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Time-resolved spectroscopy of the rapidly oscillating Ap star KIC 10195926*

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ABSTRACT

We report an analysis of high time resolution spectra of the chemically peculiar Ap star KIC 10195926 obtained with the Subaru telescope. We find that the star has low overabundances of rare earth elements compared with other rapidly oscillating Ap stars. We found only upper limits for pulsations from spectral lines of rare earth and other chemical elements. Pulsation was found only for the narrow core of the Hα line with an amplitude of $171 \pm 41\,\mathrm{m\,s^{-1}}$ and with the frequency corresponding to photometric frequency obtained from *Kepler* observations.

Key words: asteroseismology – stars: chemically peculiar – stars: individual: KIC 10195926 – stars: oscillations.

1 INTRODUCTION

Rapidly oscillating Ap (roAp) stars are main-sequence stars with chemical anomalies. In the Hertzsprung–Russell (HR) diagram, roAp stars concentrate in the region where the instability strip crosses the main sequence. Pulsation periods in roAp stars range from about 6 to 24 min. Pulsation also can be multiperiodic.

The roAp stars have strong global dipolar magnetic fields in the range from several hundred Gauss to 25 kG. To a first approximation, the magnetic fields for these stars can be described as an oblique dipole where the dipole axis is inclined to the rotational axis. The pulsation axis is also not aligned with the rotational axis, but according to the oblique pulsator model (Kurtz 1982; Shibahashi & Takata 1993; Takata & Shibahashi 1995; Bigot & Dziembowski 2002; Bigot & Kurtz 2011) it is close to the magnetic dipole axis. When an roAp star rotates, the geometry of the pulsation changes and we can see pulsation modes from different aspects.

Balmforth et al. (2001) proposed that the strong magnetic field suppresses convection in the stellar regions close to magnetic poles, and with suppressed convection the κ-mechanism in the hydrogen ionization zone excites high-frequency pulsations (see also Gautschy, Saio & Harzenmoser 1998; Théado et al. 2009), although Cunha et al. (2013) and Saio (2014) find from roAp stars with pulsation frequencies higher than the cutoff frequency that additional driving from some other mechanism is needed.

The first roAp star was found by Kurtz (1978) with photometric observations of one of the most peculiar stars known, HD 101065. At present, there are around 60 roAp stars known. A list of 35 stars was presented by Kurtz et al. (2006). Other new roAp stars were found by Kochukhov et al. (2008, 2009, 2013), González et al. (2008), Elkin et al. (2010, 2011) and Alentiev et al. (2012). 10 new roAp stars were found by Holdsworth et al. (2014) when they used the WASP (wide-field survey for transiting exoplanets) archive for searching high-frequency pulsation among A and F stars. Three roAp stars were found with the *Kepler* mission, including KIC 8677585 (Balona et al. 2011a), KIC 10483436 (Balona et al. 2011b) and KIC 10195926 (Kurtz et al. 2011). The *Kepler* mission, which was very successful in the search for exoplanets, also provided abundant, incredibly precise photometric data for different types of stars. The *Kepler* telescope observed about 190 000 stars, but only small part of them in short cadence (SC) with just under 1-min integration time. Only several dozens of stars with photometric parameters related to roAp stars were observed with *Kepler*. Many of these stars were identified as δ Sct stars and only the three roAp stars mentioned above have so far been discovered in the *Kepler* mission data.

All *Kepler* observations are divided into quarters (Q) of the 372.455-d orbital period of satellite around the Sun. The roAp star KIC 10195926 was observed with *Kepler* in long cadence (LC) with integrations of 29.4 min in all quarters, Q0–Q17, over the 4-yr mission, and in SC in quarters Q3.3, and Q6.1–Q17.2 consecutively. For the study of rapid oscillations, the SC data are more suitable as the pulsation periods are only several minutes. LC and SC data can both be used to study longer variations and for rotational period determination. Kurtz et al. (2011) used SC and LC data from *Kepler* photometry. They found that star has two main pulsation modes with periods at 17.1 and 18.1 min.

Fig. 1 shows an amplitude spectrum for the full Q6–Q17 SC data in the frequency range of the two pulsation modes of KIC 10195926.

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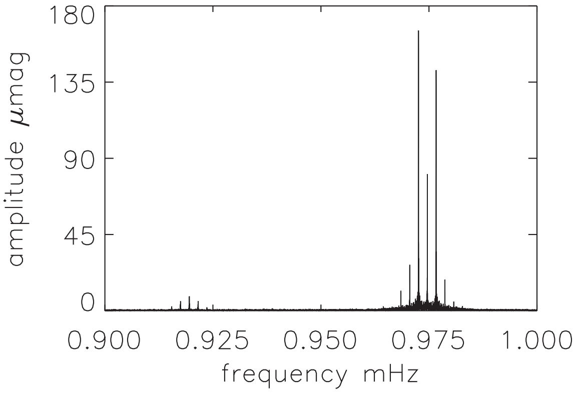

Figure 1. An amplitude spectrum for the Q6–17 SC *Kepler* data showing the presence of two pulsation mode frequencies, both split into multiplets by the changing aspect of oblique pulsation.

