequency 0.79 mHz (the lowest frequency known for the roAp stars). Still the only case of a luminous roAp star, HD 116114 shows extremely low radial velocity pulsation amplitude and only for small number of chemical elements such as europium and lanthanum.

Using the same instrument (UVES) and procedure as Elkin et al. (2005b), Freyhammer et al. (2008) searched for rapid pulsations among a group of nine evolved Ap stars inside the roAp instability region in the HR-diagram. Surprisingly they did not detect any radial velocity pulsation for these stars, but showed that only 3–5 of the stars may have magnetic field strengths considerably in excess of 2 kG. More evolved stars are theoretically expected to require relatively strong magnetic fields to suppress local surface convection and facilitate observable amplitudes of rapid pulsations (see Cunha 2002).

The bright Ap star HD 3980 (ξ Phe, V = 5.719 mag) was proposed by one of us (Hubrig) to be a good roAp candidate because of its many properties in common with those of known roAp stars, such as a magnetic field and peculiar abundances of rare earth elements, as we show in Fig. 1. A photometric search for rapid pulsations had already been performed for HD 3980 by Martinez & Kurtz (1994) who failed to detect any pulsational variability. Based on our success with high time resolution spectroscopy (e.g., Kurtz et al. 2007; Mathys, Kurtz, & Elkin 2007), we then decided to use fast spectroscopy to test this promising roAp candidate for rapid pulsations. The following sections discuss the collection of data, their analysis and the null result for rapid oscillations.

2 OBSERVATIONS AND DATA REDUCTION

HD 3980 was observed twice in 2006 July with UVES on the ESO Very Large Telescope (VLT) to search for rapid pulsations at two rotation phases roughly coinciding with the predicted times of magnetic maximum and minimum (see Sect. 3), when pulsation amplitudes are expected to be highest. On the first observing night, 2006 July 23, 104 spectra were obtained in 2.0 hr, and on 2006 July 25, another 55 spectra were collected in 1.0 hr. The seeing was relatively poor, especially on the first night when it varied from 1′′.5 to 3′′. However, the star is bright and we used an image slicer (IS#3) to optimally utilise the observing conditions at the instrument’s maximum resolution with a 0′′.3 slit. Exposure times of 40 s were then used, which together with readout and overhead times of ~28 s provided a time resolution of 68 s. We used the RED (600 nm) setting which covers the wavelength region λλ 4970 – 7010 Å, with a gap in the region λλ 5963 – 6032 Å caused by the space between the two CCD mosaic halves. The average spectral resolution is about R = 110 000. The camera uses two 2K × 4K CCDs with 15 μm pixels. Raw CCD frames were processed using the UVES pipeline to extract and merge the echelle orders to 1D spectra that were normalised to the continuum. The average signal-to-noise ratio in the continuum, estimated from 1D spectra, is about 250.

3 THE STELLAR PARAMETERS

The rotation period was determined from HD 3980’s double wave light curve by Maitzen, Weiss, & Wood (1980), who provided the elements (for the primary minimum): JD(Prim. Min. v) = 244 2314.48 + (3′′.9516 ± 0′′.0003) E. These authors also obtained 8 longitudinal magnetic field measurements which show large scatter when phased with the rotation period. For the rotation phases 0.30–0.32, 3 measurements give ⟨Bz⟩ = −780 ± 700 G, while 4 measurements at phases 0.78–0.83 give 860 ± 996 G. A single point measured near phase zero, with a conservative error estimated from the other measurements, gives 1670 ± 1000 G. These 8 measurements are insufficient to fit the magnetic field curve properly.

