On the spectroscopic nature of the cool evolved Am star HD 151878

L. M. Freyhammer,† V. G. Elkin and D. W. Kurtz

Centre for Astrophysics, University of Central Lancashire, Preston PR1 2HE

Accepted 2008 July 14. Received 2008 July 14; in original form 2008 June 14

ABSTRACT

Recently, Tiwari, Chaubey & Pandey detected the bright component of the visual binary HD 151878 to exhibit rapid photometric oscillations through a Johnson B filter with a period of 6 min (2.78 mHz) and a high, modulated amplitude up to 22 mmag peak-to-peak, making this star by far the highest amplitude rapidly oscillating Ap (roAp) star known. As a new roAp star, HD 151878 is of additional particular interest as a scarce example of the class in the northern sky, and only the second known case of an evolved roAp star – the other being HD 116114. We used the FIbre-fed Echelle Spectrograph at the Nordic Optical Telescope to obtain high time-resolution spectra at high dispersion to attempt to verify the rapid oscillations. We show here that the star at this epoch is spectroscopically stable to rapid oscillations of no more than a few tens of m s$^{-1}$. The high-resolution spectra furthermore show the star to be of type Am rather than Ap and we show the star lacks most of the known characteristics for roAp stars. We conclude that this is an Am star that does not pulsate with a 6-min period. The original discovery of pulsation is likely to be an instrumental artefact.

Key words: stars: oscillations – stars: variables: other – stars: individual: HD 151878 – stars: magnetic field.

1 INTRODUCTION

1.1 Rapidly oscillating Ap stars

After the discovery of low-amplitude pulsation for the bright and well-studied cool, magnetic chemically peculiar A (Ap) star β CrB (Hatzes & Mkrtichian 2004; Kurtz, Elkin & Mathys 2007), 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 may be a pivotal point for theoretical modelling and understanding of the driving mechanism in rapidly oscillating Ap (roAp) stars.

Ap stars are characterized by overabundances of Sr, Cr, Si, Mn and rare earth elements. Many searches for rapid oscillations in Ap stars have been made. Elkin, Kurtz & Mathys (2008a) found that 25 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 Martinez & Kurtz (1994) and found to be stable to high precision; these stars are called non-oscillating Ap stars, or noAp stars.

As seen in, for example, the astrometric HR diagram by Hubrig et al. (2005, their fig. 2) for roAp and noAp stars, the apparent noAp 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. 1997; Handler & Paunzen 1999; Hubrig et al. 2000). Nevertheless, the theoretical roAp instability strip (Cunha 2002) also predicts pulsations for the more evolved Ap stars near the terminal age main sequence, with periods in the range 16–25 min (see Fig. 1). HD 116114 (Elkin et al. 2005a) 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). Another somewhat less-evolved roAp star, HD 218994, has been recently discovered with a period of 14.2 min, which is typical of many roAp stars (González et al. 2008). Thus, HD 116114 is still the only case of a luminous roAp star near the terminal age main sequence; it shows extremely low radial velocity pulsation amplitude only for a small number of chemical elements such as europium and lanthanum.

Freyhammer et al. (2008a) searched for rapid pulsations among a group of nine evolved Ap stars inside the roAp instability strip in the HR diagram. Surprisingly, they did not detect any in the time-resolved radial velocity measurements for these stars, and showed that three to five of the stars had magnetic field strengths considerably in excess of 2 kG. While more evolved stars are theoretically expected to require relatively stronger magnetic fields to suppress local surface convection and facilitate observable amplitudes of rapid pulsations (Cunha 2002), this study made a good case for the existence of noAp stars near the terminal age main sequence.
1.2 HD 151878

HD 151878 A (\(\alpha_{2000.0} = 16 48 41.5, \delta_{2000.0} = +35 55 19\), \(V = 7.22\) mag) is the primary component of the visual binary HD 151878 and is separated by 5.8 arcsec from its 1.51 mag fainter companion. Bidelman (1985) used low-resolution, objective prism plates and classified the star as Am, where the colon means that the star is a marginal metallic line star with a difference between its spectral type determined from the Ca II K line and from the metals lines of less than five spectral subclasses. Grenier et al. (1999) classified the star as A6mFOF5, where the A6 subtype refers to the Ca II K line, F0 refers to the H spectral type and F5 refers to the metal-line type. With nine spectral subclasses difference between the Ca II K line type and metal line type, this classification indicates a strong classical Am star. Am stars are characterized by overabundance of iron-peak elements and underabundance of Ca or Sc. Importantly, the Ca deficiency of the Am stars is not a characteristic of the Ap stars (see e.g. Ryabchikova et al. 2000 and references therein for a study of seven roAp stars), making it unlikely that this star is a magnetic Ap star. No medium- or high-dispersion spectroscopy has been published for the system prior to our study. The Strömgren indices of HD 151878 (see Section 3.1) indicate spectral peculiarity and are consistent with either an Am or Ap spectral type.