Each mode is an obliquely pulsating distorted dipole mode that gives rise to a frequency multiplet split by the rotation frequency of the star. Thus, there are only two pulsation frequencies present in Fig. 1, each split by oblique pulsation into a multiplet. Since one mode dominates in amplitude, it is the central frequency of that mode, $\nu_1 = 0.972\,587$ mHz ($P = 17.136$ min), for which we search for pulsational radial velocity variations in this study. Importantly, this frequency is stable over the 4-yr *Kepler* data set.

These pulsation periods are relatively long for an roAp star and suggest that the star is close to the terminal-age main sequence, according to a theoretical models by Cunha (2002). The two pulsation modes were interpreted to have separate pulsation axes by Kurtz et al. (2011) within the improved oblique pulsator model of Bigot & Dziembowski (2002) and Bigot & Kurtz (2011). KIC 10195926 is the first pulsating star which shows evidence of separate pulsation axes for different modes. This may have significant implication for the interpretation and modelling of pulsations in the presence of magnetic fields and rotation.

There is another fruitful method to study pulsations in roAp stars. Most of these stars show pulsational radial velocity variations (e.g. Malanushenko, Savanov & Ryabchikova 1998; Kurtz, Elkin & Mathys 2007) that differ for different chemical elements. The majority of spectral lines that reveal pulsation belong to rare earth elements. The spectral lines of other chemical elements, including light elements and iron peak elements, show radial velocity pulsation amplitudes much lower than those of the rare earth elements, and in many cases no amplitude at all is detected. This behaviour is interpreted as both vertical stratification, with the lines of rare earth elements formed in higher layers of the stratified stellar atmosphere (Kochukhov & Ryabchikova 2001; Ryabchikova et al. 2001), and horizontal concentrations of rare earth elements, typically in spots near to the pulsation and magnetic poles (e.g. Freyhammer et al. 2009). Therefore, when we study pulsation behaviour of spectral lines belonging to different elements which form in different levels in the atmosphere and in spots, we can test the pulsation properties in the atmospheric vertical dimension and even in three dimensions.

In this paper, we present an analysis of high time resolution spectroscopic observations of KIC 10195926. The main goal of this project was an exploratory high time resolution spectroscopic study of the first bi-axial pulsating star, KIC 10195926. We tested whether certain elements may show significantly higher signal-to-noise ratio pulsational radial velocity variations than can be obtained from photometric light variations. The *Kepler* white light pulsation amplitude for this star reaches about 0.5 mmag, which is roughly equivalent to about 2 mmag if it were observed in Johnson *B* to compare with other roAp stars. This is not a particularly high photometric amplitude for an roAp star; hence, we were searching for the possibility of much higher amplitude in the radial velocity variations of some elements. One of the highest amplitude roAp stars is HD 99563 with a *B* amplitude of about 0.01 mag and radial velocity amplitudes up to 8 km s^{-1} (Freyhammer et al. 2009). Thus, there was some prospect of radial velocity amplitudes up to km s^{-1} level in KIC 10195926.

To test for this, high signal-to-noise ratio, high spectral resolution, high time resolution spectroscopic observations are needed near to the time of rotational pulsation maximum. With a magnitude of $Kp = 10.57$, only an 8-m class telescope is capable of this. We report in this paper the results from spectroscopic observations we obtained for this purpose with the Subaru telescope.

2 OBSERVATIONS AND DATA REDUCTION

High-resolution spectra of KIC 10195926 were collected with the high-dispersion spectrograph at Subaru telescope of the National Astronomical Observatory of Japan (Noguchi et al. 2002). Observations were carried out on 2012 June 28 beginning at BJD = 2456106.63046. From the rotational light variations, Kurtz et al. (2011) determined a rotational ephemeris of

$$\mathrm{BJD_{max}} = 2455168.91183 + \mathrm{E}\,(5.68459 \pm 0.00013)\,\mathrm{d}, \qquad (1)$$

where phase zero coincides with the time of pulsation maximum (and rotational light minimum); hence, the Subaru observations were obtained close to the time of pulsation maximum. A total of 100 spectra were gathered with exposure times of 150 s and readout plus overhead times of ∼59 s, corresponding to a time resolution of ∼209 s. This time resolution is appropriate for our objective, considering the known highest amplitude pulsation period of 17.136 min.

The observations covered the spectral range λλ4385–7120 Å, with a 60-Å gap around 5760 Å caused by the space between the two CCDs. The spectral resolution is about $R = 45\,000$. The CCD frames were processed using IRAF and ESO-MIDAS to extract and merge the echelle orders to 1D spectra that were normalized to the continuum. The weather conditions on the night of observation were not perfect, reducing the signal-to-noise ratio for the obtained spectra. We estimate the signal-to-noise ratio to be from 20 to 80 for the continuum of the reduced one-dimensional spectra. To minimize noise for further analysis, we excluded spectra with signal-to-noise ratios below 50. We made a co-added spectrum for the first 55 Subaru spectra. This co-added spectrum was used for identification of spectral lines, for testing the stellar parameters and for chemical analysis.