Hubrig et al. (2006) obtained 3 precise measurements of the longitudinal magnetic field: ⟨Bz⟩ = 1210 ± 32 G, 305 ± 26 G and 452 ± 15 G. Two more observations were obtained by Hubrig, using the same method: ⟨Bz⟩ = −828 ± 18 G (JD245 4432.51) and 1804 ± 15 G (JD245 4433.54). These measurements are, together with averaged data from Maitzen, Weiss, & Wood (1980), shown in Fig. 2 with error bars and phased with the rotation period. A least squares sine curve fit of the five Hubrig measurements provides a
mean field of $\langle B_i \rangle = 40 \pm 18$ G and amplitude of $A_{B_i} = 1918 \pm 29$ G. By intention, our two observing nights occurred near the times of magnetic extrema at rotation phases 0.94 and 0.46, respectively, which are close to the positive extremum and the negative extremum of the magnetic field curve.

Hubrig, North, & Schöller (2007) determined stellar parameters: $T_{\text{eff}} = 8240 \pm 310$ K, $\log g = 4.05 \pm 0.09$, $\log L/L_\odot = 1.296 \pm 0.052$ and a projected rotational velocity $v \sin i = 15$ km s$^{-1}$. For the 3.95 d rotation period and the longitudinal field measurements, they estimated the magnetic field geometry parameters: Mean longitudinal field ($B_\parallel$) = 1200 G, inclination angle between rotation axis and line-of-sight $i = 32^\circ$ and angle between rotation axis and magnetic dipole axis $\beta = 88^\circ$. These values, however, are highly uncertain.

Our fit to the magnetic measurements shown in Fig. 2 can also be used to constrain the inclinations of the magnetic and rotation axes. It is easy to show for a centred dipolar magnetic field that

$$B_i \propto B_\parallel \cos \alpha$$

(1)

and

$$\cos \alpha = \cos i \cos \beta + \sin i \sin \beta \cos \Omega t$$

(2)

where $\alpha$ is the angle between the magnetic pole and the line-of-sight, $i$ is the rotational inclination, $\beta$ is the angle between the rotation axis and the magnetic axis, $\Omega$ is the rotation frequency, $B_\parallel$ is the longitudinal magnetic field strength and $B_\parallel$ is the polar field strength.

It is obvious from Eq. 2 that the mean magnetic field strength

$$\langle B_i \rangle \propto \cos i \cos \beta$$

(3)

and the amplitude of the magnetic field variations

$$A_{B_i} \propto \sin i \sin \beta .$$

(4)

Thus we get

$$\tan i \tan \beta = A_{B_i} / \langle B_i \rangle ,$$

(5)

from which $\beta$ can be constrained when $i$ is known, using the values for $A_{B_i}$ and $\langle B_i \rangle$ from our fit to the magnetic data shown in Fig. 2. We derive in Sect. 6 below from the Hipparcos parallax and our estimate of $T_{\text{eff}}$ that $R = 2.19^{+0.12}_{-0.30}$ R$_\odot$, which coupled to our measurement of $v \sin i = 21.0 \pm 3.0$ km s$^{-1}$ gives a weak constraint on the rotational inclination of $i = 49^{+19}_{-12}$. Eq. 5 can then be used to estimate the magnetic obliquity to be $\beta = 88.6^{+0.8}_{-4.0}$ (accounting for all 1-sigma errors, while it becomes undetermined for 2-sigma errors). Several more precise magnetic measurements at different rotation phases are still needed to fill the gaps in the magnetic field curve. The important conclusion here is that the obliquity of the magnetic field must be near to $90^\circ$ to account for the mean magnetic field strength being close to zero.

The stellar parameters $T_{\text{eff}}$ and $\log g$ were estimated from Strömgren photometry by Martín (1993) and the Moon & Dworetsky (1983) calibrations. Then a small grid of synthetic H$_\alpha$ line profiles was compared to the observed spectra. The model spectra were produced using Kurucz model atmospheres (Kurucz, 1979), models from the NEMO database (Heiter et al. 2002) and calculations with the SYNTH program by Piskunov (1992). It is difficult to locate accurately the continuum in the broad H$_\alpha$ region. The resulting normalised profiles are slightly different for the two observing sets. This may partly be due to our continuum placement, but the H$_\alpha$ profile may itself be variable. An example of this was found in the hotter peculiar star 36 Lyn by Takada-Hidai & Aikman (1989). Variation in the H$_\alpha$ profile is consistent with small variations in the effective temperature of the star as it is rotates. For the average spectrum of the first observing night, we obtained a good fit for $T_{\text{eff}} = 8000$ K and $\log g = 4.0$, whereas for the second night $T_{\text{eff}} = 8200$ K was required.

