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The search for roAp stars: null results and new candidates from Strömgren-Crawford photometry

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Abstract The rapidly oscillating Ap (roAp) stars exhibit pulsational photometric and/or radial velocity variations on time scales of several minutes, which are essential to test current pulsation models as well as our assumptions of atmospheric structure characteristics. In addition, their chemical peculiarity makes them very interesting for probing stellar formation and evolution in the presence of a global magnetic field. To date, a limited number of only 61 roAp stars is known to show photometric variability. On the other hand, a literature survey yields 619 unique stars that have unsuccessfully been searched for variability of this kind. Strömgren-Crawford $uvby\beta$ photometry of stars from both subgroups was used to investigate whether there is a selection bias for the investigated stars. We also present new photometric measurements (202 hours on 59 different nights) of 55 roAp candidates. We did not detect any new roAp star. Although our detection limits are comparable to other surveys, we also did not find pulsations in the known roAp star HD 12098, which may be a consequence of temporal amplitude changes. On the other hand, we do find some evidence for photometric variability of beta CrB at its spectroscopically derived pulsation period. From the $uvby\beta$ photometry we conclude that the blue border of the roAp instability strip appears observationally well defined, whereas the red border is rather poorly known and studied. Within these boundaries, a total of 4646 candidates were identified which appear worth investigating for short-term pulsational variability.

Key words: stars: chemically peculiar — stars: early-type — stars: variables: general — techniques: photometric

1 INTRODUCTION

Up to now, there are 61 rapidly oscillating Ap (roAp) stars known (Joshi et al. 2016). They are located within an area of pulsational instability in the Hertzsprung-Russell diagram, across the main sequence, ranging in effective temperature from about 6600 K to 8500 K. The roAp stars share this area with δ Sct and γ Dor type pulsators, but their spectral and variability properties are markedly different.

Photometric investigations of roAp stars show a period range of five to twenty five minutes, which is consistent with acoustic (p-mode) pulsations with low degree and high radial overtone (Kurtz et al. 2011).

The driving mechanism of their oscillation modes is still not fully understood. The most probable explanation appears to be the "classical" κ-mechanism operating in the hydrogen ionization zone (e.g. Balmforth et al. 2001). Many physical processes could play a role in this context: for example coupling with the magnetic field, and its ability to freeze convection and to facilitate stratification of chemical elements. Therefore, the roAp stars are very interesting for studying pulsations in the presence of a stable magnetic field and diffusion in the stellar atmosphere. The very small percentage of such variables with respect to the total number of Ap stars already suggests that the conditions needed to excite pulsation with a detectable amplitude have to be very specific.

Even so, there appear to be additional shortcomings in the theoretical prediction of pulsation among roAp stars. For instance, theoretically predicted regions of pulsational instability (Cunha 2002) do not agree with the observed ones, in the sense that both the theoretical blue and red edges are shifted towards higher temperatures compared to observations. Furthermore, some roAp stars pulsate with frequencies higher than the acoustic cutoff frequency, which led to the suggestion that these could be driven by turbulent pressure (Cunha et al. 2013).

Therefore, as important as the knowledge about roAp stars themselves is the analysis of objects in the same temperature range which show no sign of roAp variability (noAp stars). A comparison of both groups should provide crucial constraints about the astrophysical conditions that enable pulsations in those stars.

In this paper, we present new photoelectric and CCD photometric observations for 55 roAp candidates selected on the basis of their spectral types. In total, we analyzed 202 hours of observations on 59 different nights. No new roAp star was detected.

The classification of a star as a noAp object is not straightforward because roAp stars can show, for example, strong amplitude variations from night to night (e.g., White et al. 2011; Medupe et al. 2015). The amplitudes also depend on the wavelength region observed (Medupe & Kurtz 1998), and space photometry shows that some stars pulsate with amplitudes undetectable from the ground (e.g. Holdsworth 2016). Therefore, an noAp star can only be defined by an observational upper limit of variability for a given time baseline and filter, which needs to be kept in mind when discussing these stars.

In order to select new candidates within the Strömgren-Crawford $uvby\beta$ photometric system, we analyzed the location of the roAp and noAp groups in reddening free diagrams. On the basis of newly defined areas in which roAp stars are located, we present a list of 4646 new candidates deemed worthwhile for variability searches. Several regions of Strömgren-Crawford indices (for example, $[m_1] > 0.35$) appear to be insufficiently investigated for new variables.

2 OBSERVATIONS AND DATA REDUCTION

Well established magnetic chemically peculiar stars (also known as CP2 objects) for which no or only limited time-series photometric observations from the literature (Joshi et al. 2016) are available, were selected from the catalog of Ap, HgMn and Am stars by Renson & Manfroid (2009). Although most known roAp stars are spectrally classified as SrCrEu, we extended our list of targets to earlier spectral types, i.e. silicon stars. We have not used any other photometric criteria, such as those that, for example Joshi et al. (2016) used within the Strömgren-Crawford $uvby\beta$ system. In total, we selected 55 objects for observations. Two of these targets (HD 12098 and HD 137909) are already known roAp stars with very small photometric amplitude (HD 12098) and only spectroscopically detected variability (HD 137909). From these 55 objects, 18 have already been observed before in order to detect roAp variability. However, since some roAp stars show strong variabilities in amplitude (e.g. White et al. 2011; Medupe et al. 2015), several observations on different nights are not a disadvantage.