3 STELLAR PARAMETERS AND CHEMICAL ABUNDANCES

The spectrum of KIC 10195926 has relatively weak and shallow spectral lines compared to slowly rotating roAp stars such as HD 101065, HD 134214 and HD 201601, but it is also reminiscent of faster rotators among roAp stars, such as HD 42569 and HD 83368 (HR 3831), although the latter has stronger lines of rare earth elements. Fig. 2 shows two sections of the spectrum of KIC 10195926 compared to the roAp star HD 42569. Spectral lines in both stars have asymmetric profiles, probably as a result

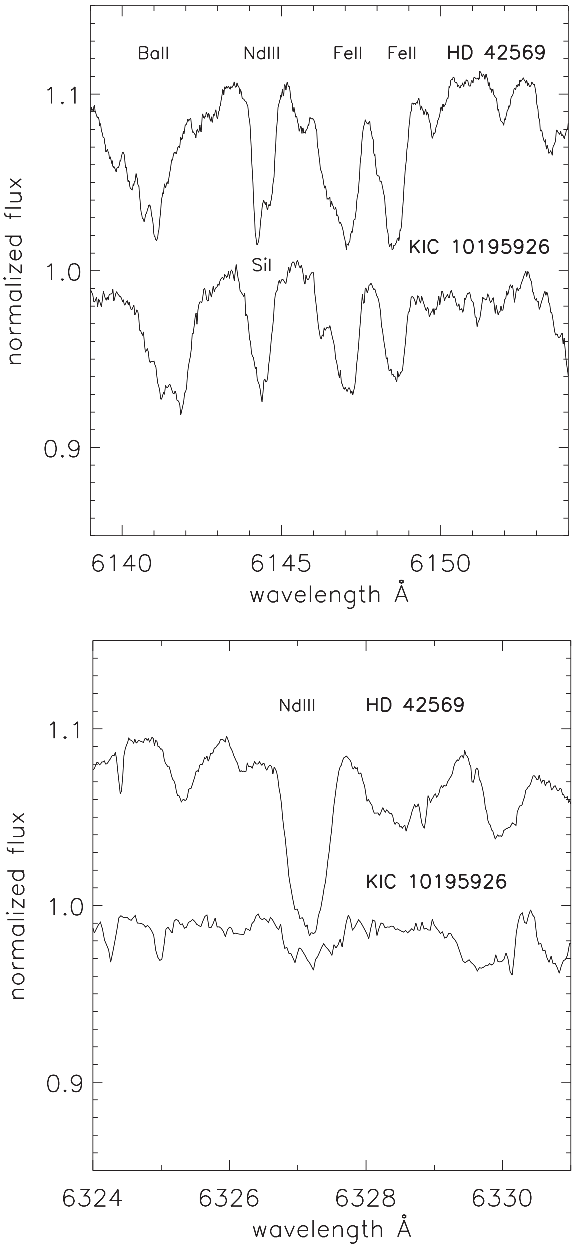

Figure 2. Sections of the spectrum of KIC 10195926 compared to the roAp star HD 42569. Many roAp stars show strong overabundances of Nd III; KIC 10195926 does not. Top: the spectral line near 6145 Å is a blend of the Nd III 6145.068 Å line and the Si II 6145.016 Å line. In the spectrum of KIC 10195926, the majority of the line belongs to Si II 6145.016 Å and only a small fraction to Nd III 6145.068 Å. The opposite is the case in the spectrum of HD 42569 where the major part of this line belongs to Nd III. Bottom: this shows the relative weakness of the Nd III 6327.265 Å line in KIC 10195926 compared to HD 42659. The spectra of HD 62459 have been offset in intensity for clarity.

of typical non-uniform surface distribution of chemical elements. The obvious difference between the spectra is that the Nd III lines do not show the overabundant line strengths in KIC 10195926 that are typical of many other roAp stars.

A spectral line list was extracted from the Vienna Atomic Line Database (VALD; Kupka et al. 1999). We also extracted from VALD the lines of rare earth elements from the DREAM data base (Biémont, Palmeri, & Quinet 1999). The line list was used for spectral line identification and for the calculation of synthetic spectra with the SYNTH code (Piskunov 1992) for comparison with the observed high-resolution spectra. The stellar atmosphere models used were downloaded from the Vienna New Model Grid of Stellar Atmospheres data base (Heiter et al. 2002).

With a high-resolution spectrum, Kurtz et al. (2011) determined for KIC 10195926 an effective temperature $T_{\rm eff} = 7200 \pm 200$ K and an estimated surface gravity $\log g = 3.6 \pm 0.3$ (cgs units). We compared synthetic profiles of Hα with the observed profile of a co-added, high signal-to-noise ratio spectrum and found good agreement. The new Subaru data confirm the stellar parameters obtained by Kurtz et al. (2011). We adopted the same $T_{\rm eff}$ and $\log g$ for the calculation of synthetic spectra and for chemical analysis of the new Subaru spectroscopic observations of KIC 10195926.

An abundance analysis of KIC 10195926 (Kurtz et al. 2011) revealed that the star has a spotted structure and shows changes of abundance for different rotational phases consistent with the *Kepler* rotational light variations. Table 4 in Kurtz et al. (2011) shows that the star has abundances close to normal for magnesium and iron and above the normal for chromium, neodymium and europium. The star belongs to cool end of the temperature range of chemically peculiar Ap stars, but does not have extreme overabundance of rare earth elements. Many other cool Ap stars have higher overabundances of rare earth elements detected from their spectra (Ryabchikova et al. 2004). For KIC 10195926 even the line of Eu II 6645 Å, which is often strong in roAp stars, is only visible at favourable rotation phase (see fig. 1 in Kurtz et al. 2011).