We performed an abundance analysis of the first set of spectra of the star, for which $T_{\text{eff}} = 8000 \pm 200$ K and $\log g = 4.0 \pm 0.2$. A Kurucz model atmosphere with $T_{\text{eff}} = 8000$ K and $\log g = 4.0$ and with enhanced (above solar) metallicity ([M/H] = +0.5) was used for calculating model spectra with SYNTH. Spectral line lists were taken from the Vienna Atomic Line Database (VALD), Kunke et al. (1999) and the DREAM database (Biémont, Palmeri, & Quinet 1999). We determined $v \sin i = 21.0 \pm 3.0$ km s$^{-1}$ from several symmetric lines. This value is slightly higher than the $v \sin i = 15$ km s$^{-1}$ found by Hubrig, North, & Schöller (2007). That could be explained by, e.g., a variable magnetic field strength which contributes to the broadening of lines with large Landé factors. A more probable explanation is line profile variations due to a spotted abundance distribution. Some spectral lines are indeed particularly narrow and give a lower value of $v \sin i$. We consider this to be an effect of these elements being concentrated in spots on the stellar surface such that their spectral lines do not reflect the full rotational broadening. An example is LiI for which spotted distributions have been demonstrated for roAp stars by Faraggiana, Gerbaldi, & Delmas (1996) and Polosukhina et al. (2000). For the strong, isolated and symmetric but non-resolved doublet LiI 6707.76 and 6707.91 Å we obtained $v \sin i = 16.5$ km s$^{-1}$.

4 SEARCH FOR RAPID RADIAL VELOCITY VARIATIONS

We searched for pulsations as periodic Doppler shifts in two ways: first by using cross-correlations of long stretches of spectral regions, then by measuring centre-of-gravity shifts of individual lines in the spectra. For frequency analyses, we used MIDAS’s TSA (Time Series Analysis) context, a discrete Fourier transform programme by Kurtz (1983) and the PERIOD04 (Lenz & Breger 2005) programme.

4.1 Cross-correlation radial velocity analyses

The cross-correlation method, using large spectral regions, is often useful for detecting pulsation in roAp star candidates and for finding additional frequencies in known roAp stars (see, e.g., Matthews et al. 1988; Balona & Zima 2002; Hatzes & Mkrichian 2004). The cross-correlation amplitudes from correlation of long spectral regions are, though, not directly comparable to those derived from line profile measurements. This is mainly due to different pulsation amplitudes and phases of different ions in the stratified roAp atmospheres, where low amplitude elements such
as Fe dilute the ‘integrated’ Doppler shifts. An example is the roAp star 10 Aql for which Elkin, Kurtz, & Mathys (2008a) found a pulsation amplitude of 6 ± 1 m s\(^{-1}\) with cross-correlation for the spectral region 5150 − 5450 Å, while individual lines of rare earth elements showed amplitudes in excess of 500 m s\(^{-1}\). 10 Aql represents a case of a roAp star for which the lines of rare earth ions are weak. Another example is HD 154708 which has a very strong magnetic field. From cross-correlation measurements of HD 154708 in the spectral range 5150 − 5800 Å Freyhammer et al. (2008) detected pulsation with an amplitude of 10 m s\(^{-1}\), while Kurtz et al. (2006a) obtained amplitudes around 60 m s\(^{-1}\) for some individual rare earth lines.