The choice of photometric filter is also important in this respect. Medupe & Kurtz (1998) demonstrated that the amplitude of roAp variability significantly drops redwards of ≈4500 Å. Therefore, using a filter passband somewhere between the near-UV and the blue will be most suitable for detecting roAp pulsations.

Our observations of roAp candidates were performed with several different telescopes, instruments and filters. We used the Johnson B (λ_c = 4400Å, FWHM = 950Å), SDSS g' (4750, 1400) and Strömgren v (4100, 160) filters. Here is an overview of the basic characteristics of the telescopes and instruments.

(1) Automatic Photoelectric Telescope (APT) T6 (0.75 m) at Fairborn Observatory (Arizona, USA);

Table 1 Observation Log and the Results from Time Series Analysis (HD 12098 and HD 137909 are known roAp stars)

HD/TYC	BD/HIP/TYC	HJD (start) [2450000+]	Δt [min]	N	Filter	Site	Upper Limit [mmag]
8441	6560	6976.50705	113.5	327	B	Suhora (gs8in)	0.7
		7012.28702	104.1	173	B	Uppsala	5.8
10783	10783	6977.18299	261.7	983	B	Suhora (gs8in)	0.4
12098	3687–2649–1	6976.53518	85.3	457	v	Suhora (Zeiss)	0.3
		6977.34519	21.7	99	v	Suhora (Zeiss)	0.6
12288	9604	6977.17831	258.7	1289	v	Suhora (Zeiss)	0.4
15089	11569	6977.27179	336.5	239	B	Suhora (MK)	1.4
		6977.27204	337.5	443	B	Suhora (MK)	1.8
		7012.40129	90.7	161	B	Uppsala	1.8
20476	2852–1042–1	7083.32199	74.0	131	g'	BOOTES-2	3.4
21190	14700	7053.67151	87.3	57	B	FRAM-Auger	8.7
25354	18912	7019.33714	162.5	292	B	Uppsala	1.3
38823	27423	7045.53101	78.9	65	B	FRAM-Auger	5.8
		7059.58522	88.8	90	B	FRAM-Auger	5.9
47074	146–1489–1	7059.42474	133.7	267	g'	BOOTES-2	1.4
50403	1343–1516–1	7051.50925	145.7	215	g'	BOOTES-2	7.0
51684	33375	7045.70282	90.1	54	B	FRAM-Auger	5.5
		7050.74948	124.3	96	B	FRAM-Auger	4.8
52181A	1352–1045–1	7070.47641	147.9	252	g'	BOOTES-2	3.8
52628	34174	7141.62517	68.6	147	B	APT	0.8
54824	34773	7140.62067	83.1	187	B	APT	0.7
		7145.62726	50.6	127	B	APT	0.7
		7146.62815	49.6	94	B	APT	2.9
55228	1346–208–1	7143.62237	69.7	125	B	APT	1.1
61600	37483	6976.65123	77.1	388	v	Suhora (Zeiss)	0.5
65339	39261	6976.64251	83.5	334	B	Suhora (gs8in)	0.5
		7014.99839	88.7	224	v	APT	1.6
		7015.99486	88.5	224	v	APT	1.1
		7019.48691	102.4	211	B	Uppsala	4.1
		7095.32740	86.4	194	B	Uppsala	2.9
68542	40311	7096.32184	126.2	172	B	Uppsala	2.5
		7133.61644	81.5	192	B	APT	0.8
		7134.61691	68.7	160	B	APT	2.5
		7149.62957	62.6	151	B	APT	1.2
96003	54141	7109.73310	88.5	219	v	APT	0.6
		7114.71982	62.9	151	v	APT	0.6
96097	54182	7143.67192	113.2	204	v	APT	1.2
		7144.71328	43.9	109	v	APT	1.4
		7145.66500	112.2	278	v	APT	1.3
		7150.62999	164.5	416	v	APT	2.6
		7151.63058	164.6	416	v	APT	2.2
97633	54879	7092.77862	126.4	296	v	APT	0.6
		7107.73745	88.2	219	v	APT	0.6
		7108.73344	88.1	219	v	APT	0.7
100809	56597	7457.77923	154.0	379	B	APT	0.4
		7459.77421	154.0	381	B	APT	1.0
105999	59487	6735.76575	171.7	110	B	FRAM-Auger	1.0
		6736.53343	190.9	93	B	FRAM-Auger	1.3
		6736.53359	192.4	231	B	FRAM-Auger	0.8
107000	59998	7131.67513	126.5	311	B	APT	0.6
		7133.67420	75.4	185	B	APT	1.0
107612	60313	7018.98447	114.1	280	v	APT	0.7
		7020.98280	112.4	261	v	APT	1.0
		7021.97194	125.1	246	v	APT	0.6
		7095.43070	91.3	121	B	Uppsala	3.6