Tiwari et al. (2007) recently announced the discovery of rapid photometric oscillations in HD 151878 with a period of 6 min and an amplitude of as much as 22 mmag peak-to-peak, making this the highest amplitude roAp star known by a significant margin. The previous highest photometric amplitude observed for a roAp star was on the discovery night for HD 60435 when a peak-to-peak variation of 16 mmag was detected for this star (Kurtz 1984). The star is the most multiperiodic of all roAp stars (Matthews, Wehlau & Kurtz 1987), and it rarely shows an amplitude this high. For roAp stars with a single, or dominant pulsation mode, the highest photometric \(B\) amplitudes are around 10 mmag peak-to-peak in, e.g. HD 99563 (Handler et al. 2006), HD 101065 (Przybylski’s star; Martinez & Kurtz 1990) and HD 83368 (HR 3831; Kurtz et al. 1997).

Thus, the announcement by Tiwari et al. (2007) of high-amplitude photometric pulsations in HD 151878 was potentially very important for many reasons: (i) the photometric amplitude they found is the highest known for any rapidly oscillating Ap star; (ii) if the star is an Am star – as two spectral classifications show – then it would be the first known rapidly oscillating Am star; that would suggest that a strong magnetic field is not required for high-overtone pulsation modes in chemically peculiar A stars, which would require a complete rethinking of theoretical models; (iii) if an error had been made in the spectral classification and HD 151878 is an Ap star, then it would be only the sixth known roAp star in the Northern hemisphere and (iv) the revised Hipparcos parallax (5.81 ± 0.61 mas; van Leeuwen 2007), along with a spectroscopically estimated effective temperature of 7000 K, shows that HD 151878 has evolved past the terminal age main sequence (Section 3.1). The most evolved roAp star, HD 116114, shows no photometric variability in Johnson \(B\) above 1 mmag on six nights of observation (Martínez & Kurtz 1994), and has the lowest radial velocity amplitudes known for a roAp star. This supports theoretical expectations (Cunha 2002) of systematically lower frequencies and amplitudes for more evolved roAp stars (at a fixed magnetic field strength). HD 151878 is inconsistent with this, unless it has a stronger field than that of HD 116114 (6 kG), which we show it does not.
Because of the importance of such a high-amplitude pulsation in HD 151878, we obtained the first high-resolution spectra of the star to study the star’s pulsation characteristics, and to study its physical properties – particularly its spectral peculiarities.

2 OBSERVATIONS AND DATA REDUCTION

A total of 74 spectra of HD 151878 were obtained in 2.55 h with the Fibre-fed Echelle Spectrograph (FIES) at the 2.56-m Nordic Optical Telescope (NOT) on 2008 April 30 (HJD 245 4857.196-245 4857.752). The observations were collected by the observatory staff as part of the Fast track Service Mode programme of the NOT. The spectra cover the wavelength range 3860–7350 Å at a resolution of \( R \sim 65000 \). The aperture of the high-resolution fibre used is 1.3 arcsec. With the 46-s readout and overhead times of the fast mode of the CCD, and 80-s exposure times, we obtained a sampling rate of 29 spectra h\(^{-1}\), i.e. three measurements per pulsation cycle for the photometric candidate frequency. The spectra were reduced with the FIES TOOL software supplied by the NOT.\(^1\) This package, based on PYTHON and PYRAF, was especially developed for FIES and performs all conventional steps of echelle data reduction, including the subtraction of bias frames, modelling and subtraction of scattered light, flat-fielding, order extraction, normalization (including fringe correction) and wavelength calibration. Barycentric velocity correction was included in the wavelength calibration. The typical signal-to-noise ratio (S/N) of the individual spectra is 40–60 (\( \lambda > 5500 – 6500 \) Å), and about 350 in the combined spectrum.

A single ThAr reference spectrum, obtained immediately after the science spectra sequence, was found sufficient to do the Doppler shift test. Radial velocity measurements of telluric lines show a wavelength stability to better than 100 m\( \text{s}^{-1} \) over 2.55 h, or to the accuracy obtainable from internal stability of telluric lines. The same stability is found with sharp lines in the stellar spectrum. Relative to five to six telluric lines, the absolute wavelength scale’s zero point deviates by only \(-330 \pm 130 \) (start) to 

\[-200 \pm 170 \text{ m}\( \text{s}^{-1} \) (end) over the 2.55-h run. The stellar spectrum has a mean radial velocity of \(-33.9 \pm 0.2 \text{ km}\( \text{s}^{-1} \).

The merged one-dimensional spectra were normalized relatively to a run master spectrum (a co-added spectrum with a high S/N), then divided by a detailed spline fit to the master spectrum, followed by a low-detail, low-frequency continuum fit performed to each individual spectrum. The line density is very high for HD 151878, especially to the blue where there is no continuum, in spite of a high-resolution fibre used. Individual spectrum. The line density is very high for HD 151878, especially to the blue where there is no continuum, in spite of a high-resolution fibre used.