Cross-correlations were performed with our HD 3980 spectra, using the average spectrum as template. For the line-rich spectral range 5000 − 5060 Å, we searched the regions 5150 − 5400 Å and 5400 − 5700 Å, but in both cases no significant signal was detected above a level of 10 m s\(^{-1}\) with \(\sigma = 3\) m s\(^{-1}\) (see Fig. 3 top panel) in the frequency domain of known roAp stars. Only low frequency peaks below 0.4 mHz are seen. However, we disregard these periodicities as they are also seen in the radial velocity measurements of telluric lines, hence are instrumental in origin. A spectral region from 6863 − 6938 Å with abundant telluric lines was used to check the instrumental stability and identify non-stellar periodicities. The results from telluric lines only show low frequency noise (due to instrumental drifts or meteorological changes). The telluric region otherwise shows stability at the level below 10 m s\(^{-1}\) with \(\sigma = 3\) m s\(^{-1}\). The spectral region longwards of 6000 Å has a lower line density and a higher scatter, but confirms these null results.

4.2 Line profile radial velocity analyses

In roAp stars, lines of rare earth elements typically show the largest Doppler shift pulsation amplitudes. Amplitudes vary for different elements and range from a few dozen metres per second up to a few kilometres per second for various roAp stars (Elkin, Kurtz, & Mathys 2008a). Also the narrow line core of the H\(\alpha\) profile shows rapid pulsations in roAp stars (Kurtz et al. 2006a, Elkin, Kurtz, & Mathys 2008a). We therefore searched for pulsations in HD 3980 using the centre of gravity method for similar lines and show amplitude spectra of selected lines in Fig. 3. Although we concentrate on analyses of lines of the rare earths, other chemical elements were also tested. All radial velocity curves subjected to period searches were de-trended beforehand with linear least square fitting, which also eliminated the barycentric velocity correction which is approximately linear during the short duration of our two runs. The H\(\alpha\) core was stable above the 20 m s\(^{-1}\) with a noise level of 7 m s\(^{-1}\).

Of the rare earth elements, we examined lines of Ce\(\ii\), Pr\(\ii\), Nd\(\ii\), Nd\(\ii\), Eu\(\ii\), and Gd\(\ii\), but no pulsations were detected from any of these lines above typical upper limits of 30 m s\(^{-1}\) (with noise levels varying from 10 to 30 m s\(^{-1}\) for the majority of good lines). Combination of 3 − 4 lines reduced the noise level of individual lines, but also did not show any reliable pulsation signal. Due to the rotational broadening and many asymmetric line profiles, the number of suitable strong, symmetric lines was rather limited. Of the non-rare-earth element lines analysed, including the strong sodium D and Mg\(\i\) lines and several Ca, Sc, Ti, Cr, Fe and Ba lines, no pulsations were detected above 15 − 30 m s\(^{-1}\). In general, some lines show intriguing peaks in the amplitude spectra for the frequency range typical for roAp stars. But as these peaks could not be confirmed by other spectral lines of the same element or by other rare earth lines, they were rejected as indications of pulsation in HD 3980. Examples of such peaks are seen in Fig. 3 for the asymmetric and blended line of Pr\(\iii\) 6090 Å which shows two peaks with frequencies 0.546 mHz and 2.752 mHz. Combining radial velocity measurements of three other Pr\(\iii\) lines (seen in the panel below that for Pr\(\iii\) 6090 Å) shows no significant peaks for these two frequencies nor for any others.

Among the Ap stars, HD 3980 has strong lines of lithium (e.g. equivalent width of 101 mÅ for Li\(\i\) 6708 Å). We therefore also searched the Li\(\i\) 6708 Å doublet for pulsation. This line shows strong variability with rotation phase, but is stable to rapid pulsations above 30 m s\(^{-1}\) with a noise level of 11 m s\(^{-1}\).

4.3 Linear trends in line profile radial velocity shifts

Line shapes of Nd, Eu and Li are observed to change strongly with rotation phase in HD 3980, such as the example in Fig. 4 with Nd\(\iii\) 6145 Å. This is a clear indication of an inhomogeneous surface distributions of elements that appear to be located in patches. The line analysis is complicated by the resulting line asymmetries, as well as by many lines that are blends because of HD 3980’s relatively high rotation velocity and strong lines of peculiar elements.

