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New analysis of ZZ Ceti star PG 2303+243

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Abstract. The new photometric observations of PG 2303+243 were obtained in 2012 during a campaign carried out with three telescopes. The analysis of these observations is presented in this paper. We identified $l = 1$ and $l = 2$ pulsation modes. The pulsation periods were compared with theoretical ones for models of ZZ Ceti stars. This allowed us to estimate the physical parameters of PG 2303+243. The star seems to be cooler and has thicker hydrogen layer than it was thought before. We have derived $M_*/M_\odot = 0.66$, $T_{\rm eff} = 11014$ K and $\log(M_{\rm H}/M_*) = -4.246$ for this star.

Keywords. stars: variables, white dwarfs: ZZ Ceti: individual: PG 2303+243

1. Observations and analysis

PG 2303+243 was observed several times since its discovery as variable white dwarf (DAV) in 1987 (Vauclair *et al.* 1987). In our work we used the published photometric data obtained in 1990 (Vauclair *et al.* 1992), 2004 (Pakštienė *et al.* 2011) and 2005 (Pakštienė 2013). The new photometric observations of PG 2303+243 were obtained during a small campaign carried out between October 4 and 11, 2012, with three telescopes: 165-cm (Molėtai, Lithuania), 180-cm (VATT, Arizona) and 46-cm (Horten, Norway).

Despite unfavourable weather conditions in all observatories, the total duration of runs amounted to 55.88 h, which corresponds to a duty cycle of 32%. The detection limit of pulsations for a false alarm probability FAP = 1/1000 is 2.93 mma (milli-modulation amplitude) at 2000 μHz. This limit is lower than it was in observations made in 2005 (3.75 mma), but higher than in the 2004 campaign (1.79 mma). Fourier transform (FT) spectra of PG 2303+243 are clearly different for different seasons. Only some modes can be found at about the same frequency, but their amplitudes differ strongly. Observational data obtained during the 2004 campaign yielded the most detailed FT spectrum so far.

In total, we detected 39 periodic terms in the Fourier spectrum of the combined 2012 data. Frequencies of four pairs differed by less than 3 μHz, so we assumed that these are single peaks broadened by variable amplitudes of the modes. An additional 10 terms were removed from the list because they were identified as harmonics or combinations. We found that 4 frequencies might have harmonics. This left us with the list of 25 modes detected in the 2012 data that are likely independent. A more detailed description of these observations and their analysis will be published elsewhere.

2. Mode identification

We assume that only $l = 1$ modes reach high amplitudes and appear as dominant peaks in the FT spectrum. We found different dominant peaks for different seasons and finally picked up five dominant modes with the highest amplitudes from 1990, 2004, 2005 and 2012 observations. In order to find an appropriate model for PG 2303+243 we

Table 1. Comparison of the observed, Π_{obs}, and theoretical, Π_{th}, periods for PG 2303+243. Indicated years correspond to the season with the smallest $\Delta\Pi$. The asterisks (*) indicate periods found in data from more than one season.

Π_{obs} [s]	A [mma]	Π_{th} [s]	$\Delta\Pi$	l	k	year	Π_{obs} [s]	A [mma]	Π_{th} [s]	$\Delta\Pi$	l	k	year
261.8	2.3	261.9	−0.1	1	4	2004	778.5!	20.9	776.6	1.9	1	16	2005
270.1	3.1	271.5	−1.4	2	8	2012	816.2!	32.2	816.9	−0.7	1	17	2012*
335.5	2.5	336.5	−1.0	2	11	2005	820.3	30.5	821.6	−1.3	2	31	2012
390.7	2.8	390.3	0.5	2	13	2004*	845.7	5.6	845.9	−0.1	2	32	2012*
434.0	1.5	435.5	−1.5	2	15	1990	857.8	4.9	859.4	−1.6	1	18	2004
453.2	2.3	455.6	−2.3	2	16	1990*	873.2	3.9	873.0	0.2	2	33	2004
482.6	5.3	480.0	2.6	2	17	1990	925.3	7.9	927.2	−1.9	2	35	2012
577.9!	11.0	577.9	0.0	1	11	1990	940.6	7.5	942.7	−2.1	1	20	2005*
578.1	2.8	578.2	−0.1	2	21	2004	955.4	3.2	953.2	2.2	2	36	1990
606.4	4.4	604.2	2.2	2	22	2005	965.3	19.7	—	—	—	—	2004*
616.4!	31.3	616.0	0.4	1	12	2004*	998.3	6.7	1000.6	−2.3	2	38	2005
682.7	1.1	680.4	2.3	1	14	1990	1043.6	1.9	1046.3	−2.7	2	40	1990*
774.7	13.3	776.6	−2.0	1	16	2012	1227.3	1.8	1227.3	0.0	2	47	1990

used a set of models calculated by Romero *et al.* (2012). Our method for selection of the model is identical to the one described by Romero *et al.* (2012). We also used three quality functions, Φ, χ^2, and Ξ, which were based on differences between theoretical and observed periods. Minimum values of Φ, χ^2 and Ξ gave us the most appropriate seismic model for the star.

The most disappointing fact was that the best matching models do not predict pulsations with the period of 965.3 s (A = 19.7 mma), though earlier analyses (Romero *et al.* 2012, Pakštienė 2013) predicted it to be an $l = 1$ mode. Thus, in the final fit, we used only four periods: 577.93 s (11.0 mma), 616.4 s (31.4 mma), 778.5 s (20.9 mma) and 816.2 s (32.2 mma), flagged with exclamation marks in Table 1. These periods give the best match for the model having $M_*/M_\odot = 0.66$, $T_{\rm eff} = 11\,014$ K and $\log(M_{\rm H}/M_*) = -4.246$ with quality function $\Phi = 0.74$ s.

Then, we considered all periods observed in four seasons and compared them with periods taken from the selected DAV model of Romero *et al.* (2012). We have found that 25 observed periods agree within 2.7 s with the theoretical ones (Table 1). This identification results in a quality function $\Phi = 1.31$ s.

3. Conclusions

We have estimated that the mass of PG 2303+243 is exactly the same as estimated from spectroscopy by Bergeron *et al.* (2004) and is larger than was found by Romero *et al.* (2012). According to our analysis, the hydrogen layer of PG 2303+243 must be much thicker ($\log(M_{\rm H}/M_*) = -4.246$) than was found by Romero *et al.* (2012) and Bergeron *et al.* (2004). The effective temperature we estimated, when compared to values published by other authors, is the lowest one, but it fits well the parameters of cool DAV stars and is very close to the red edge of the DAV instability strip. This raises even larger interest to PG 2303+243.

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