Table 1 — *Continued.*

HD/TYC	BD/HIP/TYC	HJD (start) [2450000+]	Δt [min]	N	Filter	Site	Upper Limit [mmag]
108283	60697	7109.79554	88.1	214	v	APT	0.9
		7118.71067	124.0	274	v	APT	0.8
108945	61071	7019.98178	102.7	18	v	APT	1.4
		7022.97093	115.4	20	v	APT	1.6
112528	63247	6739.81531	144.5	189	B	FRAM-Auger	1.3
		6746.49682	67.2	32	B	FRAM-Auger	9.8
115708	64936	6709.59688	94.1	221	v	MUO	0.6
117361	65754	7092.86750	116.4	226	v	APT	0.8
		7107.79969	88.4	217	v	APT	0.7
		7108.79571	88.5	212	v	APT	0.7
118022	66200	7028.95317	123.0	276	v	APT	0.8
119213	66700	7025.96276	139.6	352	v	APT	0.6
124883	69661	7113.79238	88.7	224	v	APT	1.1
		7118.81935	111.5	243	v	APT	0.5
		7139.78190	75.8	192	v	APT	1.3
		7148.79921	120.9	251	v	APT	0.7
125709	2011–105–1	7148.79789	133.9	30	v	APT	2.9
126515	70553	7113.72906	89.7	220	B	APT	0.7
		7131.76541	140.0	285	v	APT	2.9
134305	74109	7140.68059	102.4	248	B	APT	1.8
		7141.67654	102.9	253	B	APT	1.0
134793	74334	7140.75278	117.5	281	B	APT	0.6
		7141.74905	115.3	288	B	APT	0.5
137909	75695	7092.95079	113.6	271	v	APT	0.8
		7107.86215	88.1	221	v	APT	0.9
		7108.85822	88.0	220	v	APT	0.6
		7109.85830	88.0	219	v	APT	0.9
		7135.95188	67.9	144	v	APT	1.2
		7150.74538	215.7	544	v	APT	1.3
		7151.74604	215.7	535	v	APT	0.6
242006	699–1159–1	7047.30371	96.8	260	g'	BOOTES-2	1.8
242442	2390–208–1	7047.42182	98.6	190	g'	BOOTES-2	1.4
245222	1869–1770–1	7063.43180	135.9	245	g'	BOOTES-2	2.8
245416	2404–775–1	7045.53083	138.3	195	g'	BOOTES-2	2.1
		7048.49546	126.9	244	g'	BOOTES-2	5.6
246587	1861–299–1	7046.44334	132.7	185	g'	BOOTES-2	2.1
246726	2405–1110–1	7102.37786	122.9	711	B	Suhora (gs8in)	1.5
247628	2409–1922–1	7100.36153	159.6	740	B	Suhora (gs8in)	1.5
259380	2426–652–1	7072.48449	147.2	258	g'	BOOTES-2	2.2
264291	1343–2532–1	7063.52746	88.3	160	g'	BOOTES-2	2.2
266311	157–22–1	7059.51917	145.2	226	g'	BOOTES-2	2.3
268471	1895–873–1	7047.49150	99.0	191	g'	BOOTES-2	2.1
276625	2884–484–1	7050.30892	92.9	210	g'	BOOTES-2	2.4
2320–605–1	+36 363	7036.19795	126.7	312	B	Suhora (gs8in)	0.4
3009–62–1	+41 2144	7047.56523	86.6	224	g'	BOOTES-2	2.5
3021–603–1	+38 2360	7052.53427	95.5	228	g'	BOOTES-2	2.7
4520–578–1	13172	7036.33613	97.5	262	B	Suhora (gs8in)	4.0
		7045.43571	131.4	196	g'	BOOTES-2	2.4
		7048.28533	126.9	126	g'	BOOTES-2	3.5

(2) BOOTES-2, 0.6 m RC telescope, EMCCD Andor iXon-889+ in Andalucía, Spain;
(3) F(/Ph)otometric Robotic Atmospheric Monitor (FRAM-Auger) 0.3 m FRAM-Auger Schmidt-Cassegrain, G4-16000 CCD telescope of the Pierre Auger Observatory (Malargüe, Argentina);
(4) Masaryk University Observatory (MUO, Brno, Czech Republic), 0.6 m, G2-4000 CCD;
(5) Sandvreten Observatory (Uppsala, Sweden), 0.406 m, f/9 RC telescope, SBIG STL-6303 CCD;
(6) Mt. Suhora Observatory (Poland):
  - 0.034 m refractor (MK), G2-402 CCD,
  - 0.2 m RC telescope (gs8in), SBIG ST-10 CCD,
  - 0.6 m Zeiss telescope, Apogee AltaU-47 CCD.

The integration times varied between 10 and 30 s depending on the instrument and target brightness.

The photoelectric data of the APT were reduced by compensating for coincidence losses and subtracting the sky background. Extinction corrections were determined with the standard Bouguer method from the target star data themselves.

The reductions of the time series CCD observations were performed using a standard technique. First, bias subtraction, dark correction and flat fielding were applied. Then, differential aperture photometry was performed using two different program packages:

- Image Reduction and Analysis Facility (IRAF, Stetson 1987),
- C-Munipack under Windows[1].

To account for different seeing conditions, several apertures were used and tested. For each data set, we have chosen the aperture which yielded the smallest scatter in the differential target star light curves. If several comparison stars were available, these were checked individually to exclude variable objects.

