A&A manuscript no.
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08.01.1, 08.01.3, 08.08.2, 08.09.2, 08.15.1, 08.18.1

ASTRONOMY
AND
ASTROPHYSICS
22.6.1999

Spectral analysis of the multi mode pulsating subluminous B star PG 1605+072 ⋆ ⋆⋆

U. Heber[1], **I.N. Reid**[2], **K. Werner**[3]

[1] Dr. Remeis-Sternwarte, Astronomisches Institut der Universität Erlangen-Nürnberg, Sternwartstr. 7, D 96049 Bamberg, Germany (E-mail heber@sternwarte.uni-erlangen.de)
[2] Palomar Observatory 105-24, California Institute of Technology, Pasadena, CA 91125, USA
[3] Institut für Astronomie und Astrophysik, Universität Tübingen, D 72076 Tübingen

Received ; accepted

Abstract. PG 1605+072 has unique pulsational properties amongst the members of the new class of pulsating sdB (EC 14026) stars. It has the longest periods and the richest, most puzzling frequency spectrum (55 periods). We present a quantitative analysis of a Keck HIRES spectrum using NLTE and LTE model atmospheres. Atmospheric parameters ($T_{\rm eff}$, $\log g$, $\log \frac{n_{\rm He}}{n_{\rm H}}$), metal abundances, and the rotational velocity are determined. He, C, N and O are subsolar as well as the intermediate mass elements Mg and Si, whereas Ne and Fe are solar. This abundance pattern is caused by diffusion. PG 1605+072 displays considerable line broadening probably caused by rotation (v sini = 39 km/s, P<8.7h) and, therefore, is predicted to evolve into an unusually fast rotating white dwarf. Unequal rotational splitting may explain its puzzling pulsation pattern. The solar Fe abundance and the rapid rotation nicely confirms recent predictions of diffusion/pulsation models.

Key words: stars: abundances — stars: atmospheres — stars: oscillations — stars: horizontal branch — stars: rotation — stars: individual: PG 1605+072

1. Introduction

Hot subluminous B stars (sdB) form a homogeneous group dominating the population of faint blue stars ($B<16^{\rm m}$). Following ideas outlined by Heber (1986) the sdB stars can be identified with models for extreme HB (EHB) stars, which differ markedly from those for normal HB stars. An EHB star bears great resemblance to a helium main-sequence star of half a solar mass and its further evolution should proceed similarly (i.e. directly to the white dwarf graveyard, Dorman et al. 1993).

Recently, several sdB stars have been found to be pulsating (termed EC14026 stars after the prototype, see O'Donoghue et al. 1999 for a review), defining a new instability strip in the HR-diagram. The study of these pulsators offers the possibility of applying the tools of asteroseismology to investigate the structure of sdB stars. The existence of pulsating sdB stars was predicted by Charpinet et al. (1996), who uncovered an efficient driving mechanism due to an opacity bump associated with iron ionization in EHB models. However, in order to drive the pulsations, iron needed to be enhanced in the appropriate subphotospheric layers, possibly due to diffusion. Subsequently, Charpinet et al. (1997) confirmed this assumption by detailed diffusion calculations. Even more encouraging was the agreement of the observed and predicted instability strip.

Thirteen pulsating sdB stars are well-studied photometrically (O'Donoghue et al. 1999). A precise knowledge of effective temperature, gravity, element abundances and rotation is a prerequisite for the asteroseismological investigation.

PG 1605+072 was selected for a detailed quantitative spectral analysis because it displays the richest frequency spectrum amongst the EC 14026 stars (>50 periods have been identified, Kilkenny al. 1999). Recently, Kawaler (1999) predicted from his modelling of the pulsations that PG 1605+072 should be pulsating.

2. Observation and data reduction

A high resolution optical spectrum of PG 1605+072 was obtained with the HIRES echelle spectrograph (Vogt et

Send offprint requests to: U. Heber

⋆ Based on observations obtained at the W.M. Keck Observatory, which is operated by the Californian Association for Research in Astronomy for the California Institute of Technology and the University of California

⋆⋆ based on observations collected at the ESO Southern Observatory al. 1994) on the Keck I telescope on July 20, 1998 using the blue cross disperser to cover the full wavelength region between 3700Å and 5200Å at a resolution 0.09Å.