A large number of spectral lines show quasi-linear drifts in radial velocities which appear as low frequency
peaks in their amplitude spectra. Different lines may show different drifts over the interval of 1 − 2 hr. We have noticed the same effect for several other Ap and roAp stars (see, e.g., Freyhammer et al. 2008). For HD 99563, Elkin, Kurtz, & Mathys (2005c) detected and discussed even larger trends for particular lines. For the roAp star β CrB, Kurtz & Leone (2006b) similarly detected non-linear low frequency trends which they de-trended from the radial velocity series. For the moderately fast rotating Ap stars, the trends are partly caused by spots seen at different aspects. For example, HD 99563 has \( v \sin i = 30 \, \text{km} \, \text{s}^{-1} \) and HD 3980 has \( v \sin i = 21 \, \text{km} \, \text{s}^{-1} \); both these stars show stronger trends than those seen for the slower rotator β CrB (\( v \sin i = 3.5 \, \text{km} \, \text{s}^{-1} \)). We observe that these trends also vary from element to element, depending on the particular surface distribution.

For HD 3980 we de-trended linear drifts prior to the radial velocity analyses. However, those trends clearly contain physical information about the star’s surface distribution. The Li i 6708 Å doublet shows one of the strongest trends with a linear radial velocity change of about 0.77 km s\(^{-1}\) h\(^{-1}\). We believe that this is the result of a concentrated strong spot of Li seen at varying aspects with rotation. Considerable line profile changes with the rotation phase are clearly visible in this line during our 2 hr run supplemented with existing spectra in the ESO Archive at several other rotation phases. The available data only allow a crude tomo-graphic study, but do indicate different surface distributions of various elements. A full Doppler imaging study (such as Lehmann et al. 2007) of this star over its rotation period is needed.

4.4 The second observing run

The second observing run, obtained about half a rotation period (0.49 phase difference) after the first run, collected 55 spectra in 1 hr. Though only half the length of the first run, this set is sufficient for searching for frequencies in the known range for roAp stars. As for the previous run, this set also shows linear radial velocity drifts of comparable, or slightly higher amplitudes. Again, we see drifts for the rare earth element lines with increasing radial velocity, while lines of iron peak elements and light elements show no drifts at all, consistent with spots for the rare earth elements and a more uniform distribution for the lighter elements.

After de-trending the radial velocity series for individual lines, the frequency analysis again showed that there is no pulsation above amplitudes of 30 m s\(^{-1}\) for noise levels of \( \sigma = 10 \, \text{m} \, \text{s}^{-1} \). Cross-correlations of this set of spectra with their mean spectrum as template excluded periodic variability above 10 m s\(^{-1}\) (\( \sigma = 3 \, \text{m} \, \text{s}^{-1} \)).

Line profile shapes in the average spectrum are very similar to those of the first run, although they cover two opposite sides of the spotted stellar surface at the moments of maximum and minimum magnetic field strengths. Spectral lines such as Li ii and Eu ii that also have rather comparable line profile shapes, differ strongly from the same lines in spectra from the ESO archive at rotation phases 0.2 and 0.8. For example at rotational phase 0.77, the lines of Nd iii (see, e.g., Nd iii 6145 Å in Fig. 4) have double profiles with a sharper, stronger and more blue component. For this phase, the data suggest that Nd is concentrated in two different spots, one at each magnetic pole. In both our observing runs this line seems more symmetric and wide, which may correspond to an extended surface region with overabundance of neodymium.

5 CHEMICAL ABUNDANCES

The presence of high overabundances of rare earth elements is one of the characteristics of known roAp stars. Another important property is that their abundances of the first two ionised states of neodymium and praseodymium show more than 1 dex difference, with the doubly ionised ions, which form higher in the atmosphere, being the most abundant (Ryabchikova et al. 2004, Kurtz et al. 2007). This ionisation disequilibrium anomaly may be explained mostly by concentration of rare earth elements in high atmospheric layers (stratification) and partly by non-LTE (NLTE) effects (Mashonkina et al. 2005). NLTE effects may enhance the ionisation of Nd ii or Pr ii and accordingly weaken their absorption lines, while strengthening those of the second ionisation state. The disequilibrium may not be limited to roAp stars, which are relatively cool Ap stars, but may also exist for hotter Ap stars.