The total reduced data set comprised 202 hours of observations on 59 different nights (Table 1). Time series analysis of the differential light curves was conducted by applying a standard Fourier technique and Phase Dispersion Minimization. All computations were done within the program package Peranso (Paunzen & Vanmunster 2016).

Defining the upper limit of variability is not straightforward and has often been discussed in the literature (Reegen et al. 2008). In general, the statistical significance of noise in a Fourier spectrum is underestimated. Here we employ a conservative approach and define the upper limit of variability as the upper envelope of the peaks in an amplitude spectrum (Fig. 1).

[1] *http://c-munipack.sourceforge.net/*

3 ANALYSIS AND RESULTS

Time series analysis of the targets revealed only upper limits for variability in the frequency range of known roAp stars. The upper limits range from 0.3 to 9.8 mmag with a mean of 1.9 mmag and a median of 1.3 mmag. This is well within the range of other ground based surveys (Handler & Paunzen 1999; Joshi et al. 2016) with similar or larger telescopes. Although we have not detected any new roAp stars, establishing the upper limits across the observed instability strip is also important for testing and improving models that take into account the excitation and visibility of pulsations under the influence of a magnetic field (Saio 2008). In this respect, it would also be interesting to examine, for example, the high precision *Kepler Space Telescope* (Murphy 2014) or *K2* data for the absence of short-term variability among stars in this region of the Hertzsprung-Russell diagram.

In the following, we want to discuss our results for the two already known roAp stars in more detail.

HD 12098: This star was reported as an roAp pulsator with a period of about 7.7 min by Girish et al. (2001). They presented photometric data in Johnson B for 16 individual nights with durations of one to nine hours. The reported amplitudes range from 0.38 to 1.47 mmag with a mean of 0.94 mmag. Such a strong amplitude variation was also found, for example, for the roAp star HD 217522 (Medupe et al. 2015) for which the amplitude ranges from 2.0 mmag, causing it to be hidden in the noise ($<$ 0.3 mmag). Another prominent case, among others, is HD 24355 (Holdsworth et al. 2016). Its behavior can be explained by the Oblique Pulsator Model (Kurtz 1982, Bigot & Kurtz 2011, Saio et al. 2012). Within this model, the amplitude can even approach a zero value depending on the inclination of the rotation axis to the line-of-sight as well as the magnetic to rotation axis for a given rotation period. We observed HD 12098 on two consecutive nights and could not detect its variability in Strömgren v (Table 1), although our detection level should have permitted this. This case shows how important it is not only to have high quality observations during several nights but also to use a filter in the blue wavelength region (Medupe & Kurtz 1998).

HD 137909 (β CrB): Hatzes & Mkrtichian (2004) detected pulsational variability in their radial velocity

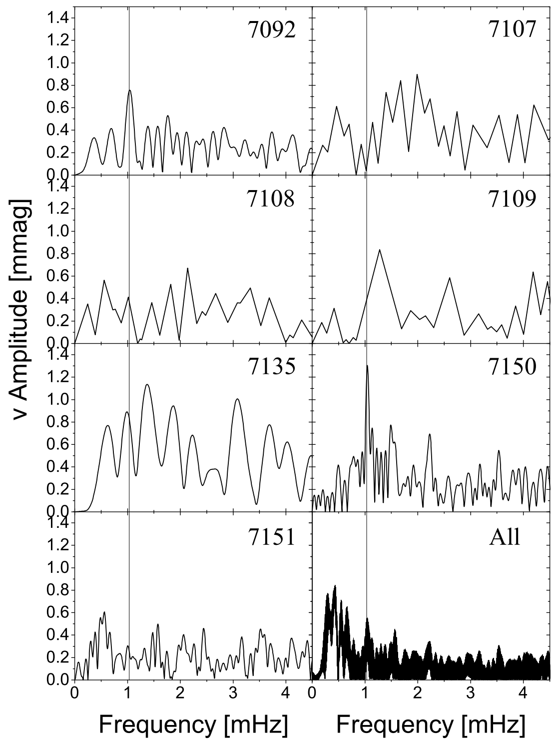

Fig. 1 Fourier spectra of the observations for all nights (Table 1) of HD 137909 (β CrB). The spectroscopically detected frequency of 1.03 mHz is indicated by a *vertical line*.

measurements with a period of 16.2 min (1.029 mHz) and an amplitude of about $140\,\mathrm{m\,s^{-1}}$. Later, Kurtz et al. (2007) confirmed this period on the basis of individual lines of the first ionization stage of rare earth elements and in Hα. However, the amplitude was only $30\,\mathrm{m\,s^{-1}}$. Since no recent photometric time series were found in the literature, we observed HD 137909 on seven nights with the APT (Table 1). Although we cannot claim a statistically significant detection, on two nights we found a peak above the noise level (1.042(17) and 1.046(16) mHz, respectively) very close to the spectroscopic period. Within errors, the photometric frequencies are in excellent agreement with the spectroscopic one. However, on the other five nights, no similar peaks were detected.

In Figure 1, the Fourier spectra of all nights are shown. Further photometric observations are needed to unambiguously confirm the spectroscopically found pulsational frequency. Again, characteristics of the variability for HD 137909 show the advantage of precise photometric as well as spectroscopic observations over more than one night.