3 SPECTROSCOPIC ANALYSIS

3.1 The stellar parameters

We first estimated the stellar parameters of HD 151878 from Strömgren photometry compiled by Hauck & Mermilliod (1998) and from Olsen (1983). From the \( \beta \) index alone, \( \beta = 2.759 \), we derived \( T_{\text{eff}} = 7300 \pm 150 \) K using the Moon & Dworetsky (1985) calibration. The Strömgren indices for the combined light of both components of HD 151878 are:

\[ V = 7.223 \pm 0.005, \ b-y = 0.227 \pm 0.003, m_1 = 0.249 \pm 0.004 \text{ and } c_1 = 0.677 \pm 0.004 \]

From the calibrations for A stars given by Crawford (1979), we derive \( E(b - y) = 0.040, \delta m_1 = -0.061 \text{ and } \delta c_1 = -0.021 \). These \( \delta m_1 \) and \( \delta c_1 \) indices indicate strong line blocking in the \( u \) and \( v \) filters and are typical of strongly peculiar Am and Ap star spectra. Using calibrations by Napiwotzki, Schoenberner & Wenske (1993), the \text{TEMPLOGG} code\(^2\) indicates that \( E(b - y) = 0.024, T_{\text{eff}} = 7100, \log g = 4.05 \text{ and } [\text{Fe/H}] = 0.745 \). We note that these calibrations are less reliable for stars with peculiar abundances and stratified atmospheres, than for normal stars.

However, a lower temperature is supported by the spectra. Model spectra were produced from Kurucz model atmospheres with \( T_{\text{eff}} = 7000, 7250, 7500 \) K and \( \log g = 3.0, 3.5, 4.0 \), solar metallicity ([M/H] = 0) and \( \xi = 2 \text{ km}\( \text{s}^{-1} \) using SYNTH (Piskunov 1992). Spectral line lists were taken from the Vienna Atomic Line Data base (VALID; Kupka et al. 1999) and the DREAM data base (Biemont, Palmeri & Quinet 1999), using a microturbulence of \( \xi = 2 \text{ km}\( \text{s}^{-1} \). The best fit to the wings of \( \text{H} \alpha \) was obtained for the adopted temperature \( T_{\text{eff}} = 7000 \pm 150 \text{ K and } \log g = 3.5 \pm 0.5 \). With these parameters fixed, individual lines in the combined spectrum were directly compared to the synthetic line profiles to provide a first look at the spectroscopic nature of HD 151878 (Section 4.3).

\text{Hipparcos} obtained 138 measurements of the star that show no variability above 9.6 mmag amplitude. A marginally significant 14.2 h period is seen at that amplitude, but cannot be confirmed independently and does not agree well with the low \( \sin i \) we observe (see below), if related with the stellar rotation. The \text{Hipparcos} catalogue (Perryman et al. 1997) gives in its Double and Multiple Systems Annex individual apparent magnitudes for the two components of HD 151878: \( V_1(A) = 7.467 \pm 0.009 \text{ and } V_1(B) = 8.924 \pm 0.022 \). As the combined magnitude \( V_1(AB) = 7.215 \) agrees well with that of Olsen (1983), we here use the individual ones to characterize the two stars. It is assumed that the secondary still is on the main sequence, with a temperature of \( T_{\text{eff}}(B) = 7050 \pm 550 \) K. Using bolometric corrections from interpolation in the tables by Flower (1996) (accounting for the uncertainty of \( T_{\text{eff}} \)), the revised \text{Hipparcos} parallax 5.81 ± 0.61 mas (van Leeuwen 2007) and a conservative interstellar absorption \( A_V = 0.050–0.056 \) mag from NASA’s IR dust maps provide (all errors included) \( \log L_1/L_\sun = 1.38^{+0.09}_{-0.10} \) and \( \log L_2/L_\sun = 0.80^{+0.11}_{-0.10} \). Using the standard relation \( L = 4\pi\sigma T^4 \) and the solar temperature \( T_{\text{eff}}(\sun) = 5785 \) K, the relative radii of HD 151878’s stars become \( R_1/R_\sun = 3.35^{+0.34}_{-0.42} \) and \( R_2/R_\sun = 1.72^{+0.24}_{-0.20} \). This places the primary star just past the H core exhaustion (Fig. 1) with a mass of \( 1.82 \pm 0.06 \) M\(_\sun\). From the HR diagram by Cunha (2002), rapid oscillations of 0.6–0.9 mHz are then predicted for HD 151878’s primary, in contrast with the 2.78 mHz found by Tiwari et al. (2007).

3.1.1 Upper limit of a magnetic field

The roAp star HD 116114 has a 6-kG magnetic field that may be important to sustain its pulsations as it is an evolved main-sequence star. Being more evolved, HD 151878 is expected to have a similar, or stronger, magnetic field to exhibit observable rapid oscillations. Although strong magnetic fields are not expected in Am stars, we used the FIES spectra to firmly exclude such a strong field.