For our abundance analysis, we created a co-added Subaru spectrum of KIC 10195926. We calculated a range of synthetic spectra for various chemical abundances and compared them with the observations for optimal agreement. Average abundances for different chemical elements are presented in Table 1 corresponding to a rotational phase of 0.97 according to equation (1). The results are compared with those from Kurtz et al. (2011) and with solar abundances from Asplund et al. (2009). The abundances in Table 1 represent three phases of rotation, but two of those (columns 4 and 6) are close in phase and the abundances obtained for both these phases do not differ significantly.

The spectral line near 6708 Å has been detected in some other Ap stars and most probably belongs to the lithium doublet, Li I 6707.761 and 6707.912 Å (Faraggiana et al. 1986; Polosukhina et al. 1999; Kochukhov 2008). The Subaru spectrum also shows a spectral feature near 6708 Å which is a wide blend of the Li I doublet and an unknown line. For this doublet of Li I, we found a chemical abundance 2 dex higher than solar. This is consistent with some other cool Ap stars.

The silicon abundance obtained in KIC 10195926 is about 0.5 dex above solar and similar to other cool Ap stars. As shown by Ryabchikova et al. (2004) for 13 cool Ap stars, the silicon abundance can be from solar up to 0.5 dex above solar. There is an Ap star, HD 110066, that has a 1.2 dex overabundance of silicon, but this star has a higher effective temperature than roAp stars. The abundance of calcium in KIC 10195926 is slightly higher than normal. Comparing with the results of Ryabchikova et al. (2004), the average abundance of calcium in cool Ap stars is 0.5 dex above solar.

We did not find lines of scandium and nickel in our Subaru spectrum. We deduce that scandium is thus deficient by more than 1 dex and nickel by more than 2 dex. On the other hand, at rotational phase 0.31, shown in column 2 of Table 1, the lines of Sc II and Ni I were good enough to fit with synthetic spectra. For the phase 0.97, the lines of these elements disappeared. The lines of Ti II were identified

Table 1. Chemical abundances for KIC 10195926 for different rotational phases from Kurtz et al. (2011) (columns 2 and 4) and this work (column 6) and the corresponding solar abundances (Asplund et al. 2009) (column 8). The errors quoted are internal standard deviations for the set of lines measured. Columns 3, 5 and 7 give the number of lines used for each element or ion.

Ion	log $N/N_{\rm tot}$ $\phi = 0.31$	$N_{\rm lines}$	log $N/N_{\rm tot}$ $\phi = 0.95$	$N_{\rm lines}$	log $N/N_{\rm tot}$ $\phi = 0.97$	$N_{\rm lines}$	log $N/N_{\rm tot}$ Sun
Li I					−8.90	1	−10.95
Mg I	−4.4 ± 0.1	3	−4.3 ± 0.1	4	−4.35 ± 0.04	3	−4.40
Si I	−4.4 ± 0.2	3	−4.1 ± 0.1	4	−4.08 ± 0.08	5	−4.49
Si II	−4.2 ± 0.1	3	−4.0 ± 0.2	4	−4.00 ± 0.10	3	−4.49
Ca I	−5.1 ± 0.1	18	−5.3 ± 0.2	10	−5.39 ± 0.14	9	−5.66
Sc II	−8.7 ± 0.1	3	−9.9 ± 0.2	2			−8.85
Ti II	−6.3 ± 0.1	3	−7.4 ± 0.3	3	−8.07 ± 0.24	6	−7.05
Cr I					−5.67 ± 0.21	8	−6.36
Cr II	−5.7 ± 0.1	6	−5.7 ± 0.1	8	−5.64 ± 0.09	12	−6.36
Mn I					−5.68 ± 0.43	5	−6.57
Fe I	−4.3 ± 0.1	25	−4.6 ± 0.1	29	−4.73 ± 0.20	43	−4.50
Fe II	−4.3 ± 0.1	7	−4.6 ± 0.1	7	−5.03 ± 0.19	12	−4.50
Ni I	−5.9 ± 0.1	4	−6.7 ± 0.2	3			−5.78
Sr II	−8.8 ± 0.2	2	−8.0 ± 0.2	2			−9.13
Y II	−8.9 ± 0.1	2	−8.8 ± 0.3	5	−8.88 ± 0.08	3	−9.79
Ba II	−9.0 ± 0.1	3	−10.4 ± 0.3	2	−11.14 ± 0.21	5	−9.82
Nd III			−9.3 ± 0.1	3	−9.58 ± 0.08	4	−10.58
Eu II			−8.4 ± 0.1	4	−9.45 ± 0.26	4	−11.48

in the Subaru spectrum and show a deficiency of 1 dex in comparison with solar abundance of this element. This can be compared to the results of Ryabchikova et al. (2004), who obtained titanium abundances for several Ap stars that typically show overabundance up to 1 dex or close to normal abundance. Abundances obtained for chromium lines are the same for all three measurements and above solar by 0.7 dex. We detected in KIC 10195926 about 1 dex overabundance of manganese and a small deficiency of iron. There are differences for Fe II for which the abundance from the Subaru spectrum is smaller than that obtained by Kurtz et al. (2011). These differences may be a consequence of our higher signal-to-noise ratio co-added spectrum from Subaru compared with the previous observations made with smaller telescopes.

