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Spectroscopic study of pulsations in the atmosphere of roAp star 10 Aql

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Abstract. We present the analysis of spectroscopic time-series observations of the roAp star 10 Aql. Observations were carried out in July 2006 with the UVES and SARG spectrographs and simultaneously with the MOST mini-satellite photometry. All these data were analysed for radial velocity (RV) variations. About 150 lines out of the 1000 measured reveal a clear pulsation signal. Frequency analysis of the spectroscopic data gives three frequencies that coincide with the photometric ones. Phase-amplitude diagrams created for the lines of different elements/ions show that atmospheric pulsations may be represented by a superposition of standing and running wave components, similar to other roAp stars. The highest RV amplitudes, 300–400 $\mathrm{m\,s^{-1}}$, were measured for Ce II, Dy III, Tb III, and two unidentified lines at λ 5471, 5556 Å.

We discovered a ≈0.4 period phase jump in the RV measurements across the Nd III line profiles, indicating the presence of the pulsation node in stellar atmospheres. The phase jump occurs at nearly the same atmospheric layer for the two main frequencies. There is no rotational modulation in the average spectra for the 6 different nights we analysed.

Key words: stars: atmospheres – stars: chemically peculiar – stars: magnetic fields – stars: oscillations – stars: individual: 10 Aql (HD 176232)

1. Introduction

10 Aql (HD 176232) was detected as a rapidly oscillating Ap (roAp) star by Heller and Kramer (1988) who found three periods of ≈11.6, 12.1 and 13.4 min. Kochukhov *et al.* (2002) detected RV pulsations with amplitudes between 30 and 130 $\mathrm{m\,s^{-1}}$ and a period about 11.5 min. Later Hatzes and Mkrtichian (2005) confirmed RV variations and registered the highest RV amplitude 398 $\mathrm{m\,s^{-1}}$ for an unidentified line at λ 5471.40 Å. 10 Aql was chosen for contemporaneous spectroscopic observations with large ground based telescopes suited to obtain high time resolution, high spectral resolution, and high signal-to-noise ratio spectra simultaneous with high precision photometric observations with MOST, the Canadian photometric space telescope (Walker *et al.*, 2003).

The main photometric results are published by Huber *et al.* (2008). Here we focus on the spectroscopic analysis and are using MOST data primarily for a comparison of the frequency analysis results.

2. Observations and data reduction

Our observations of 10 Aql were obtained in 2006 with the UVES spectrograph at the 8.2-m telescope UT2 (Kueyen), of the VLT at Paranal (Chile) on July 3, 9, 15, and 17, and with the high resolution spectrograph (SARG) at the 3.55-m *Telescopio Nazionale Galileo* (TNG) at the Observatorio del Roque de los Muchachos (La Palma, Spain) on July 14, 15, and 16. For a frequency analysis we used an additional data set obtained also during the MOST observing run with the UVES instrument on July 24 in the context of the observing programme 079.D-0567 (ESO Archive was used to extract these data).

Each UVES data set except the last one consists of 211 spectra. The total number of spectra observed on July 24 was 105. The peak signal-to-noise (S/N) ratio of individual spectra is up to 300, the spectral region covered is 4960–6990 Å (the wavelength coverage is complete, except for a 100 Å gap centred at 6000 Å), the resolving power is $\lambda/\Delta\lambda \approx 115\,000$, the time resolution (exposure and read out) is 70 s. We were able to measure radial velocity amplitude from a single line with the accuracy up to $10\,\mathrm{m\,s^{-1}}$. All UVES spectra were reduced and normalized to the continuum level with a routine specially developed by D. Lyashko for a fast reduction of time-series observations (Tsymbal *et al.*, 2003). The total number of 207 spectra were obtained with SARG in the 4572–7922 Å spectral range. Resolving power is $\sim$100 000, S/N is up to 150, and time resolution is 120 s. The SARG spectra were reduced using standard ESO-MIDAS software with the same main steps as described above.

3. Radial velocity measurements and frequency analysis

To perform a careful line identification and to choose lines for pulsation measurements we have synthesised the whole spectral region with the model atmosphere parameters T_{eff}=7550 K, $\log g$=4.0 with abundances from Ryabchikova *et al.* (2000) and a magnetic field modulus of $\langle B_{\mathrm{s}}\rangle$=1.5 kG (Kochukhov *et al.*, 2002).