In general, it seems that the capabilities of ground-based photometric observations to detect new roAp stars have reached their limits. Suitable telescopes and instrumentations need to achieve a time resolution of less than one minute in the blue wavelength region (i.e. Johnson B and Strömgren v filter) with a photometric accuracy in the sub-mmag region. At first sight, current on-going ground-based photometric surveys such as ASAS (Pojmański 2009 and references therein) and SuperWASP (Pollacco et al. 2006), just to mention two, seem to neither have the time resolution nor the accuracy for this purpose (Bernhard et al. 2015; Hümmerich et al. 2016).

In this context, it is interesting to discuss the paper by Holdsworth et al. (2014b). These authors presented 350 stars which are variable on periods less than 30 min on the basis of SuperWASP data and concluded that this variability is due to pulsation. The observations, using a broadband filter with a passband from 4000 to 7000 Å, are such that two consecutive 30 s integrations at a given pointing are typically repeated every 10 min. Such a time sampling is a-priori unfavorable for detecting variability in a period range up to 30 min. This situation can however be mitigated by a significant number of observations over a long time baseline which then cover the whole pulsational phase. Among the 15 known roAp stars in their sample, Holdsworth et al. (2014b) were able to detect one (HD 12932 with a published amplitude of 4 mmag in Johnson B). Other roAp stars with even higher amplitude, such as HD 99563 and HD 101065, were not detected. In addition to the cadence of the data, saturation of objects brighter than $V < 8$ mag may also play a significant role here. Most of the known roAp stars are brighter than that limit and therefore their pulsations are very difficult to detect in SuperWASP data. This might explain the non-detection of many known roAp stars.

Holdsworth et al. (2014b) also selected 543 Ap stars from Renson & Manfroid (2009) on spectroscopic grounds and found no new roAp stars. This has to be taken into account when interpreting the results on the variability of the newly detected variables (as the authors themselves pointed out). In total, Holdsworth et al. (2014b) presented 10 out of the 350 variable objects as new roAp stars. Their reasoning, that these are true roAp variables, is based on low-resolution spectra and an enhancement of Sr, Cr and Eu, typical for CP2 stars (Ryabchikova & Romanovskaya 2017). However, another observable that distinguishes roAp variables from other pulsators is the typical Pr-Nd anomaly (Ryabchikova et al. 2004) that should be searched for by high resolution spectroscopy. Apart from that, independent confirmation of variability for these and the remaining > 300 stars, and determination of its origin, are desirable. Nevertheless, the capability of the SuperWASP data to detect new roAp stars on such a large scale is promising.

One way to provide a homogeneous study of the occurrence of the roAp phenomenon is to use space-based data. Several roAp stars were found and analyzed within the *Kepler* and *K2* fields (Smalley et al. 2015 and references therein). Other roAp stars were investigated with the *BRITE-Constellation* (Weiss et al. 2016), *MOST* (Gruberbauer et al. 2011) and *Wide-Field Infrared Explorer* (*WIRE*) (Bruntt et al. 2009) satellite missions. The next milestone is expected to be the recently launched *Transiting Exoplanet Survey Satellite* (*TESS*) mission (Ricker et al. 2015). With a cadence of 2 min, a time baseline of up to one year and the predicted accuracy, it should be quite suitable for detecting roAp stars in both hemispheres on a large scale. However, as *TESS* will observe in a very wide near-infrared (NIR) passband, it remains to be seen by how much the roAp pulsation amplitudes will be diminished in comparison to blue-filter data. Nevertheless, the *TESS* data set will provide a homogeneous view for both noAp and roAp stars.

Another approach is the search for radial velocity shifts due to pulsations (Ryabchikova et al. 2007; Kochukhov et al. 2013). The amplitudes can reach up to $5\,\mathrm{km\,s^{-1}}$ with typical values between 100 and $500\,\mathrm{m\,s^{-1}}$ (Elkin et al. 2005). Such accuracies are nowadays even achievable with a 60 cm telescope (Pribulla et al. 2015). However, the spectral and time resolution have to be appropriate for the expected pulsational period and line blending. But also here, the candidates have to be selected with care. Freyhammer et al. (2008), for example, observed nine luminous CP stars and found only upper limits for radial velocity amplitudes of 20 to $65\,\mathrm{m\,s^{-1}}$. The 350 photometrically variable candidates reported by Holdsworth et al. (2014b) are excellent targets for such observations. Last, but not least, one can also search for the typical Pr-Nd anomaly (Ryabchikova et al. 2004) in known CP stars using high resolution spectroscopy, as a spectroscopic signature of the roAp phenomenon that appears to be an abundance in differences of second and first ions for Pr and Nd of at least 1.5 dex and up to 2.5 dex. Stars with this spectral feature then need to be tested for rapid photometric variations.

3.1 New Strömgren-Crawford Photometric Criteria to Search for roAp Stars

Although a significant number of stars was searched for roAp variability in the past, we want to estimate the amount of potential candidates not checked for pulsations to date. To this end, criteria to find such candidates have to be established. A basic selection can be done either by spectroscopic or photometric means (or by a combination of both). In the past, both approaches have been successfully applied (e.g. Handler & Paunzen 1999; Martinez et al. 2001; Paunzen et al. 2012).