To compare HD 3980 spectrally with the roAp stars, we measured its chemical abundances and tested for ionisation disequilibria for Nd and Pr. Abundances were determined

![Figure 3. Amplitude spectra for spectral lines of HD 3980. There are no significant peaks.](image-url)
by fitting synthetic spectra to the observed average spectra. Model spectra were calculated as described in Sect. 3. The resulting abundances for the 2hr run average spectrum are presented in Table 1. Solar abundances are from Asplund, Grevesse, & Sauval (2005). Only lines of Mg i suggest slightly less than solar abundances. The Fe abundance is near solar, or slightly greater. Notably, we detected large overabundances of manganese. This element typically shows overabundances for the hotter group of peculiar HgMn stars, while for cooler roAp stars, Mn mostly shows abundances slightly above solar (Ryabchikova et al. 2004).

The rare earth elements and lithium (Fig. 2) show abundances that are much greater than solar. We find indications of ionisation disequilibria for both neodymium and praseodymium: \( \Delta [\text{Nd}]_{\text{III-II}} = 1.4 \pm 0.3 \) and \( \Delta [\text{Pr}]_{\text{III-II}} = 1.2 \pm 0.2 \) (where the errors are calculated from the error in the mean abundance for each ion’s set of lines), consistent with the spectroscopic signature for most roAp stars discovered by Ryabchikova et al. (2004). Thus, we find HD 3980 is spectrally comparable to known roAp stars. Three lines of terbium also suggest ionisation disequilibrium for this element.

6 DISCUSSION

The cool Ap star HD 3980 shows no rapid oscillations in radial velocity above a few tens of m s\(^{-1}\) at two rotational phases separated by half a rotation period. We have shown that at least one of these coincides with a rotation phase near a magnetic extremum when pulsation amplitude for an oblique pulsator is expected to be highest. The methods applied, and the lengths of the data sets acquired, would be sufficient for detecting pulsations in all known roAp stars. We therefore now reconsider whether HD 3980 is a good roAp candidate, when comparing its characteristics to those of known roAp stars. If indeed it is a good candidate, it either does not pulsate (thus is a noAp star), or we failed to detect the pulsations, or, alternatively, the roAp class characteristics are still too poorly established to physically discern noAp stars from roAp stars.

The blue edge of the roAp instability strip where it crosses the main sequence is not firmly established. Hubrig et al. (2003) showed that it is around 8500 K, while the theoretical roAp instability strip by Cunha (2002) extends up to around 9500 K. Ryabchikova et al. (2004) suggest a transition region (noAp/roAp) around 8100 K where cooler Ap stars may be rapid oscillators. HD 3980 has a precise parallax \( (\pi = 14.91 \pm 0.35, \text{van Leeuwen 2007}) \) that for \( A_V = 0.054 \) (NASA/IPAC IRSA maps) gives a luminosity of \( \log L/L_\odot = 1.27 \pm 0.03 \) (including all uncertainties). We found an effective temperature of \( 8100 \pm 200 \) K (estimated error) which places the star well inside the theoretical roAp instability strip. The luminosity was derived using a bolometric correction, \( BC = 0.024 \pm 0.009 \), from the relations by Flower (1996) for the range of \( T_{\text{eff}} \) within its error. From this luminosity and \( T_{\text{eff}} \) we derive a radius of \( R = 2.19^{+0.19}_{-0.16} \) \( R_\odot \). Eq. 5 then gives the magnetic obliquity to be \( \beta = 88^{+0.8}_{-4.0} \). Bolometric corrections are notoriously difficult to determine for A stars with peculiar abundances. If one similarly uses the bolometric calibration by Landstreet et al. (2007), accounting for a 0.1 mag intrinsic error in the calibration, the corresponding luminosity and ra-