The magnetically sensitive line \( \text{Fe} \) i 6149 Å line (see Fig. 2) is often used as a diagnostic line for determining the magnetic field

\[^1\text{http://www.not.iac.es/instruments/fies/fiestool/FIESStool.html}\]

\[^2\text{Available at http://ams.astro.univie.ac.at/templogg}\]
modulus \((B)\) from the line splitting of its Zeeman components (see e.g. Mathys 1989; Freyhammer et al. 2008b). By comparing the averaged FIES spectrum to model spectra calculated using SYNTHIMAG (Piskunov 1999) and rotationally broadened to \(v \sin i = 8 \text{ km s}^{-1}\), it is seen that partial splitting would be visible in Fe\(\text{II}\) 6149 Å at 6.4 kG. Already at 5.7 kG, the line shape is very broad with at flat core, highly different from the observed line.

No magnetically resolved lines were found in the spectrum, and for 21 Fe lines with different Landé factors (and magnetic sensitivity), no clear relation of magnetic broadening with Landé factor could be detected for a relatively high scatter of \(\sigma(B)\) = 2.0 kG. The line broadening was determined by fitting linewidths with Gaussian profiles. The observed spectra therefore firmly exclude any field stronger than \((B) \sim 5.5 \text{ kG}\).

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, and then by measuring centre-of-gravity shifts of individual lines in the spectra. For frequency analyses, we used a discrete Fourier transform programme by Kurtz (1985) and the PERIOD04 (Lenz & Breger 2005) programe. For the run length of 2.55 h and sampling interval of 126 s, the frequency resolution is about 0.1 mHz and the Nyquist frequency is 4.0 mHz. Without simultaneous reference spectra, we have little control over spectrograph stability on timescales of about an hour, so we only consider the frequency range 0.4–4.0 mHz.

Figure 2. A normalized spectral region of HD 151878 (bottom spectrum), compared with those of two roAp stars, HD 128898 (α Ciri) and HD 176232 (10 Aql). The spectra are mutually shifted in intensity by 0.25 for viewing. Selected atomic lines are indicated: dotted lines mark locations of the rare earth elements Nd and Pr. Note the relatively weak Nd and Pr lines of HD 151878, for which Nd\(\text{II}\) 6145 Å is a blend totally dominated by Si\(\text{I}\) 6145 Å.

4.1 Cross-correlation radial velocity analyses

The cross-correlation method, using large spectral regions, has been successful 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). 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 the different pulsation amplitudes of different elements in the stratified roAp atmospheres, where low-amplitude elements such as Fe dilute the ‘integrated’ Doppler shifts. However, for detecting low-amplitude pulsations, the method is very efficient, especially in cases where amplitude and phase are comparable for the most abundant elements.

Cross-correlations were performed with our HD 151878 spectra, using the average spectrum as template. For the line-rich spectral regions \(\lambda \lambda 6150–5800\) and \(5150–5800\) Å, no variability is seen above 10 m s\(^{-1}\) (\(\sigma = 3–4\text{ m s}^{-1}\); see Fig. 3) in the frequency domain of known roAp stars. The wavelength region \(\lambda \lambda 6150–6400\) Å has a lower line density and a higher scatter, but excludes variability above 20 m s\(^{-1}\) (\(\sigma = 7\text{ m s}^{-1}\)).

The spectral region \(\lambda \lambda 6863–6938\) Å with abundant telluric lines was used to check the instrumental stability and identify non-stellar periodicities. The telluric lines only showed low-frequency noise below 0.4 mHz, due to instrumental drifts or meteorological changes: a mostly linearly decreasing velocity of \(-95\text{ m s}^{-1}\), and elsewhere stability at the level above 9 m s\(^{-1}\) (\(\sigma = 3\text{ m s}^{-1}\)).

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 to a few kilometres per second for various roAp stars (Elkin et al. 2008a). Also, the narrow line core of the H\(\alpha\) profile (see Fig. 4) shows rapid pulsations in roAp stars (Kurtz et al. 2006; Elkin et al. 2008a). We therefore searched for pulsations in HD 151878 using such lines and show amplitude spectra of a subset of these in Fig. 5. 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 first detrended with linear least-squares fitting.

The H\(\alpha\) core was stable with highest peaks in the amplitude spectrum of 43 m s\(^{-1}\) with an amplitude standard deviation noise level of 13 m s\(^{-1}\); H\(\beta\) was stable to 85 m s\(^{-1}\) (\(\sigma = 22\text{ m s}^{-1}\)). Of the rare earth elements, lines of Ce\(\text{II}\), Pr\(\text{II}\), Pr\(\text{III}\), Nd\(\text{II}\), Nd\(\text{III}\), Eu\(\text{II}\), Tm\(\text{II}\) and La\(\text{II}\) excluded rapid pulsations with typical upper limits of 320 m s\(^{-1}\) and noise levels varying from 70 to 110 m s\(^{-1}\) for the
Figure 4. Same as Fig. 2, but for the spectral region in the vicinity of the Hα line, again compared with those of the two roAp stars. Note that the – for roAp stars typical – core-wing anomaly (Cowley et al. 2001) is much less pronounced for HD 151878.