For a spectroscopic-based selection, the catalog by Renson & Manfroid (2009) and its previous versions have been used. Since the roAp stars are normally characterized as cool CP SrCrEu stars, they can be traced in this catalog or at least the CP1 (Am/Fm) stars can be excluded as candidates. However, this catalog is an inhomogeneous compilation which is outdated. A new version is very much needed to perform an assessment of possible roAp candidates, not yet photometrically investigated.

For an efficient and viable selection based on photometry, systems are needed that provide parameters that are reddening free and are metallicity and luminosity sensitive. For such a purpose, only intermediate to narrow band photometric systems are suitable. This excludes applying 2MASS (Skrutskie et al. 2006) measurements, for example. The same is true for the SDSS photometric system used for APASS (Henden et al. 2015). We mention just these two all-sky surveys because they (will) provide deep homogeneous photometric data from the UV to NIR region. In principle, three well-known photometric systems are able to supply the required information: Geneva 7-color (Golay 1972; Nicolet 1996), Strömgren-Crawford $uvby\beta$ (Strömgren 1966) and Vilnius (Straižys & Sviderskiene Straizys & Sviderskiene (1972); Smriglio et al. (1986)). Unfortunately, from these, only the Strömgren-Crawford system is nowadays still relatively widely employed. In addition, it was also utilized for roAp candidate selection in the past (Joshi et al. 2009).

In the literature, several definitions of the different photometric parameters within the Strömgren-Crawford system are available. Because sometimes different definitions are given, we list the ones implemented for our study, which are:

- $[c_1] = c_1 - 0.19(b-y)$,
- $[m_1] = m_1 + 0.33(b-y)$,
- $[u-b] = (u-b) - 1.53(b-y)$,
- $a0 = 1.54[m_1] + 0.74r - 0.27$,
- $r = 0.35[c_1] - \beta + 2.565$.

It is important to use the whole variety of these indices because they are sensitive to different parameters as briefly discussed in the following. All known roAp stars, besides one (KIC 7582608 with $T_{\rm eff} = 8700$ K; Holdsworth et al. 2014a), fall in the "cool region" of $T_{\rm eff} \leq 8500$ K as defined by Napiwotzki et al. (1993). There, β and $[m_1]$ are measures for $T_{\rm eff}$ and $[c_1]$ is an indicator for the Balmer discontinuity, thus the luminosity $[m_1]$ is also sensitive to metallicity. For the intermediate region (11 000 K $\leq T_{\rm eff} \leq$ 8500 K), these indices are replaced by $a0$ and r. The $[u-b]$ color index is sensitive to $T_{\rm eff}$ throughout the whole range and was also used to calibrate CP stars (Megessier 1988). Although there are three different indices which are sensitive to $T_{\rm eff}$, this is vital for the study of CP stars because they exhibit significant flux depressions at 4100, 5200 and 6300 Å (Adelman 1980). Measuring $T_{\rm eff}$ using different spectral regions avoids introducing systematics into the analysis.

Often, the δc_1 and δm_1 indices were applied to select targets (Joshi et al. 2006). Both indices are defined as the deviation from a standard line of unreddened, solar abundant, main-sequence stars such that they are negative for stars with overbundances of elements. One has to keep in mind that δc_1 is also sensitive to luminosity. The standard line can be defined either by observational data or by stellar atmosphere models and synthetic photometry. Thus, the calculation of δc_1 and δm_1 is not straightforward and the interpretation of these indices can be ambiguous.

We now evaluate how the regions of known noAp and roAp stars overlap in the different photometric Strömgren-Crawford diagrams. For this, lists for both groups are needed.

We have searched the literature for stars which were investigated for roAp variability. Of course, these investigations were performed with different instruments and filters. Also the overall quality of the observing nights, the time baseline and cadence play a role. It is therefore not really possible to compare directly all these different sources when it comes to defining to which limit a star does not show any roAp variability (see also the discussion above about amplitude variations over time). We used the following 21 references to generate a list of noAp objects

- Kurtz (1984)
- Matthews & Wehlau (1985)
- Heller & Kramer (1988)
- Matthews et al. (1988)
- Belmonte (1989)
- Kurtz (1989)
- Martinez (1989)
- Weiss & Schneider (1989)
- Kreidl (1991)
- Nelson & Kreidl (1993)
- Schutt (1993)
- Martinez & Kurtz (1994)
- Dorokhova & Dorokhov (1998)
- Handler & Paunzen (1999)
- Martinez et al. (2001)
- Joshi et al. (2006)
- Joshi et al. (2009)
- Paunzen et al. (2012)
- Paunzen et al. (2013)
- Paunzen et al. (2015)
- Joshi et al. (2016)

Table 2 The list of 4646 new roAp candidates selected on the basis of Strömgren-Crawford $uvby\beta$ diagrams. The errors are taken from Paunzen (2015).

