

SPECTRAL ANALYSIS OF FOUR MULTI-MODE PULSATING sdB STARS

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Abstract. Four members of the new class of pulsating sdB stars are analysed from Keck HIRES spectra using NLTE and LTE model atmospheres. Atmospheric parameters (T_{eff} , $\log g$, $\log(\text{He}/\text{H})$), metal abundances and rotational velocities are determined. Balmer line fitting is found to be consistent with the helium ionization equilibrium for PG 1605+072 but not for PG 1219+534 indicating that systematic errors in the model atmosphere analysis of the latter have been underestimated previously. All stars are found to be helium deficient probably due to diffusion. The metals are also depleted with the notable exception of iron which is solar to within error limits in all four stars, confirming predictions from diffusion calculations of Charpinet et al. (1997). While three of them are slow rotators ($v \sin i < 10 \text{ km/s}$), PG 1605+072 displays considerable rotation ($v \sin i = 39 \text{ km/s}$, $P < 8.7 \text{ h}$) and is predicted to evolve into an unusually fast rotating white dwarf. This nicely confirms a prediction by Kawaler (1999) who deduced a rotation velocity of 130 km/s from the power spectrum of the pulsations which implies a low inclination angle of the rotation axis.

Key words: stars: atmospheres, abundances, subdwarfs, rotation, individual: PG 1605+072, Feige 48, KPD 2109+4401, PG 1219+534

1. INTRODUCTION

It is now well established that the hot subluminous B stars can be identified with models of the extreme horizontal branch (EHB) stars (Heber 1986, Saffer et al. 1994).

Recently, several sdB stars have been found to be pulsating (termed EC 14026 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.

We selected four EC 14026 stars for a detailed quantitative spectral analysis: PG 1605+072 was chosen because it has the lowest gravity and, therefore, has probably already evolved beyond the extreme horizontal branch phase. It also displays the richest frequency spectrum amongst the EC 14026 stars (>50 periods have been identified, Kilkenny et al. 1999). Recently, Kawaler (1999) predicted from his modelling of the pulsations that PG 1605+072 should be rotating. PG 1219+534 was chosen because it has the shortest pulsation periods and has a helium abundance larger than most other sdB stars (O'Donoghue et al. 1999). For Feige 48 and KPD 2109+4401 only 4 or 5 frequencies have been found so far. Feige 48 is also the coolest of all EC 14026 stars known.

2. OBSERVATIONS

High resolution optical spectra of the four pulsating sdB stars were obtained with the HIRES echelle spectrograph (Vogt et al. 1994) on the Keck I telescope on July 20, 1998 using the blue cross disperser

to cover the full wavelength region between 3700 Å and 5200 Å at a resolution 0.09 Å.

The spectra are integrated over one pulsation cycle or more since the exposure times (600–900 s) were long compared to the pulsational periods.

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 H 1504+65 (a very hot pre-white dwarf devoid of hydrogen and helium) which was observed in the same night. Its spectrum has only a few weak lines of highly ionized metals in the blue (3600–4480 Å) where the strong Balmer lines are found in the sdB stars. Therefore we normalized individual spectral orders 1 to 20 (3600–4480 Å) of the sdB stars by dividing through the smoothed spectrum of H 1504+65. The remaining orders were normalized by fitting the continuum with spline functions (interpolated for orders 26 and 27 which contain H β). 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 H β . Therefore, we excluded H β from the fit procedure. Moreover, the resulting T_{eff} and $\log g$ are also in excellent agreement with those from the fit of a low resolution spectrum of PG 1605+072 obtained at the ESO NTT. Details on the analysis of PG 1605+072 can be found in Heber et al. (1999a).

3. ATMOSPHERIC PARAMETERS

The simultaneous fitting of Balmer and helium 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 (H γ to H 12), He I (4471, 4026, 4922, 4713, 5016 and 5048 Å) and He II 4686 Å lines are fitted to derive all three parameters simultaneously.

The analysis is based on grids of metal line blanketed LTE model atmospheres for solar metallicity and the Kurucz ATLAS6 Opacity Distribution Functions (see Heber et al. 1999b). Synthetic spectra are calculated with Lemke's LINFOR program (see Moehler et al. 1998). In addition, a grid of H–He line blanketed, metal-free NLTE model atmospheres (Napiwotzki 1997), calculated with the ALI code of Werner & Dreizler (1999), have been used.