Figure 5. Amplitude spectra for individual and combined RV time series for selected elements. Note the different ordinate scales. Eu shows some power in the signal around 2 mHz, but the dominant peaks are not in common with peaks for the other two studied Eu lines.

majority of good lines. Combining lines of the same ion reduced the noise level, such as six Nd lines: $A_{\text{max}} = 153 \text{ m s}^{-1}$ ($\sigma = 45 \text{ m s}^{-1}$) and six Pr lines: $A_{\text{max}} = 135 \text{ m s}^{-1}$ ($\sigma = 42 \text{ m s}^{-1}$), or combined for all 12 lines $A_{\text{max}} = 111 \text{ m s}^{-1}$ ($\sigma = 31 \text{ m s}^{-1}$).

Of the non-rare earth element lines analysed, including the strong sodium D and Mg I lines and several Ca, Sc, Ti, Cr, Fe, Y and Ba lines, no pulsations were detected above typical upper limits of 100–200 m s$^{-1}$ ($\sigma = 30–100 \text{ m s}^{-1}$). In general, some lines, such as Eu in Fig. 5, 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 the star (using a $4\sigma$ significance criterion). Iron is strong and abundant in HD 151878 but normally exhibits the lowest pulsation amplitudes in known roAp stars. With 15 lines, the typical upper amplitude limit for HD 151878 was 150 m s$^{-1}$ ($\sigma = 40–45 \text{ m s}^{-1}$).

We conclude that there is no evidence of pulsation in the radial velocities of our spectroscopic times series.
4.3 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 the abundances of the first two ionized states of neodymium and praseodymium show more than 1 dex difference, with the doubly ionized ions, which form higher in the atmosphere, giving the highest abundance (Ryabchikova et al. 2004; Kurtz et al. 2007). This ionization disequilibrium anomaly may be explained mostly by concentration of rare earth elements in high atmospheric layers (stratification) and partly by non-LTE effects (Mashonkina, Ryabchikova & Ryabtsev 2005). Non-LTE effects may enhance the ionization of Nd II or Pr II and accordingly weaken their absorption lines, while strengthening those of the second ionization state.

To compare HD 151878 spectrally with the roAp stars, we estimated its chemical abundances for selected elements and tested for ionization disequilibria for Nd and Pr. Abundances were determined by fitting synthetic spectra to the observed average spectrum. The model spectra were calculated with SYNTH as described in Section 3.1, using a Kurucz model atmosphere with $T_{\text{eff}} = 7000$ K, $\log g = 3.5$ and slightly enhanced (above solar) metallicity: $[\text{M/H}] = \log (N_{\text{M}}/N_{\odot}) - \log (N_{\text{M}}/N_{\odot})_{\odot} = +0.2$. We tried microturbulence values of $\xi = 2, 4$ and $5 \text{ km s}^{-1}$ and found the best agreement in derived abundances for strong and weak iron lines using $\xi = 4 \text{ km s}^{-1}$, which was then adopted. A projected rotation velocity of $v \sin i = 8.3 \pm 0.6 \text{ km s}^{-1}$ was determined from several symmetric iron lines, and the macroturbulence velocity was optimized, on a line-by-line basis, in the range $5–8 \text{ km s}^{-1}$. The latter parameter was chosen such that the model spectra matched wings and core of the observed line profiles. However, in some cases a 1σ to 2σ larger $v \sin i$ could also be used for a lower macroturbulence velocity.

The resulting abundances for the 2.55 h average spectrum are presented in Table 1 and shown graphically in Fig. 6. Solar abundances are from Asplund, Grevesse & Sauval (2005). Relative abundances are given on the scale $\log \epsilon_{\text{Ca}} - \log \epsilon_{\odot} = \log (N_{\text{Ca}}/N_{\odot}) - \log (N_{\text{Ca}}/N_{\odot})_{\odot}$. Most of the measured elements are stronger than solar, increasing in abundances with atomic number Z. Lines of Ca and Sc II have significantly less than solar abundances. Ca and Ca II lines were all deficient (including the Ca II K and H lines) and give combined $\log \epsilon_{\text{Ca}} = 5.59 \pm 0.14 \text{ dex}$. Ca and Sc deficiency and overabundance of metallic elements are Am star characteristics. The Ca deficiency is consistent with the spectral classification of Grenier et al. (1999), which suggests strongly deficient Ca II from the weakness of the K line, but is inconsistent with the Am: (marginal Am) classification of Bidelman (1985). The former classification is, however, more consistent with the Strömgren $\delta$m and $\delta$c indices. Fig. 7 shows our observed Ca II K line compared to model spectra for three different Ca abundances. A lower than solar Ca II abundance is required, which confirms Grenier’s result and the Am status of the star.