Lines of Ba II are very strong in many cool Ap stars with typical overabundances around 1.0 dex (e.g. Ryabchikova et al. 2004). In KIC 10195926, the lines of Ba II are very weak and the majority of them suffer heavy blending. We estimated abundances of barium from five Ba II lines and found a deficiency of more than 1 dex. This is unusual for roAp stars. From 13 cool Ap stars presented by Ryabchikova et al. (2004), only two have a solar abundance of barium and one star shows a small deficiency of this element. Note that for 10 stars, Ryabchikova et al. (2004) determined the Ba II abundance only from one line.

The new Subaru spectrum for KIC 10195926 confirms that lines of rare earth elements such as Nd III and Eu II are present and show some overabundance of these elements. As shown in Fig. 2, the spectral lines of Nd III are weak in comparison with many other cool Ap stars. The abundances obtained from Nd III lines are up to 1 dex above solar. The lines of Eu II are the most prominent in the spectra of KIC 10195926 amongst of other rare earth element lines. Using Eu II in the Subaru spectrum, we found a 2-dex overabundance of this element. This result is lower than that determined by Kurtz et al. (2011) at the same rotational phase. We did not find in the spectrum any lines of Pr III, which are normally strong in roAp stars. Lines of other rare earth elements, including La II, Ce II and Sm II, were unsuitable for chemical abundance determination, or not found at all.

4 FOURIER ANALYSIS OF THE SUBARU DATA

We used the high-resolution Subaru spectra and ESO-MIDAS software to measure radial velocities for individual spectral lines of KIC 10195926 with the centre-of-gravity method, and for wide spectral bands with a cross-correlation method. Frequency analyses of the radial velocities were performed using ESO-MIDAS's time series analysis and a discrete Fourier transform program by Kurtz (1985). The spectral lines were identified by comparison of the co-added spectrum of KIC 10195926 with synthetic spectra calculated with the SYNTH code of Piskunov (1992). We began to test spectra of KIC 10195926 for pulsation using a cross-correlation technique over large spectral regions with the average spectrum as a template. This method is appropriate for initial pulsation searching as it is sensitive and can detect pulsations in roAp stars (e.g. Mkrtichian, Hatzes & Kanaan 2003). It may fail to detect pulsations when the spectral region used does not have rare earth element lines, or there are only a small number of such lines with the majority of lines being those of other elements that typically do not demonstrate pulsation. We did not detect pulsations in KIC 10195926 using this method with a precision from 40 to 80 m s^{-1} for different width spectral bands. Two amplitude spectra for the cross-correlation method over spectral regions 4400–4600 and 5000–5600 Å are shown in Fig. 3 in the two upper frames.

KIC 10195926 is not rich in spectral lines of rare earth elements. The spectrum shows lines of iron peak elements that do not pulsate at all or pulsate with much lower amplitudes than rare earth element lines for other known roAp stars. As previously mentioned, the lines of different chemical elements demonstrate different pulsation amplitudes in roAp stars as a consequence of stratification. Normally in roAp stars the radial velocity pulsation amplitudes are highest in rare earth element lines.

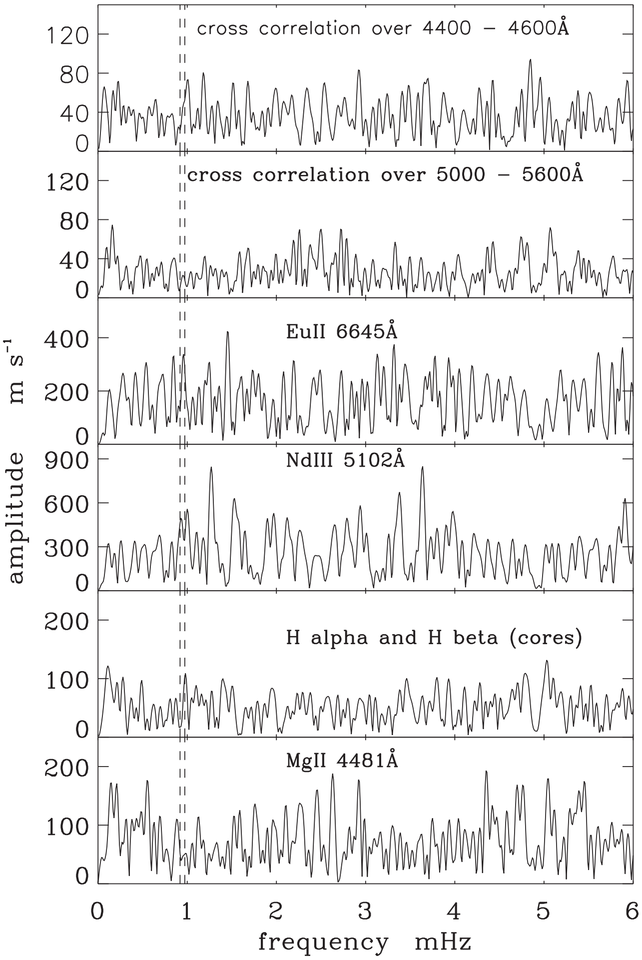

Figure 3. Examples of the amplitude spectra calculated for KIC 10195926. The two upper frames illustrate the cross-correlation method over two different spectral ranges. The two middle frames show amplitude spectra for rare earth element lines of Eu II and Nd III. The fifth frame shows an amplitude spectrum for a combination of two measurements for the narrow cores of Hα and Hβ. The bottom frame shows an amplitude spectrum for one strong line of Mg II. The dashed lines show the position of two photometric frequencies 972.58 and 919.55 μHz from Kurtz et al. (2011); these are the central frequencies of the multiplets seen in Fig. 1.