PG1605+072

The results ($T_{\text{eff}} = 31\,900\text{ K}$, $\log g = 5.29$, $\log(\text{He}/\text{H}) = -2.54$) are in agreement with those 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.

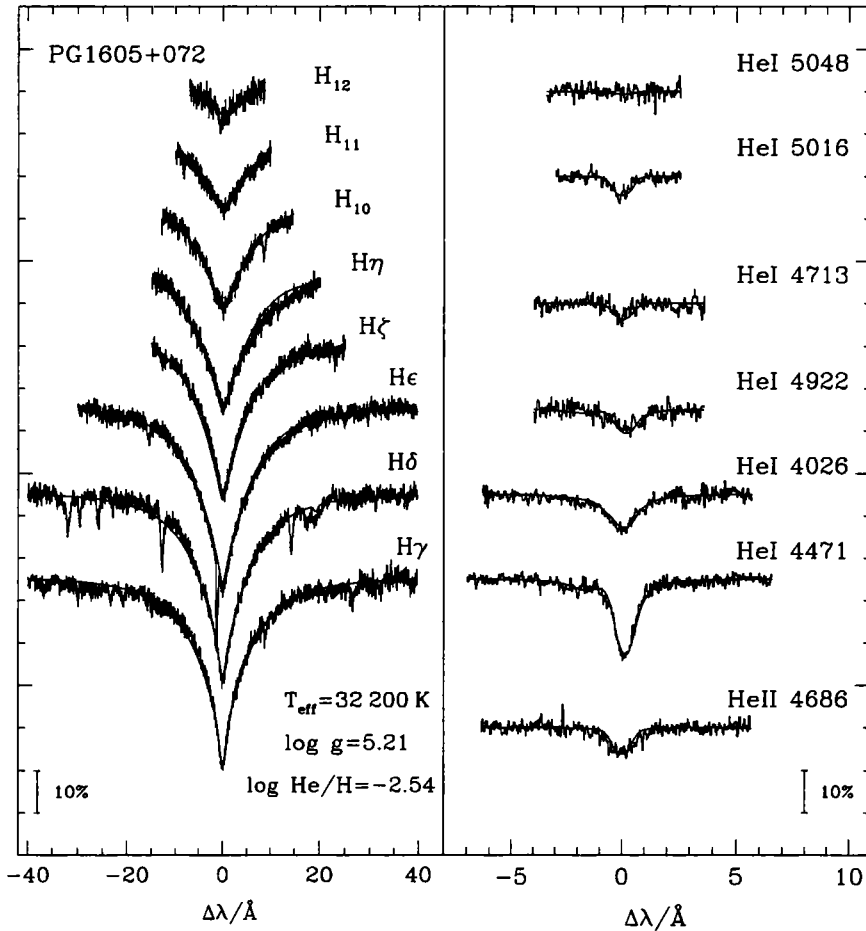


Fig. 1. Balmer and helium line profile fits for PG 1605+072 of the HIRES spectrum from NLTE model atmospheres.

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_{eff} and abundances by matching these ionization equilibria. Gravity is derived subsequently from the Balmer lines by keeping T_{eff} and $\log(\text{He}/\text{H})$ fixed. These two steps are iterated until consistency is reached. C II is represented by the 4267 Å 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_{eff} . The ionization equilibria of He, N and Si require T_{eff} to be higher than from the Saffer procedure, i.e. 33 200 K (He), 33 900 K (N) and 32 800 K (Si).

Since this difference could be caused by NLTE effects, we repeated the procedure for T_{eff} and $\log(\text{He}/\text{H})$ using NLTE models. Alternatively, applying Saffer's procedure with the NLTE model grid (see Fig. 1) yields T_{eff} almost identical to that obtained with the LTE grid. Evaluating the He ionization equilibrium in NLTE, indeed, results in T_{eff} being consistent with that from Saffer's procedure. We therefore conclude that the higher T_{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. Since its origin is obscure, we finally adopted the averaged atmospheric parameters: $T_{\text{eff}} = 32\,300 \pm 300$ K, $\log g = 5.25 \pm 0.05$, $\log(\text{He}/\text{H}) = -2.53 \pm 0.1$. Helium is deficient by a factor of 30 as is typical for sdB stars.