We do not find indication of ionization disequilibria for neither neodymium nor praseodymium and simply give the combined abundance of the first two ionized states in Table 1. The abundances for Nd, Pr and Eu are about 1 dex above solar, which is low for most known roAp stars, such as HD 128898 and 10 Aql (Figs 2 and 4).

Table 1. Chemical abundances for HD 151878 for selected elements, and their corresponding solar abundances (Asplund et al. 2005). The errors quoted are internal standard deviations for the set of lines measured. The two measured Li lines are components in the same blend, Li i 6707.76 and Li ii 6707.91 Å.

| Ion | Number of lines | $\log \epsilon_{\text{Ca}}$ HD151878 | $\log \epsilon_{\text{Ca}}$ Sun |
|-----|----------------|-------------------------------|-------------------------------|
| Li  | 2              | $2.69 \pm 0.20$              | $1.05 \pm 0.10$              |
| Na  | 3              | $6.52 \pm 0.09$              | $6.17 \pm 0.04$              |
| Si  | 7              | $7.79 \pm 0.06$              | $7.51 \pm 0.04$              |
| S   | 3              | $7.48 \pm 0.15$              | $7.14 \pm 0.05$              |
| Ca I| 5              | $5.71 \pm 0.06$              | $6.31 \pm 0.04$              |
| Ca II| 4             | $5.48 \pm 0.20$              | $6.31 \pm 0.04$              |
| Sc  | 4              | $1.13 \pm 0.40$              | $3.05 \pm 0.08$              |
| Ti  | 4              | $4.58 \pm 0.31$              | $4.90 \pm 0.06$              |
| Cr  | 16             | $5.98 \pm 0.14$              | $5.64 \pm 0.10$              |
| Fe  | 14             | $7.63 \pm 0.07$              | $7.45 \pm 0.05$              |
| Co  | 5              | $5.33 \pm 0.06$              | $4.92 \pm 0.08$              |
| Ni  | 12             | $6.83 \pm 0.09$              | $6.23 \pm 0.04$              |
| Cu  | 4              | $4.71 \pm 0.07$              | $4.21 \pm 0.04$              |
| Y   | 7              | $3.04 \pm 0.16$              | $2.21 \pm 0.02$              |
| Zr  | 3              | $3.13 \pm 0.20$              | $2.59 \pm 0.04$              |
| Ba  | 3              | $3.37 \pm 0.06$              | $2.17 \pm 0.07$              |
| La  | 3              | $2.36 \pm 0.10$              | $1.13 \pm 0.05$              |
| Ce  | 4              | $2.73 \pm 0.10$              | $1.58 \pm 0.09$              |
| Pr  | 11             | $1.72 \pm 0.28$              | $0.71 \pm 0.08$              |
| Nd  | 10             | $2.35 \pm 0.20$              | $1.45 \pm 0.05$              |
| Eu  | 3              | $1.62 \pm 0.12$              | $0.52 \pm 0.06$              |
Sct pulsations. From our velocity measurements $\delta = 6149 \, \text{Å}$ line, we exclude magnetic fields stronger than 5.5 kG at Nainital, India. The same tele-

(Without removing linear $\epsilon = 6.07^\circ$ and Li II $6707.76$ and Li II $6707.91$ Å with a rotationally

in HD 99563 (Elkin, Kurtz & Mathys $\epsilon$ 2005a), the latter with amplitudes of 26–125 m s$^{-1}$, measured in lines of the rare earth elements Eu, La and Zr and in the core of the H$\alpha$ line. The highest radial velocity amplitudes yet detected are for lines of Eu II in HD 99563 (Elkin, Kurtz & Mathys 2005b) where individual components generated by surface spots can reach amplitudes of even 8 km s$^{-1}$. The roAp stars also have strong magnetic fields that range from several hundred Gauss to 24.5 kG in HD 154708. Furthermore, they have strong abundances of rare earth elements and almost all of them show ionization disequilibria for Pr and Nd.

HD 151878 fails to show these characteristics and is spectroscopically unlike the roAp stars. It shows no rapid oscillations with radial velocity amplitudes above a few tens of metres per second at the time of our observations. The methods applied, and the length of the data set acquired, would be sufficient for detecting pulsations in most known roAp stars. The roAp stars are oblique pulsators with amplitude modulation of their pulsation with rotation. There is no clear correlation between photometric pulse amplitude and radial velocity pulsation amplitude in the roAp stars, but the photometric high amplitude roAp stars – e.g. HD 83368, HD 60435, HD 99563 and HD 101065 – have H$\alpha$ radial velocity amplitudes of hundreds of m s$^{-1}$ to 2.5 km s$^{-1}$; we would expect HD 151878 to be similar. Therefore, for the spectacularly high photometric amplitude reported by Tiwari et al. (2007), it is improbable that we observed at a rotation phase where the radial velocity amplitude was undetectable at the high precision of our measurements.