TYC	V	σV	N	$(b-y)$	$\sigma(b-y)$	N	$[m_1]$	$\sigma[m_1]$	N	$[c_1]$	$\sigma[c_1]$	N	β	$\sigma\beta$	N
5-334-1	9.000		1	0.208		1	0.169		1	0.740		1	2.732		1
5-958-1	8.430		1	0.173		1	0.242		1	0.742		1	2.779		1
11-1234-1	8.014	0.013	4	0.229	0.003	4	0.164	0.006	4	0.698	0.013	4	2.719	0.003	2
13-974-1	7.663	0.024	2	0.104	0.001	2	0.211	0.001	2	0.914	0.008	2	2.847		1
19-1437-1	6.098	0.016	3	0.154	0.005	3	0.194	0.007	3	0.805	0.021	3	2.796	0.007	3
20-386-1	8.122	0.004	2	0.179	0.001	2	0.196	0.004	2	0.799	0.015	2	2.774		1
23-173-1	7.590		1	0.183		1	0.176		1	0.798		1	2.750		1
23-524-1	9.650		1	0.187		1	0.199		1	0.732		1	2.762		1
25-677-1	8.550		1	0.170		1	0.192		1	0.777		1	2.762		1
27-637-1	8.370		1	0.181		1	0.194		1	0.708		1	2.739		1
31-919-1	8.666		1	0.172		1	0.235		1	0.804		1	2.806		1
32-127-1	8.390		1	0.199		1	0.183		1	0.720		1	2.754		1
32-385-1	8.860		1	0.202		1	0.178		1	0.687		1	2.721		1
35-339-1	9.360		1	0.188		1	0.171		1	0.725		1	2.750		1
41-782-1	8.257	0.011	2	0.194	0.001	2	0.171	0.007	2	0.674	0.008	2	2.745		1
41-820-1	8.300		1	0.168		1	0.182		1	0.771		1	2.759		1

Notes: Only a portion of this table is shown here to demonstrate its form and content. A machine-readable version of the full table is available (*http://www.raa-journal.org/docs/Supp/ms4196Tab2full.txt*).

In total, the final list (available in electronic form) includes 620 stars from which 109 objects have been found in more than one reference. For the next step, the 61 roAp stars listed in Joshi et al. (2016) were taken and all objects searched for $uvby\beta$ colors in the catalog by Paunzen (2015). This catalog includes only stars with Tycho identifiers and is therefore limited to objects brighter than 15th magnitude (98% of the stars in that catalog are between 4th and 12th magnitude). In the following, only stars with complete $uvby\beta$ measurements can and will be considered. Those are 416 (67% of all noAp) and 42 (69% of all roAp) objects, i.e. a representative number for both subgroups.

In Figure 2 we present three diagrams of unreddened indices: β versus $[m_1]$, $[c_1]$ versus $[m_1]$ and r versus $a0$. It is obvious that the blue boundary of the roAp phenomenon is well defined and a significant number of objects hotter than the known roAp stars have already been observed. However, the red border appears more fuzzy. The reddest star in these diagrams is HD 101065 (Przybylski's Star), but also HD 69013 and HD 143487 are located in the region with $a0 > 0.3$. These stars also have the largest $[m_1]$ and $[u-b]$ values. For HD 101065, several detailed investigations are available in the literature. Shulyak et al. (2010) concluded that there is nothing special in HD 101065 compared to other known cool CP and roAp stars except its relatively low $T_{\rm eff}$ (6400 K) and a high abundance of rare earth elements. Erroneous measurements of $uvby\beta$ can also be excluded as a cause for the outstanding location in the diagrams because there are four consistently different references over almost two decades available. Therefore, the range for the search of roAp candidates on the basis of Strömgren-Crawford $uvby\beta$ colors should be significantly extended to cooler CP stars. In this respect, it is especially interesting to study the possible overlap with solar-type oscillations, which are in the same frequency region, but according to theory should be suppressed by effects of the magnetic field that are required to excite roAp pulsations (Balmforth et al. 2001). Helioseismology found that the mode amplitudes of solar acoustic oscillations are anti-correlated with solar magnetic activity.

Using the diagrams shown in Figure 2, we define new and extended boundaries for the location of known roAp stars for a further search of other variable stars of this type:

$$0.58 > [m_1] > 0.22,$$
$$1.40 > [u-b] > 1.00,$$
$$0.54 > a0 > 0.10,$$
$$[3.2 - (0.95 * [m_1])] > \beta > [2.94 - (0.95 * [m_1])],$$
$$[1.75 - (3.1 * [m_1])] > [c_1] > [1.25 - (3.1 * [m_1])],$$
$$[0.16 - (0.5 * a0)] > r > 0.5 * a0.$$

Applying these relations to the catalog by Paunzen (2015), we find a list (available in electronic form) of