We identified just several rare earth element lines that are suitable for radial velocity measurements. One of the best in our Subaru spectrum of KIC 10195926 is Eu II 6645 Å. The amplitude spectrum for this line is illustrated in Fig. 3 where no radial velocity variations were detected with an amplitude more than 300 m s^{-1}. A similar result, but with poorer precision, was obtained for Eu II 6049 Å. An amplitude spectrum for the combination of the two Eu II lines 4435.58 and 4522.58 Å shows no pulsation higher than 120 m s^{-1}. We also did not detect any pulsations using Nd III lines. The amplitude spectrum for one of the best Nd III lines, 5102 Å, is shown in Fig. 3.

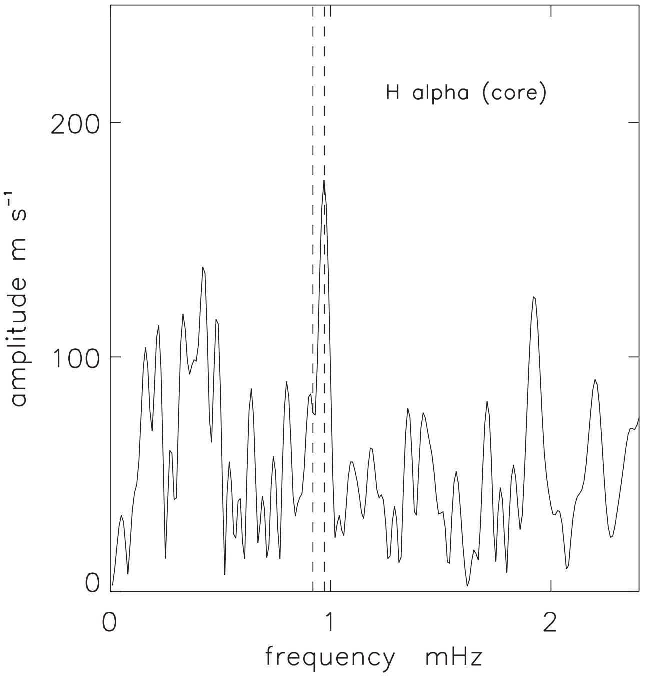

Figure 4. The amplitude spectrum for the Hα narrow core in KIC 10195926. The dashed lines are the same as in Fig. 3. There is a peak corresponding to the highest amplitude photometric pulsation frequency discovered with *Kepler* observations by Kurtz et al. (2011); see also Fig. 1.

The narrow cores of the Balmer lines in cool Ap stars also demonstrate rapid radial velocity variations in roAp stars. Our Subaru spectrum covers the region with two Balmer lines, Hα and Hβ. We have measured the central position of the narrow cores of these lines. The amplitude spectrum for combination of these two cores is shown in the fifth frame in Fig. 3 and shows no peak higher than 100 m s^{-1}. We obtained an intriguing result from measurement of only the Hα core alone, as shown in Fig. 4. There is a 4σ peak with the frequency of 0.976 mHz, corresponding to the principal pulsation period detected by Kurtz et al. (2011). The pulsation amplitude for this peak is 171 ± 41 m s^{-1}, giving a power signal-to-noise ratio of 17.4. The false alarm probability (FAP) of finding a peak with this signal-to-noise ratio at the same frequency as the photometric pulsation is FAP $= \exp(-17.4) = 2.8 \times 10^{-8}$. While no clear peak was found for the Hβ core, this is not a surprise, as pulsation amplitudes detected in cores of Balmer lines can significantly decrease from Hα to Hβ. For example, in HD 24712 the amplitude in the Hα core is almost two times larger than in the core of Hβ according to Ryabchikova et al. (2007).

We also measured radial velocities using lines of other chemical elements, including magnesium, chromium, manganese, iron and yttrium. No pulsation was found for any of these lines. In the bottom frame of Fig. 3, the result is shown for one of the strongest lines in available spectral region, Mg II 4481 Å.

5 DISCUSSION AND CONCLUSIONS

The pulsation behaviour of spectral lines in roAp stars depends on several factors. Different chemical elements demonstrate different radial velocity amplitudes with pulsation period. Lines of rare earth elements show highest amplitudes while lines of iron peak and light elements show much lower pulsation radial velocity amplitudes or even none at all. Pulsation amplitudes for rare earth elements may range from several km s^{-1} to several dozens of m s^{-1}. In KIC 10195926, we found only upper limits for pulsation in lines of rare earth elements, including Nd III ($\leq$300 m s^{-1}) and Eu II lines ($\leq$120 m s^{-1}). Lines of these ions often show pulsations in roAp stars; hence, we expect that higher signal-to-noise ratio spectra for KIC 10195926 may find measurable radial velocity amplitudes for these ions. For individual spectral lines, the noise level in our spectra is too high to detect possible low-amplitude pulsation.