The evolutionary tracks in Fig. 1, as well as those in fig. 1 of Cunha (2002), indicate that HD 151878 is past the terminal age main

sequence. 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 for slowly rotating Ap stars ($v \sin i = 1–3$ km s$^{-1}$).

Freyhammer et al. (2008a) searched for pulsations in nine evolved cool Ap stars located inside the theoretical instability strip, the majority having estimated temperatures below 8100 K. With only slightly better precision and upper limits on radial velocity ampli-

tudes as in this study, these authors found nine null results. Out of seven stars, only three stars had magnetic fields significantly stronger than 2 kG, which possibly explains most of their null re-

sults for such evolved stars.

Based on comparison of synthetic spectra with HD 151878’s Fe I 6149 Å line, we exclude magnetic fields stronger than 5.5 kG in this star. The magnetic field seems too weak for the star’s evolved state to suppress local convection and enable pulsational driving of rapid pulsations to reach observable amplitudes. In this respect, the small, or absent, magnetic field is another Am star characteristic.

Our abundance analysis found that HD 151878 has only mildly strong abundances of rare earth elements and no ionization disequili-

bria for Nd and Pr. In these respects, HD 151878 does not resemble known roAp stars. Its Ca II and Sc deficiencies are a clear sign of an Am, rather than Ap, nature. Our abundance analysis agrees with the Am spectral classifications. We conclude that HD 151878 is a cool evolved Am star. As a such, rapid oscillations are unexpected.

Evolved Am stars are known to be potential pulsators (unlike their main-sequence counterparts, which rarely are), exhibiting $\delta$ Sct pulsations (such as $\delta$ Delphini). In fact, the evolutionary state and dimensions of HD 151878 resemble those of the pulsating evolved cool Am star HD 98851 (Joshi et al. 2003). However, the time-scales of pulsating Am stars are much longer (~hours) than those of roAp stars (~minutes). Our spectra only cover 2.55 h and are not suited for searching for $\delta$ Sct pulsations. From our velocity measurements of H$\alpha$ and H$\beta$, we see no indication of variability on time-scales of 1–3 h and amplitudes above 60–250 m s$^{-1}$ (without removing linear trends).

Could HD 151878B be the source of the pulsations? This star was inside the diaphragm of the photometric observations of Tiwari et al. (2007), but to cause a 22 mmag change in the combined light, the much fainter secondary would have to pulsate with an amplitude of 100 mmag. While such an amplitude is characteristic of $\delta$ Scuti stars, it is unheard of a roAp star (the highest known is 16 mmag for HD 60435). The secondary star is located at the red border of the roAp instability strip, and is even possibly outside of it. We conclude that the secondary star could not be the source of the observed 6-min, 22-mmag photometric variations.

This leads to the obvious question as to what is the cause of the observed variations reported by Tiwari et al. (2007). Their light curves are convincing; the peaks in their amplitude spectra are highly significant. Their observations were obtained with the 1-m Sampurnanand telescope of ARIES at Nainital, India. The same tele-

scope has been used for many years in the ‘Nainital – Cape survey’ for northern roAp stars (see e.g. Joshi et al. 2006, and references therein). Joshi et al. discovered apparent roAp pulsations in another star classified as an Am star, HD 207561 (see their fig. 3 and accompanying discussion). On two consecutive nights, it showed significant high-amplitude pulsation with a frequency of 2.75 mHz...
(P = 6.1 min) – the same frequency as found by Tiwari et al. (2007) for HD 151878 – yet no further signal was seen again in observations obtained on 17 individual nights over three observing seasons. We therefore suggest that the signal published for HD 151878 is instrumental in origin.

ACKNOWLEDGMENTS

We thank Margarida Cunha for the evolutionary tracks and other data for constructing Fig. 1 of this paper, which is directly based on fig. 1 of Cunha (2002). An anonymous referee is thanked for his/her comments. This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We acknowledge using extracts of the introduction by Elkin et al. (2008b). This research has made use of data obtained using the UK’s AstroGrid Virtual Observatory Project, which is funded by the Science & Technology Facilities Council and through the EU’s Framework 6 programe. We acknowledge support for this work from the Particle Physics and Astronomy Research Council (PPARC) and from the UK’s Science and Technology Facilities Council (STFC) and thank the NOT telescope staff for advice in planning and for collecting the observations.