Feige 48

Since no He II line can be detected, the helium ionization equilibrium can not be evaluated. The procedure of Saffer et al. (1994) results in $T_{\text{eff}} = 29\,400$ K, $\log g = 5.51$, $\log(\text{He}/\text{H}) = -2.90$. Feige 48 has the lowest helium abundance among our programme stars.

KPD 2109+4401

The helium ionization equilibrium and the Saffer et al. procedure give (averaged) parameters $T_{\text{eff}} = 31\,800$ K, $\log g = 5.79$, $\log(\text{He}/\text{H}) = -2.22$ for KPD 2109+4401.

PG 1219+534

Unlike for PG 1605+072, the helium ionization equilibrium and the Saffer et al. procedure give discrepant results: $T_{\text{eff}} = 33\,200$ K,

$\log g = 5.93$, $\log(\text{He}/\text{H}) = -1.60$ (Saffer et al. procedure, Fig. 2) and $T_{\text{eff}} = 35\,200\text{ K}$, $\log g = 6.03$, $\log(\text{He}/\text{H}) = -1.41$ (He ionization equilibrium, Fig. 3). At the lower T_{eff} the Balmer lines are well matched through out the entire profile, whereas for He II 4686 Å there is a significant mismatch (see Fig. 2). At the higher T_{eff} He II 4686 Å is well reproduced, but the Balmer line cores are not reproduced at all (see Fig. 3). Despite of its high gravity, PG 1219+534 has an unusually high helium abundance, i.e. it is deficient by a factor of 2 to 5 only. The line cores of He I 4026 Å and 4471 Å cannot be reproduced by either model. We conclude that our models do not describe the outermost layers of the atmosphere correctly where the cores of the Balmer and He I lines are formed. We point out that PG 1219+534 has the highest helium abundance and the shortest pulsation periods, which might affect the outermost layers.

4. ABUNDANCES

Weak metal lines are present in the spectra of all program stars. However, the number of detectable lines differs considerably. The largest number of metal lines is present in Feige 48 (C, N, O, Ne, Mg, Si, Al, S and Fe) and PG 1605+072 (which lacks Al and S). In PG 1219+534 only N, S and Fe are detectable.

The metal lines are sufficiently isolated to derive abundances from their equivalent widths except for the crowded region from 4635 Å to 4660 Å in PG 1605+072 which we analyse by detailed spectrum synthesis. Results are plotted in Fig. 4. Upper limits are shown when no line of a species was detectable. Although several O lines are available in the spectra of PG 1605+072 and Feige 48, it was impossible to determine the microturbulent velocity in the usual way, i.e. by minimizing the slope in a plot of the O abundances versus equivalent widths, due to the lack of sufficiently strong lines. We adopted $5 \pm 5\text{ km/s}$ which translates into small systematic abundance uncertainties of $\pm 0.05\text{ dex}$ for most ions. The analysis is done in LTE. A temperature uncertainty of $\Delta T_{\text{eff}} = 1000\text{ K}$ translates into abundance uncertainties of less than 0.1 dex. Hence systematic errors are smaller for most ions than the statistical errors.

Like helium the metals are deficient with the notable exception of iron, which is solar to within the error limits. The high gravity stars (KPD 2109+4401 and PG 1219+534) have considerably lower O and Si abundances than the stars of somewhat lower gravity which point to the (selective) action of diffusion. It is, however, puzzling that