The atmosphere of this star probably does not have the overabundant layers of ionized rare earth elements formed in the upper layers of the atmosphere where pulsation amplitudes reach maximum. The lack of these overabundances in the high atmospheric layers in KIC 10195926 might be explained by the combination of the relatively fast rotation and a weak magnetic field. Rotation would generate meridional circulation, which would in turn produce weak turbulence in the atmosphere. If a strong magnetic field were present, as in HR 3831, the turbulence would be suppressed sufficiently for elemental diffusion to effectively occur. If KIC 10195926, however, has only a weak field as inferred from the available observations, then the suppression of turbulence is inefficient in this case and elemental diffusion is hindered by turbulent mixing.

We detected radial velocity pulsation with an amplitude of 171 ± 41 m s^{-1} for the core of Hα line. Some other roAp stars show similar pulsation amplitudes in the Hα line core. For a group of 26 other roAp stars, Elkin, Kurtz & Mathys (2008) found radial velocity pulsation amplitudes from 30 m s^{-1} in HD 116114 and HD 137909 to 3.4 km s^{-1} in HD 99563. Half of the stars in this group show pulsation amplitude in the Hα core less than or equal to 200 m s^{-1}. In KIC 10195926, the upper limit of the pulsation amplitude found from the combination of the two best Eu II lines is below 120 m s^{-1}. For brighter stars with narrower and stronger spectral lines, we can get precision of only few m s^{-1}, so lower amplitude pulsation in lines other than Hα are probably present in KIC 10195926.

Cunha (2002) calculated theoretical boundaries of the roAp instability strip near the main sequence and predicted how pulsation frequencies change with the evolution of stars across the main sequence. According to Cunha (2002), it can be expected that the roAp stars with pulsation frequencies between 2.1 and 3.2 mHz are near the zero-age main sequence, while those with frequencies from 0.7 to 1.0 mHz are more evolved stars and close to the terminal-age main sequence. KIC 10195926, with pulsation frequencies 972.58 and 919.55 μHz, is probably close to the end of its main-sequence stage.

We can compare KIC 10195926 with other stars with pulsation periods corresponding to the end of main-sequence phase. The first one is the known low-amplitude roAp star β CrB, which was an enigma until pulsations were found by Hatzes & Mkrtichian (2004) and confirmed by Kurtz et al. (2007), definitely establishing its roAp status. Pulsation radial velocity amplitudes in β CrB are about 30 m s^{-1} and the star also does not show extreme peculiarity (Kurtz et al. 2007). Another evolved low-amplitude roAp star is HD 116114 (Elkin et al. 2005). This star is also peculiar, but has overabundances of rare earth elements only about 1 dex, instead of 3 dex or even more for many roAp stars.

Freyhammer et al. (2008) studied luminous cool Ap stars to search for rapid radial velocity variations. They mentioned that evolved roAp stars need a strong magnetic field to pulsate, as a weak field might be not be sufficient to suppress convection around the magnetic poles. In the case of KIC 10195926, there are photometric pulsations, but the magnetic field strength is not known yet. The spectral lines are rather wide for an roAp star with $v\sin i = 21 \pm 1$ km s^{-1} and do not show evidence of splitting or magnetic broadening. Spectropolarimetric methods, used and described for example by Kudryavtsev et al. (2006) and Hubrig et al. (2004), are suitable to measure the longitudinal component of magnetic field from circular polarization spectral lines and may be useful for testing the magnetic field strength in KIC 10195926.

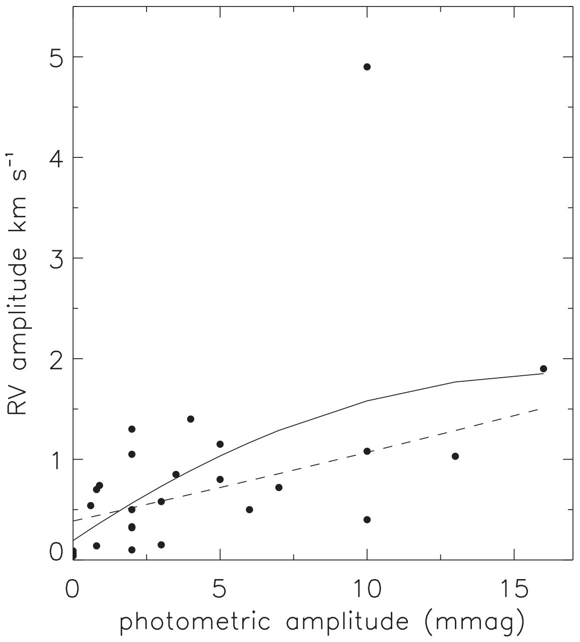

Figure 5. Photometric and spectroscopic pulsation amplitudes for a sample of roAp stars. The photometric *B* amplitudes were taken from Kurtz et al. (2006) and the spectroscopic ones from Elkin et al. (2008), Ryabchikova et al. (2007) and Kochukhov (2006). The solid line is a non-linear regression for all data; the dashed line is the same but without HD 99563, which has an exceptionally high pulsation amplitude of 4.9 km s^{-1}.