REFERENCES

Asplund M., Grevesse N., Sauval A. J., 2005, Proc. ASP Conf. Ser. Vol. 336, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis in honor of David L. Lambert. Astron. Soc. Pac., San Francisco, p. 25

Balona L. A., Zima W., 2002, MNRAS, 336, 873

Bidelman W. P., 1985, AJ, 90, 341

Biémont E., Palmeri P., Quinet P., 1999, Ap&SS, 269, 635

Cowley C. R., Hubrig S., Ryabchikova T. A., Mathys G., Piskunov N., Mittermayer P., 2001, A&A, 367, 939

Crawford D. L., 1979, AJ, 84, 1858

Cunha M. S., 2002, MNRAS, 333, 47

Elkin V. G., Riley J. D., Cunha M. S., Kurtz D. W., Mathys G., 2005a, MNRAS, 358, 665

Elkin V. G., Kurtz D. W., Mathys G., 2005b, MNRAS, 364, 86

Elkin V. G., Kurtz D. W., Mathys G., 2008a, Contributions of the Astronomical Observatory Skalnate Pleso, 38, 317

Elkin V. G., Kurtz D. W., Freyhammer L. M., Mathys G., Hubrig S., 2008b, MNRAS, in press (doi:10.1111/j.1365-2966.2008.13819.x)

Flower B. J., 1996, ApJ, 469, 355

Freyhammer L. M., Kurtz D. W., Cunha M. S., Mathys G., Elkin V. G., Riley J. D., 2008a, MNRAS, 385, 1402

Freyhammer L. M., Elkin V. G., Kurtz D. W., M. S., Mathys G., Martinez P. 2008b, MNRAS, 389, 441

González J. F., Hubrig S., Kurtz D. W., Elkin V., Savanov I., 2008, MNRAS, 384, 1140

Grenier et al., 1999, A&AS, 137, 451

Handler G., Paunzen E., 1999, A&AS, 135, 57

Handler G. et al., 2006, MNRAS, 366, 257

Hatzes A. P., Mkrtichian D. E., 2004, MNRAS, 351, 663

Hauck B., Mermilliod M., 1998, A&AS, 129, 431

Hubrig S., Kharchenko N., Mathys G., North P., 2000, A&A, 355, 1031

Hubrig S. et al., 2005, A&A, 440, L37

Joshi S. et al., 2003, MNRAS, 344, 431

Joshi S., Mary D. L., Martínez P., Kurtz D. W., Girish V., Seetha S., Sagar R., Ashoka B. N., 2006, A&A, 455, 303

Kupka F., Piskunov N., Ryabchikova T. A., Stempels H. C., Weiss W. W., 1999, A&AS, 138, 119

Kurtz D. W., 1984, MNRAS, 209, 841

Kurtz D. W., 1985, MNRAS, 213, 773

Kurtz D. W., van Wyk F., Roberts G., Marang F., Handler G., Medupe R., Kilkenny D., 1997, MNRAS, 287, 69

Kurtz D. W., Elkin V. G., Cunha M. S., Mathys G., Hubrig S., Wolff B., Savanov I., 2006, MNRAS, 372, 286

Kurtz D. W., Elkin V. G., Mathys G., 2007, MNRAS, 380, 741

Lenz P., Breger M., 2005, Commun. Asteroseismol., 146, 53

Martínez P., Kurtz D. W., 1990, MNRAS, 242, 636

Martínez P., Kurtz D. W., 1994, MNRAS, 271, 129

Mashonkina L., Ryabchikova T., Ryabtsev A., 2005, A&A, 441, 309

Mathys G., 1989, Fundamental Cosmic Phy., 13, 143

Matthews J. M., Wehlau W. H., Kurtz D. W., 1987, ApJ, 313, 782

Matthews J. M., Wehlau W. H., Walker G. A. H., Yang S., 1988, ApJ, 324, 1099

Moon T. T., Dworetsky M. M., 1985, MNRAS, 217, 305

Napiwotzki R., Schoenberner D., Wenske V., 1993, A&A, 268, 653

North P., Jaschek C., Hauck B., Figueras F., Torra J., Kunzi M., 1997, ESA SP-402, Hipparcos – Venice 97. ESA Publications Division, Noordwijk, p. 239

North P., Betrix F., Besson C., 2005, EAS Pub. Ser., 17, 333

Olsen E. H., 1983, A&A, 54, 55

Perryman M. A. C. et al., 1997, A&A, 323, L49

Piskunov N. E., 1992, in Glagolevskij Yu. V., Romanyuk I. I., eds, Stellar Magnetism. NAUKA, St Petersburg, p. 92

Piskunov N. E., 1999, in Nagendra K. N., Stenflo J. O., eds, Astrophys. Space Sci. Library Vol. 243, Solar Polarization. Kluwer Academic Publisher, Dordrecht, p. 515

Ryabchikova T. A., Savanov I. S., Hauck B., Figueras F., Torra J., Kunzi M., 1997, ESA SP-402, Hipparcos – Venice 97. ESA Publications Division, Noordwijk, p. 239

Ryabchikova T., Nesvacil N., Weiss W. W., Kochukhov O., Stütz C., 2004, A&A, 423, 705

Tiwari S. K., Chaubey U. S., Pandey C. P., 2007, Inf. Bull. Var. Stars, 5787, 1

van Leeuwen F., 2007, A&A, 474, 653

This paper has been typeset from a \TeX\/\LaTeX\ file prepared by the author.