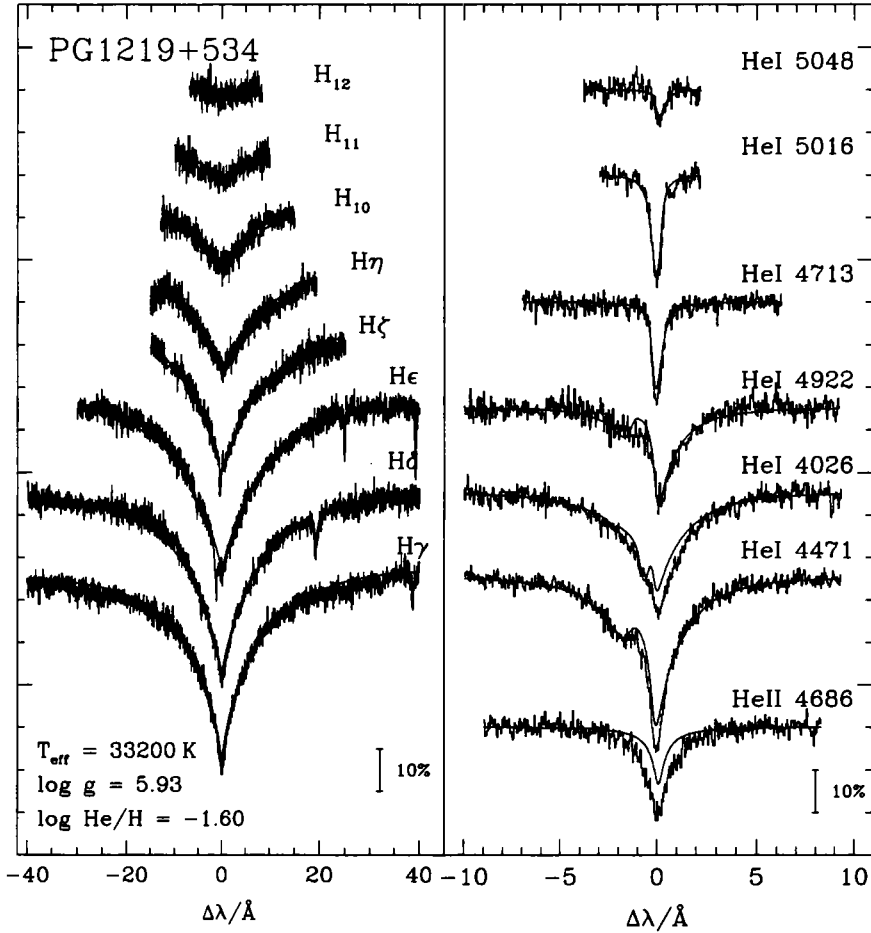


Fig. 2. Balmer and helium line profile fits for PG 1219+534 of the HIRES spectrum. Note the mismatch of the He II 4686 Å line profile and the cores of He I 4026 Å and 4471 Å.

iron is solar irrespective of the gravity. UV spectroscopy is required to determine more precise iron abundances. We point out that a solar surface abundance is in perfect agreement with the diffusion calculations of Charpinet et al. (1997).