**Table 1. Chemical abundances for HD 3980 for selected elements, and their corresponding solar abundances (Asplund, Grevesse, & Sauval 2005).** The errors quoted are internal standard deviations for the set of lines measured.

| Ion  | Number of lines | \( \log \epsilon \) HD 3980 | \( \log \epsilon \) Sun |
|------|----------------|----------------------------|-------------------------|
| Li i | 1              | 4.20                       | 1.05 ± 0.10             |
| Mg i | 3              | 7.23 ± 0.05                | 7.53 ± 0.09             |
| Si i | 2              | 7.00 ± 0.50                | 7.51 ± 0.04             |
| Si ii| 2               | 8.30 ± 0.20                | 7.51 ± 0.04             |
| Ca i | 4              | 7.23 ± 0.20                | 6.31 ± 0.04             |
| Sc ii| 3               | 4.04 ± 0.20                | 3.05 ± 0.08             |
| Cr i | 9               | 7.14 ± 0.08                | 5.64 ± 0.10             |
| Cr ii| 12              | 7.23 ± 0.14                | 5.64 ± 0.10             |
| Mn i | 7               | 7.04 ± 0.09                | 5.39 ± 0.03             |
| Mn ii| 6               | 7.35 ± 0.18                | 5.39 ± 0.03             |
| Fe i | 15              | 7.80 ± 0.28                | 7.45 ± 0.05             |
| Fe ii| 6               | 7.96 ± 0.22                | 7.45 ± 0.05             |
| Y ii | 3               | 3.87 ± 0.47                | 2.17 ± 0.04             |
| Ba ii| 2               | 3.05 ± 0.15                | 2.17 ± 0.07             |
| La ii| 4               | 4.37 ± 0.08                | 1.13 ± 0.05             |
| Ce ii| 6               | 4.33 ± 0.34                | 1.58 ± 0.09             |
| Pr iii| 7             | 4.53 ± 0.39                | 0.71 ± 0.08             |
| Pr iv| 8               | 3.34 ± 0.21                | 0.71 ± 0.08             |
| Nd iii| 5            | 5.35 ± 0.36                | 1.45 ± 0.05             |
| Nd iv| 12              | 4.00 ± 0.80                | 1.45 ± 0.05             |
| Sm iii| 3             | 3.60 ± 0.14                | 1.01 ± 0.06             |
| Eu iii| 3             | 2.90 ± 0.43                | 0.52 ± 0.06             |
| Gd iv| 4               | 4.50 ± 0.31                | 1.12 ± 0.04             |
| Tb iii| 2             | 3.85 ± 0.35                | 0.28 ± 0.30             |
| Tb iv| 1               | 2.10                       | 0.28 ± 0.30             |
| Er ii| 1               | 4.30                       | 0.93 ± 0.06             |

**Figure 4.** Change of the Nd iii 6145.07 Å line profile with rotational phase. Our search for pulsation was done for phases corresponding to the upper and lower spectra.
Radial velocity study of HD 3980

Figure 5. Relative abundances (log $\epsilon$ − log $\epsilon_\odot$) for HD 3980 (circles with error bars) compared to those of the roAp star $\beta$ CrB (diamonds) from Kurtz et al. (2007), and the Am star 32 Aqr (asterisks) by Adelman et al. (1997) showing the strong overabundances typical of the cool Ap stars.

Figure 6. A theoretical HR-Diagram for a sample of roAp stars. Luminosities were calculated using Hipparcos trigonometric parallaxes (Perryman et al. 1997) except for HD 3980, for which the revised parallax of van Leeuwen (2007) was used. The Moon & Dworetsky (1985) calibration of Strömgren photometric indices was employed for estimating the effective temperature. The position of HD 3980 is shown by the filled diamond which is the size of the error bar in log $L/L_\odot$. Solid lines are evolutionary tracks for stars with 1.5, 1.7 and 2.0 $M_\odot$ taken from Schaller et al. (1992).

dius become: log $L/L_\odot = 1.25 \pm 0.07$ and $R = 2.14^{+0.30}_{-0.26} R_\odot$, resulting in $\beta = 88^\circ 6^{+0.9}_{-0.4}$.