The exposure time (600s) is longer than the pulsational periods (206–573s). The standard data reduction as described by Zuckerman & Reid (1998) resulted in spectral orders that have a somewhat wavy continuum. In order to remove the waviness we used the spectrum of H1504+65 (a very hot pre-white dwarf devoid of hydrogen and helium, Werner 1991) which was observed in the same night. Its spectrum has only few weak lines of highly ionized metals in the blue (3600–4480Å) where the strong Balmer lines are found in the sdB stars. Therefore we normalized individual spectral orders 1 to 20 (3600–4480Å) of the sdB stars by dividing through the smoothed spectrum of H1504+65. The remaining orders were normalized by fitting the continuum with spline functions (interpolated for orders 26 and 27 which contain Hβ). Judged from the match of line profiles in the overlapping parts of neighboring orders this procedure worked extremely well. Atmospheric parameters determined from individual Balmer lines are found to be consistent with each other except for Hβ. Therefore, we excluded Hβ from the fit procedure. Moreover, the resulting $T_{\rm eff}$ and $\log g$ are also in excellent agreement with those from the fit of a low resolution spectrum obtained at the ESO NTT (provided by S. Moehler). Weak lines of C, N, O, Ne, Mg, Si, and Fe can also be identified.

3. Atmospheric parameters

The simultaneous fitting of Balmer and He line profiles by a grid of synthetic spectra (see Saffer et al. 1994) has become the standard technique to determine the atmospheric parameters of sdB stars. The Balmer lines (Hγ to H 12), He I (4471Å, 4026Å, 4922Å, 4713Å, 5016Å, 5048Å) and He II 4686Å lines are fitted to derive all three parameters simultaneously.

The analysis is based on grids of metal line blanketed LTE model atmospheres for solar metalicity and Kurucz' ATLAS6 Opacity Distribution Functions (see Heber et al. 1999). Synthetic spectra are calculated with Lemke's LINFOR program (see Moehler et al. 1998).

The results are listed in Table 1 and compared to published values obtained from low resolution spectra. The formal errors of our fits are much smaller than the systematic errors (see below). The agreement with the results from low resolution spectra analysed with similar models (Koen et al. 1998) as well as from our own low resolution spectrum for PG 1605+072 is very encouraging.

Four species are represented by two stages of ionization (He I and He II, C II and C III, N II and N III, Si III and Si IV). Since these line ratios are very temperature sensitive at the temperatures in question, we alternatively can derive $T_{\rm eff}$ and abundances by matching these ionization equilibria. Gravity is derived subsequently from the Balmer lines by keeping $T_{\rm eff}$ and $\log\frac{n_{\rm He}}{n_{\rm H}}$ fixed. These two steps are iterated until consistency is reached. C II is represented by the 4267Å line only, which is known to give notoriously too low carbon abundances. Indeed the carbon ionization equilibrium can not be matched at any reasonable $T_{\rm eff}$. The ionization equilibria of He, N and Si require $T_{\rm eff}$ to be higher than from the Saffer procedure, i.e. 33 200K (He), 33900K (N) and 32 800K (Si). Table 1 lists the result for the He ionization equilibrium.

Table 1. Atmospheric parameters for PG 1605+072 from different methods, see text

method	$T_{\rm eff}$ [K]	$\log g$	$\log\frac{n_{\rm He}}{n_{\rm H}}$
LTE:			
Koen et al. (1998)	32 100±1000	5.25±0.1	–
NTT, low res.	32 300	5.31	-2.46
HIRES, H+He	31 900	5.29	-2.54
HIRES, He	33 200	5.34	-2.42
NLTE:			
NTT, low res.	32 500	5.25	-2.46
HIRES, H+He	32 200	5.21	-2.54
HIRES, He	32 400	5.21	-2.53
adopted	32 300±300	5.25±0.05	-2.53±0.1

This difference could be caused by NLTE effects. Therefore we repeated the procedure for $T_{\rm eff}$ and $\log\frac{n_{\rm He}}{n_{\rm H}}$ using a grid of H-He line blanketed, metal free NLTE model atmospheres (Napiwotzki 1997), calculated with the ALI code of Werner & Dreizler (1999). NLTE calculations for N and Si are beyond the scope of this letter.

Applying Saffer's procedure with the NLTE model grid (see Fig. 1) yields $T_{\rm eff}$ almost identical to that obtained with the LTE grid. Evaluating the He ionization equilibrium in NLTE, indeed, results in $T_{\rm eff}$ being consistent with that from Saffer's procedure (see Table 1). We therefore conclude that the higher $T_{\rm eff}$ derived above from the ionization equilibrium in LTE is due to NLTE effects.

However, a systematic difference in $\log g$ persists, the LTE values being higher by 0.06 – 0.08 dex than the NLTE results (see Table 1). Since its origin is obscure, we finally adopted the averaged atmospheric parameters given in Table 1. Helium is deficient by a factor of 30 as is typical for sdB stars.