Both the centre-of-gravity and bisector methods were used for RV measurements. First, we measured practically all lines (about 2000) in the July 03 observational set and detected about 150 lines that show a pulsation signature. It is now well known that pulsational variability is more pronounced in the lines of rare-earth ions, especially those of Pr and Nd, which are strong and numerous in the roAp spectra (see, for example, Kochukhov, Ryabchikova 2001). 10 Aql differs from others roAp stars in this context. REE lines are weak, REE abundances are lower than in other roAp stars, although the REE anomaly – a

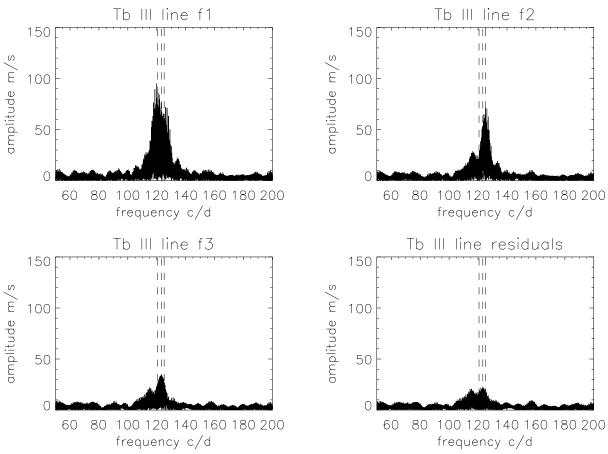

Figure 1. The amplitude spectra of RV variations of the Tb III 5505.37 Å line. The dashed lines show the position of the MOST photometric frequencies.

characteristic of roAp stars – is present. Many of the pulsating lines have equivalent widths less than 5 mÅ, so the errors of velocity measurements are rather high. For RV analysis we used the lines with equivalent widths larger than 5 mÅ. The maximum RV amplitudes, as large as 420 m s^{-1}, were detected in unidentified lines at λ 5471.41 Å and λ 5556.13 Å and in the Dy III λ 5730.34 Å line, which all have equivalent widths around 9–11 mÅ and residual depths around 6–7%.

Due to similarity of the pulsation patterns in the unidentified and Dy III lines, one could suppose that they belong to the same atomic species. Strong Nd III and Pr III lines that usually exhibit the largest amplitudes in roAp stars show the lowest amplitudes in 10 Aql (probably due the existence of a nodal zone, as will be shown below). Nd II and Pr II lines are very weak, so the blending problem in this star is more acute. Even slight blending results in an abrupt decrease of the amplitude. For this reason, only the 70 cleanest lines were chosen for the final amplitude and phase analysis.

We performed a frequency analysis of our measurements by applying the standard discrete Fourier transformation (DFT) to the RV data. The total time coverage of the spectroscopic data is about 25 hours. The period corresponding to the highest pulsation amplitude was improved by the sine-wave least-square fitting of the RV data with pulsation period, amplitude, and phase treated as free parameters. This fit was removed from the data and then a Fourier analysis was applied to the residuals. This procedure was repeated for all frequencies with S/N above 5 in the power spectrum. The primary frequency (f_1) found was at 119.69 c d^{-1}, which corresponds to a 1-day alias of the frequency seen

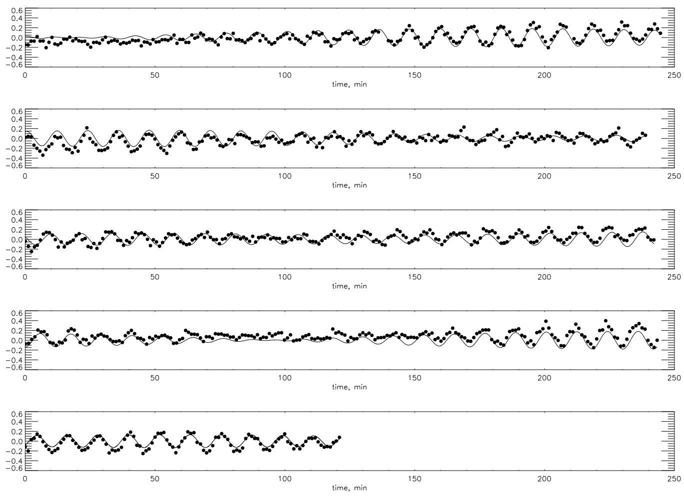

Figure 2. The RV variations of the Tb III 5505.37 Å line.

in simultaneous MOST photometry. The second signal (f_2) is at 125.09 c d^{-1} and the third frequency (f_3) is at 123.30 c d^{-1}. All three frequencies appear in RV data for most pulsating lines. No clear signal can be found in the data after pre-whitening of the three frequencies, although in the residuals for several lines some signal appears near 117–118 c d^{-1} and 126–127 c d^{-1}. However, this signal has S/N <2. Figure 1 shows an amplitude spectrum for the Tb III 5505.37 Å line; the other panels show the next prewhitening steps.

The MOST photometric observations give the same frequencies. The only difference is that the frequency f_2 has the highest amplitude in the MOST data and f_1 is the second strongest (Huber *et al.*, 2008). This can be explained by the different time coverage of the spectroscopic data compared to continuous photometric set. If one instead does a frequency analysis of that part of photometric data taken at the times of spectroscopic monitoring, one indeed obtains f_1 with the highest amplitude in photometric data (Huber, private communication).