The roAp stars have strong magnetic fields that range from several hundred Gauss to 24.5 kG in HD 154708 (Hubrig et al. 2005). HD 3980 has a longitudinal field, which is within this range. The evolutionary tracks in Fig. 6, as well as those in figure 1 of Cunha (2002), indicate that HD 3980 in the midst of its life on the main sequence, halfway evolved from the ZAMS to the TAMS. Cunha (2002) argued that more evolved roAp stars require stronger magnetic fields to suppress the upper envelope convection and enable the rapid oscillations to reach observable amplitudes. She further speculated that the magnetic field intensities needed for suppressing the convection in roAp stars more often are found in roAp stars with magnetically resolved lines. That typically requires a magnetic field modulus of $\sim 3$ kG and a slowly rotating Ap star ($v \sin i = 1\mbox{ - }3 \mbox{ km s}^{-1}$). Based on the longitudinal field measurements of HD 3980, it could have a magnetic field modulus more then 3 kG. The rotational broadening dominates any magnetic splitting of lines at this field intensity and direct measurement is not possible.

Freyhammer et al. (2008) searched for pulsations in 9 evolved cool Ap stars located inside the theoretical instability strip, the majority having estimated temperatures below 8100 K. With similar precision and upper limits on radial velocity amplitudes as in this study, these authors found 9 null results. Out of 7 stars, only 3 had magnetic fields significantly stronger than 2 kG, which possibly explains most of their null results for such evolved stars. The magnetic field of HD 3980 is strong enough to suppress local convection and enable pulsational driving of rapid pulsations to reach observable amplitudes. The star does not appear to be near the terminal end of its main sequence lifetime, in which case this explanation may be less likely. Hubrig et al. (2000) pointed out the apparent deficiency of close binaries among roAp stars (although a ‘handful’ of exceptions are known). In this context, it is interesting to note that...
HD 3980 is component of a common proper-motion visual binary (see, e.g., Perryman et al. [1997]).

Our abundance analysis found that HD 3980 has strong enhancement of rare earth elements, ionisation disequilibria for Nd and Pr and inhomogeneous surface distributions of these elements. In these respects, HD 3980 strongly resembles known roAp stars. Only a relatively high temperature, compared to the typical roAp stars, may explain why no pulsations are found. We cannot exclude extremely low amplitude pulsations of about 5–10 m s$^{-1}$. Low-amplitude oscillations in roAp stars are known from, e.g., $\beta$ CrB [Kurtz et al. 2007], HD 154708 [Kurtz et al. (2006)] and HD 116114 [Elkin et al. (2005)]. For such low pulsation amplitudes, $\lesssim 1$ m s$^{-1}$ or even sub-0.1 m s$^{-1}$, high precision measurements are required, such as Kochukhov et al. (2007) obtained with HARPS for HD 75445. This in turn requires the stars to be slow rotators, although cross-correlation for long spectral regions partly compensates for that. In the case of HD 3980, even the high precision of cross-correlation analysis did not detect low amplitude pulsations.

It is important to find roAp stars with rotation periods of a few days, such as for HD 3980, as they can be subjected to 3D pulsation and abundance studies, such as HR 3831 (Kochukhov et al. 2007). But if the pulsation amplitudes are very low, such a study would be limited to very few individual lines or elements and will not be very informative.

We have found that HD 3980 is a bright, nearby, Li-spotted Ap star with a short rotation period which makes it an excellent observing target for Doppler imaging. We demonstrated that the surface distribution is spotted for several elements, such as Nd, Eu and Li. We have shown that the star has similar characteristics to the known roAp stars, but that it is stable to pulsations with an upper limit of 30 m s$^{-1}$, less than the amplitudes of the known roAp stars.

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