4. Metal abundances

The metal lines are sufficiently isolated to derive abundances from their equivalent widths except for the crowded region from 4635Å to 4660Å which we analyse by detailed spectrum synthesis. Results are listed in Table 2 and plotted in Figure 2. Although several O lines are available, it was impossible to determine the microturbulent velocity($v_{\rm t}$) in the usual way, i.e. by minimizing the slope in a plot of the O abundances versus equivalent widths. We adopted $v_{\rm t}$= 5±5km/s which translates into small systematic abundance uncertainties of ±0.05dex for

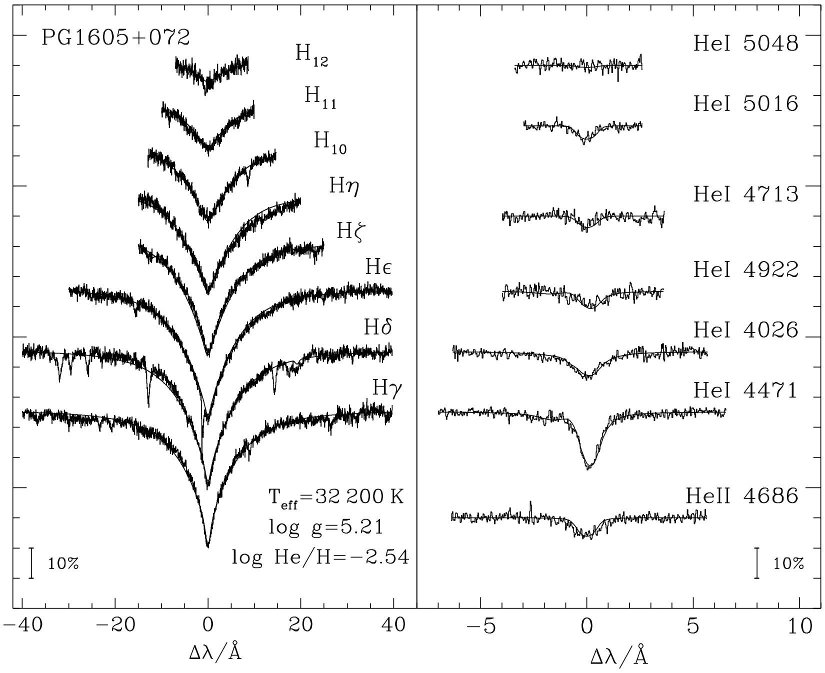

Fig. 1. Balmer and He line profile fits for PG 1605+072 of the HIRES spectrum from NLTE model atmospheres.

most ions. The analysis is done in LTE and we therefore used a model ($T_{\rm eff}$= 33500 K, log g= 5.35) that is consistent with the He, N and Si ionization equilibria. A temperature uncertainty of $\Delta\ T_{\rm eff}$=1000 K translates into abundance uncertainties of less than 0.1 dex. Hence systematic errors are smaller for most ions than the statistical errors given in Table 2.

Table 2. Metal abundances for PG 1605+072 compared to solar composition. n is the number of spectral lines per ion.

ion	n	log ϵ	[M/H]
C III	2	7.80±0.07	−0.83
N II	5	7.62±0.16	−0.33
N III	2	7.66±0.24	−0.29
O II	25	8.00±0.21	−0.88
Ne II	4	7.57±0.19	−0.12
Mg II	1	7.16	−0.33
Si III	3	7.11±0.06	−0.35
Si IV	4	7.07±0.16	−0.39
Fe III	4	7.62±0.39	+0.30

Carbon and oxygen are depleted by 0.8–0.9 dex with respect to solar composition whereas nitrogen, magnesium and silicon are only slightly deficient (factor 2). Surprisingly neon and iron are solar to within error limits. This peculiar abundance pattern is probably due to diffusion, i.e. the interplay of gravitational settling and radiative levitation. The iron abundance is of special interest as an diffusive enrichment in subphotospheric layers is necessary to drive the pulsations. Its surface abundance is consistent with the diffusion calculations of Charpinet et al. (1997).

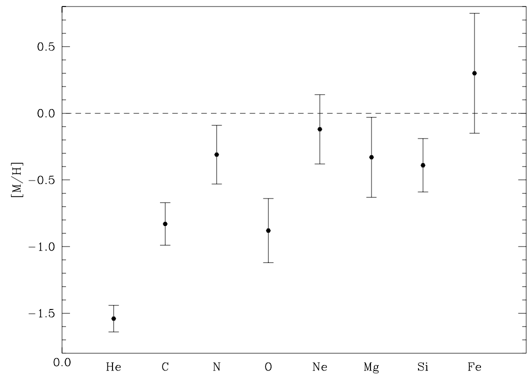

Fig. 2. Abundances of PG 1605+072 relative to the sun. For Mg an uncertainty of 0.3 dex was assumed.