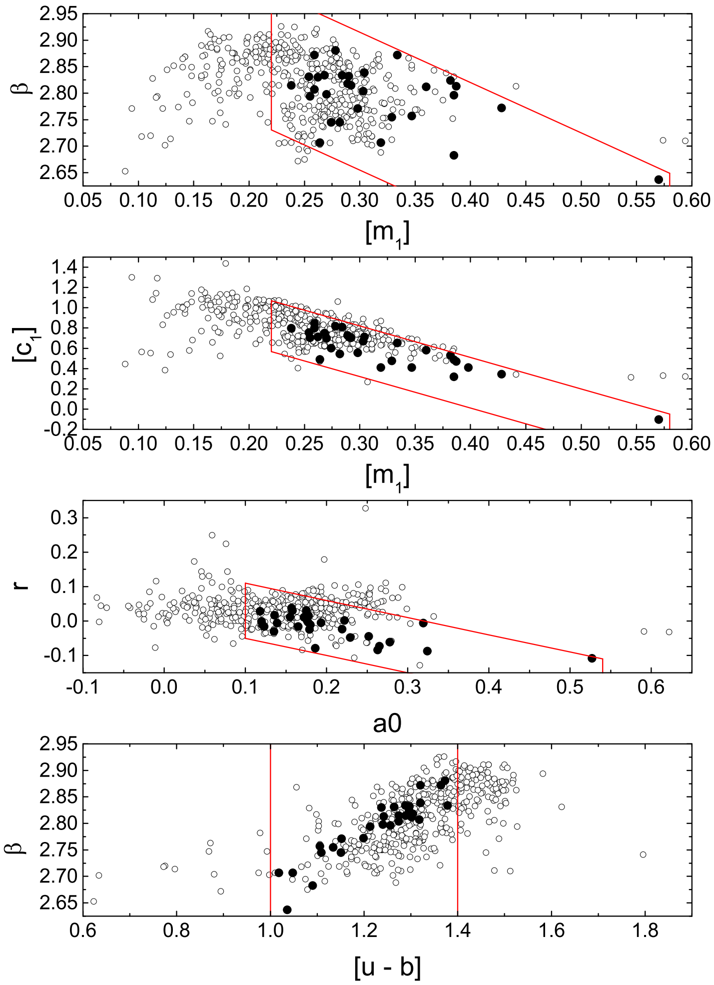

Fig. 2 The location of 416 noAp (*open circles*) and 42 roAp (*filled circles*) within three reddening free Strömgren-Crawford $uvby\beta$ diagrams. The *red solid lines* indicate boxes defined from the known roAp stars in which we searched for new candidates (*color online*).

4646 new candidates (Table 2). This sample is intentionally a-priori unbiased by any additional spectral type information and can be used as a starting point for searches for roAp variables.

Criteria for selecting roAp candidates from Strömgren-Crawford photometry can be manyfold. For instance, comparing with the boundaries of the roAp phenomenon as defined by Joshi et al. (2016), who use different parameters (and exclude HD 101065), more stars satisfy our criteria. The main reasons are that we do allow for measurement errors, and for a possible extension of the borders of the roAp domain compared to current knowledge. Ideally, one would desire an inspection of all stars from our sample to define (non)variability. Such a large sample can only be comprehensively investigated with data already collected by automatic surveys or by forthcoming space photometry missions.

4 CONCLUSIONS

We investigated some characteristics of noAp and roAp stars using available data from the literature and new photometric observations. These stars are interesting because the driving mechanism of their oscillation modes is most probably due to the "classical" κ-mechanism operating in the hydrogen ionization zone, with some possible contributions by turbulent pressure (Cunha et al. 2013). The roAp stars possess a structured and stable magnetic field which triggers diffusion and stratification of chemical elements. The latter leads to strong chemical peculiarities on the stellar surface (spots), which give the possibility to directly measure their rotational period due to light variations. Such a combination is unique among stars on the Upper Main Sequence where convection does not dominate the outer stellar atmosphere.

An enormous effort was spent in the last three decades to search for roAp stars. The detection of these variables is made difficult by the low pulsation amplitudes (typically only a few mmag) that are largest in the blue optical spectral region and the excited period range (five to twenty five minutes). Other complicating facts are that the amplitudes can vary strongly even between consecutive nights, and that the amplitudes can be so low (or even zero according to the Oblique Pulsator Model) that they are undetectable from the ground. This also makes the definition of an noAp star, i.e. an object that does not pulsate, difficult; one always has to include the upper limit for a given period of time and filter.

The results of our new observations of 55 stars (202 hours on 59 different nights) were combined with already published ones for apparent noAp and roAp stars. For the objects with available Strömgren-Crawford $uvby\beta$ photometry, reddening-free diagrams were generated and analyzed. From these diagrams we concluded that the blue border of the observed roAp instability strip is well determined and investigated. The opposite is true for the red border where still only a small number of possible candidates have been observed. On the basis of these diagrams, we defined limits for $[m_1]$, $[c_1]$, $[u-b]$, $a0$, r and β in which we searched for new roAp candidates. In total, we found 4646 stars brighter than 15th magnitude. We suggest using surveys like SuperWASP or the forthcoming *TESS* mission to search for pulsation in these stars.

Based on the published and newly observed data for HD 12098 and HD 137909, we discussed the necessity of high quality photometric observations on several nights to establish variability for this star group. This difficulty may be overcome by searching for radial velocity variability or the unique Pr-Nd anomaly present in roAp stars, followed by a photometric search.

Further ground and space based efforts are very much needed to shed more light on the roAp phenomenon. In particular, an analysis of the possible connection with solar-type oscillations is necessary to understand the changes from radiative to convective dominated stellar atmospheres and their different/common pulsational behavior in the presence of a magnetic field.

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