We have to stress the importance of simultaneous precise photometry for the spectroscopic time-series study, in particular to avoid alias problems in frequency analysis. Moreover, one relatively short spectroscopic set that is usually no longer than 2–4 hours does not allow one to resolve close frequencies. Incorrect conclusions can be drawn from amplitude modulations caused only by the beating effect. In the case of 10 Aql, a superposition of the three close frequencies fully explains the observed amplitude modulation, which is illustrated in Fig. 2 where RV variations of the Tb III 5505.37 Å line are presented for UVES data (from top to bottom for nights July 3, 9, 15, 17 and 24; the reference time point for each data set is the HJD time of the first observation). The solid line shows a sinusoidal fit including all three frequencies.

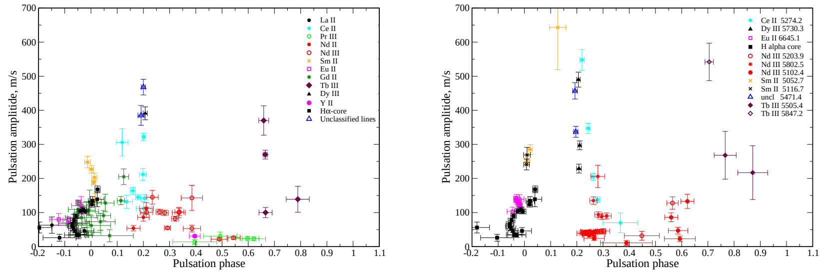

Figure 3. Amplitude-phase diagram for the f_1 frequency in the July 03 UVES data. **Left**: centre of gravity measurements; **right**: bisector measurements.

4. Pulsational analysis

We did not find any evidence of rotational modulation during a month of our spectroscopic observations. The average spectra in all sets agree to within better than 0.5% which means that the rotation period should be at least of order several months.

Following Ryabchikova *et al.* (2007 a), we analysed the amplitude-phase diagrams and interpreted observations in terms of pulsational wave propagation. The pulsational behaviour of 10 Aql is quite similar to that found in other roAp stars: pulsation appears in the layers where La and Eu are concentrated, then goes through the layers where the Hα-core is formed, reaches a maximum of RV and then the amplitude decreases (see Ryabchikova *et al.* 2007 b). At the same time, the RV maximum is attained in Ce II and Dy III lines and not in Nd II, Nd III, Pr III lines, as it is observed in most other roAp stars. In the layers where Nd and Pr lines are formed, pulsation amplitude falls practically to zero, and this is accompanied by the rapid phase change. When RV amplitude increases again in Tb III lines, the phase changes by ~0.4 (left panel in Fig. 3). We attribute this phenomenon to the presence of a node. Similar amplitude-phase diagrams were obtained for the f_2 frequency. The phase-amplitude diagrams are also similar for all 4 nights of our UVES observations.

The same picture was derived from bisector measurements of individual lines (right panel in Fig. 3). As mentioned above, the REE lines usually showing the highest pulsation signal are weak in 10 Aql. Fortunately, there is sufficiently deep line, Nd III 5102.435 Å, which is suitable for precise bisector measurements. Although the centre-of-gravity RV amplitude is very small (30–40 $\mathrm{m\,s^{-1}}$), the bisector amplitude changes across the line profile with a minimum around 0.83 of the normalised flux. RV amplitude change is accompanied by a phase jump. We found the same behaviour in all 4 nights and in both of the highest highest amplitude frequencies f_1 and f_2. Fig. 4 shows bisector measurements for this Nd III 5102.44 Å line. Thus, 10 Aql is the second roAp star after 33 Lib (Mkrtichian *et al.*, 2003) to show direct evidence of an atmospheric node.

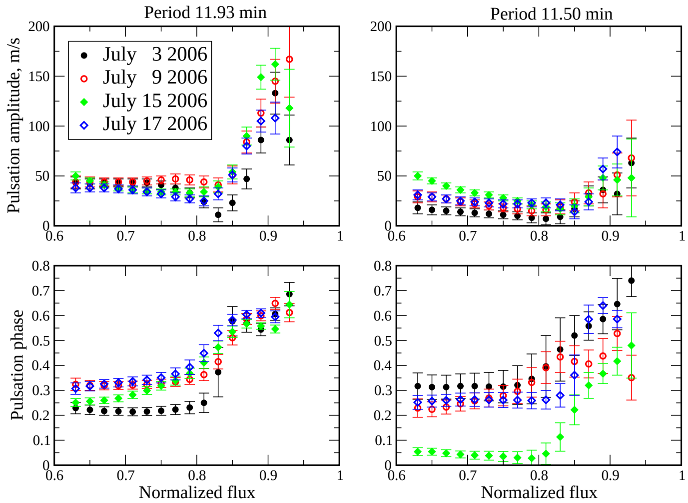

Figure 4. Bisector measurements of the Nd III 5102.435 Å line.

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