5. Projected rotational velocities

The spectral lines of PG 1605+072 are considerably broadened, which we attribute to stellar rotation and derive v sin i = 39km/s, by fitting the strongest metal lines. In Figure 3 we compare a section of the spectrum of PG 1605+072 to that of the pulsating sdB star Feige 48 observed with the same instrumental setup. However, non-radial oscillations in these objects should be associated with motions which could lead to line broadening similar to the rotation effect. For a radial pulsation with a sinusoidal velocity curve a radius change of ΔR/R=$\frac{v P}{\pi R}$ ≥3% for PG 1605+072 would be required. In comparison Feige 48 is very sharp-lined (v sin i<8km/s) corresponding to $\Delta R/R<0.6\%$ if sin i=1. Although the intensity amplitudes of the pulsations in Feige 48 are considerably smaller than for PG 1605+072 we regard rotation as the more likely reason for the broadening of the lines of the latter. Time resolved spectroscopy should allow to disentangle both effects as well as to search for temperature changes associated with the pulsations.

Assuming a mass of $0.5\,M_\odot$ the radius of $R=0.28\,R_\odot$ follows from the gravity. Since sin i cannot be constrained the corresponding rotation period of PG 1605+072 must be smaller than 8.7h. PG 1605+072 displays the most complex power spectrum with more than 50 frequencies identifiable (Kilkenny et al. 1999), 39 being bona fide normal pulsation frequencies.

Usually rotation becomes manifest in the power spectrum by the characteristic splitting into equidistantly spaced multiplet components as is observed e.g. for the pre-white dwarf PG 1159-035 (rotation period: 1.4 d, Winget et al. 1991). Such multiplet's, however, have not been identified for PG 1605+072. Fast rotation introduces higher order terms that result in unequally spaced multiplet components. Recently, Kawaler (1999), was able to identify the five main peaks by considering mode trapping and rotational splitting. He predicted that PG 1605+072 should be rapidly rotating (130 km/s). The measured v sin i= 39 km/s, hence, is a nice confirmation of Kawaler's prediction.

Rotation is interesting also from the point of view of stellar evolution. PG 1605+072 is probably already in a post-EHB phase of evolution (Kilkenny et al. 1999) and will evolve directly into a white dwarf, i.e. will shrink from its present radius of $0.28\,R_\odot$ to about $0.01\,R_\odot$. Hence PG 1605+072 will end its life as an unusually fast rotating white dwarf if no loss of angular momentum occurs. Isolated white dwarfs, however, are known to be very slow rotators (e.g. Heber et al. 1997).

6. Conclusion

Atmospheric parameters of PG 1605+072 and abundances of several elements have been determined at the highest accuracy achieved so far for an EC14026 pulsator. Together with the complex pulsation pattern this makes PG1605+072 the most interesting object of its class.

The high projected rotational velocity of PG 1605+072 (v sin i=39 km/s) may be a key observation to understand its puzzling power spectrum. This measurement nicely confirms a recent prediction from pulsational models (Kawaler, 1999).

Although the helium abundance is low (≈1/30 solar) as is typical for sdB stars, most metals are only mildly depleted (0.3–0.8 dex) whereas Ne and Fe are solar. The solar iron abundance is in perfect agreement with the predictions from the diffusion models of Charpinet et al. (1997). The determination of abundances of several other elements provides a serious test of diffusion models.

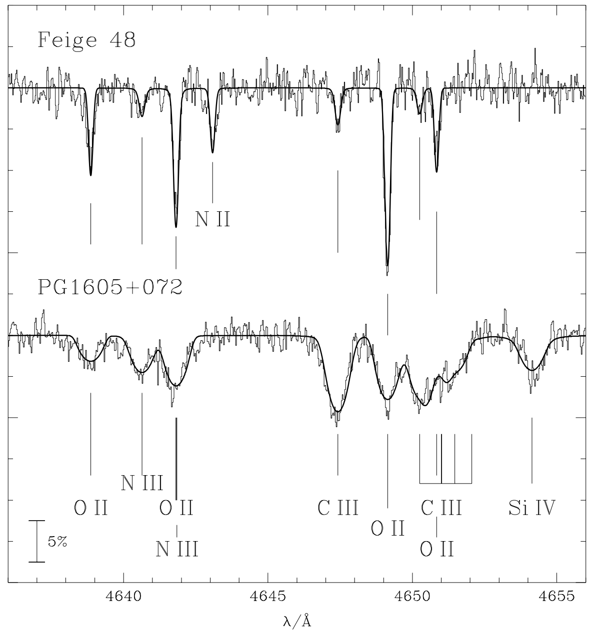

Fig. 3. Fit of a section of the metal line spectrum of PG 1605+072, (bottom, v sini=39 km/s) compared to that of Feige 48 (top, no rotation), another pulsating sdB star.

Acknowledgements. We thank Sabine Moehler for providing us with her low resolution spectrum of PG 1605+072 and Ralf Napiwotzki and Gilles Fontaine for fruitful discussions. A travel grant by the DFG is gratefully acknowledged.

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