The photometric pulsation amplitude of KIC 10195926 obtained in white light by *Kepler* is relatively small, while ground-based photometry of roAp stars finds highest pulsation amplitudes typically in the blue, for example through Johnson *B* and Strömgren *v* filters. Fig. 5 presents photometric pulsation amplitudes obtained in the Johnson *B* filter taken from Kurtz et al. (2006) versus maximum radial velocity pulsation amplitudes obtained from different lines of rare earth elements from Elkin et al. (2008), Ryabchikova et al. (2007) and Kochukhov (2006). This figure illustrates that even for low photometric amplitude below 1 mmag, radial velocity amplitude can be more than 500 m s^{-1}.

The small number of rare earth element lines and low rare earth element abundances, together with a relatively high value of $v\sin i$, significantly reduce the precision of radial velocity measurements in KIC 10195926; hence, we only estimate upper limits for pulsation amplitudes. We also confirm that chemical abundances of rare earth elements in this star are amongst the lowest of all roAp stars.

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REFERENCES

Alentiev D., Kochukhov O., Ryabchikova T., Cunha M., Tsymbal V., Weiss W., 2012, MNRAS, 421, L82
Asplund M., Grevesse N., Sauval A. J., Scott P., 2009, ARA&A, 47, 481
Balmforth N. J., Cunha M. S., Dolez N., Gough D. O., Vauclair S., 2001, MNRAS, 323, 362
Balona L. A. et al., 2011a, MNRAS, 410, 517
Balona L. A. et al., 2011b, MNRAS, 413, 2651
Biémont E., Palmeri P., Quinet P., 1999, Ap&SS, 269, 635
Bigot L., Dziembowski W. A., 2002, A&A, 391, 235
Bigot L., Kurtz D. W., 2011, A&A, 536, A73
Cunha M. S., 2002, MNRAS, 333, 47

Cunha M. S., Alentiev D., Brandão I. M., Perraut K., 2013, MNRAS, 436, 1639

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

Elkin V., Kurtz D. W., Mathys G., 2008, Contrib. Astron. Obs. Skalnate Pleso, 38, 317

Elkin V. G., Kurtz D. W., Mathys G., Freyhammer L. M., 2010, MNRAS, 404, L104

Elkin V. G., Kurtz D. W., Worters H. L., Mathys G., Smalley B., van Wyk F., Smith A. M. S., 2011, MNRAS, 411, 978

Faraggiana R., Gerbaldi M., Castelli F., Floquet M., 1986, A&A, 158, 200

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

Freyhammer L. M., Kurtz D. W., Elkin V. G., Mathys G., Savanov I., Zima W., Shibahashi H., Sekiguchi K., 2009, MNRAS, 396, 325

Gautschy A., Saio H., Harzenmoser H., 1998, MNRAS, 301, 31

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

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

Heiter U. et al., 2002, A&A, 392, 619

Holdsworth D. L. et al., 2014, MNRAS, 439, 2078

Hubrig S., Kurtz D. W., Bagnulo S., Szeifert T., Schöller M., Mathys G., Dziembowski W. A., 2004, A&A, 415, 661

Kochukhov O., 2006, A&A, 446, 1051

Kochukhov O., 2008, A&A, 483, 557

Kochukhov O., Ryabchikova T., 2001, A&A, 374, 615

Kochukhov O., Ryabchikova T., Bagnulo S., Lo Curto G., 2008, A&A, 479, L29

Kochukhov O., Bagnulo S., Lo Curto G., Ryabchikova T., 2009, A&A, 493, L45

Kochukhov O., Alentiev D., Ryabchikova T., Boyko S., Cunha M., Tsymbal V., Weiss W., 2013, MNRAS, 431, 2808

Kudryavtsev D. O., Romanyuk I. I., Elkin V. G., Paunzen E., 2006, MNRAS, 372, 1804

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

Kurtz D. W., 1978, Inf. Bull. Var. Stars, 1436, 1

Kurtz D. W., 1982, MNRAS, 200, 807

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

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

Kurtz D. W. et al., 2011, MNRAS, 414, 2550

Malanushenko V., Savanov I., Ryabchikova T., 1998, Inf. Bull. Var. Stars, 4650, 1

Mkrtichian D. E., Hatzes A. P., Kanaan A., 2003, MNRAS, 345, 781

Noguchi K. et al., 2002, PASJ, 54, 855

Piskunov N. E., 1992, in Glagolevskij Y. V., Romanyuk I. I., eds, Physics and Evolution of Stars: Stellar Magnetism. "NAUKA", Sankt-Petersburg branch, Sankt Petersburg, p. 92

Polosukhina N., Kurtz D., Hack M., North P., Ilyin I., Zverko J., Shakhovskoy D., 1999, A&A, 351, 283

Ryabchikova T. A., Savanov I. S., Malanushenko V. P., Kudryavtsev D. O., 2001, Astron. Rep., 45, 382

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

Ryabchikova T. et al., 2007, A&A, 462, 1103

Saio H., 2014, in Guzik J. A., Chaplin W. J., Handler G., Pigulski A., eds, Proc. IAU Symp. 301, Precision Asteroseismology. Cambridge Univ. Press, Cambridge, p. 197

Shibahashi H., Takata M., 1993, PASJ, 45, 617

Takata M., Shibahashi H., 1995, PASJ, 47, 219

Théado S., Dupret M.-A., Noels A., Ferguson J. W., 2009, A&A, 493, 159

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