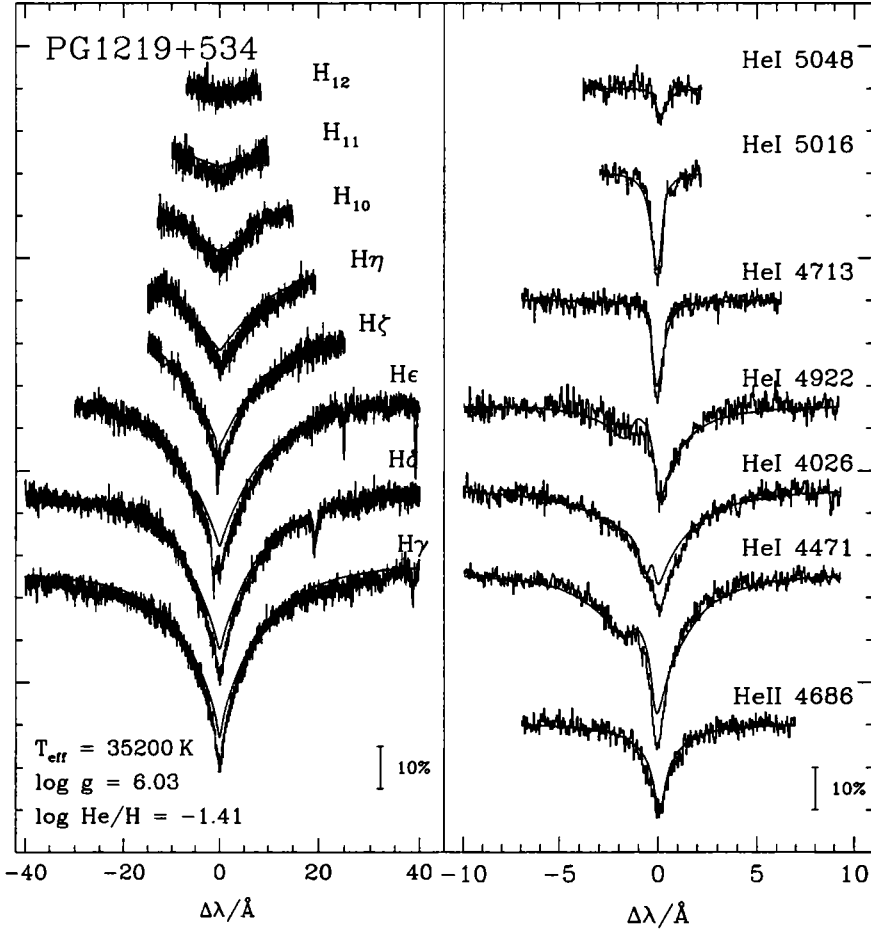


Fig. 3. Helium line profile fits for PG 1219+534 of the HIRES spectrum to determine T_{eff} and $\log(\text{He}/\text{H})$ simultaneously, $\log g$ is adjusted to match the Balmer line wings. Note the mismatch of the cores of the Balmer lines and of He I 4026 Å and 4471 Å.

5. ROTATION VELOCITIES

The spectral lines of PG 1605+072 are considerably broadened, which we attribute to stellar rotation and derive $v \sin i = 39 \text{ km/s}$, by fitting the strongest metal lines. In Fig. 5 we compare a section of the spectrum of PG 1605+072 to that of the Feige 48, which (like

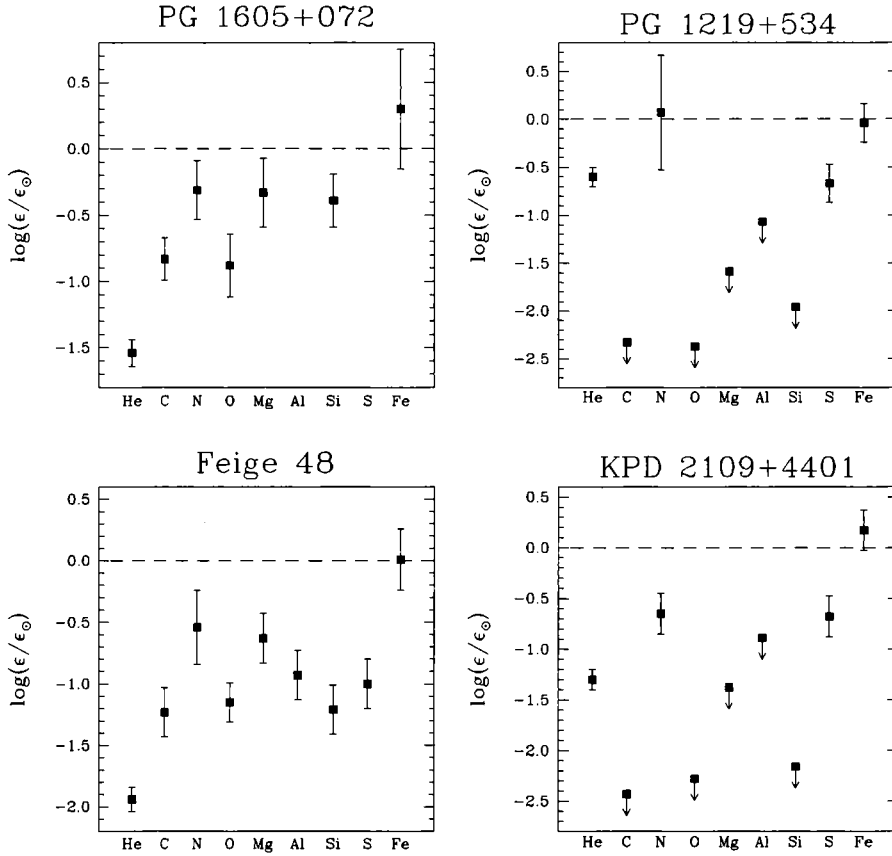


Fig. 4. Abundances of PG 1605+072 relative to the sun. Upper limits are denoted by arrows.

PG 1219+534 and KPD 2109+4401) are very sharp-lined ($v \sin i$; 8–10 km/s).

Assuming a mass of $0.5 M_{\odot}$ the radius of $R = 0.28 R_{\odot}$ for PG 1605+072 follows from the gravity. Since $\sin i$ cannot be constrained, the corresponding rotation period of PG 1605+072 must be smaller than 8.7 h. 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 multiplets, 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. Taken at face value a low inclination angle of 17 degrees results.

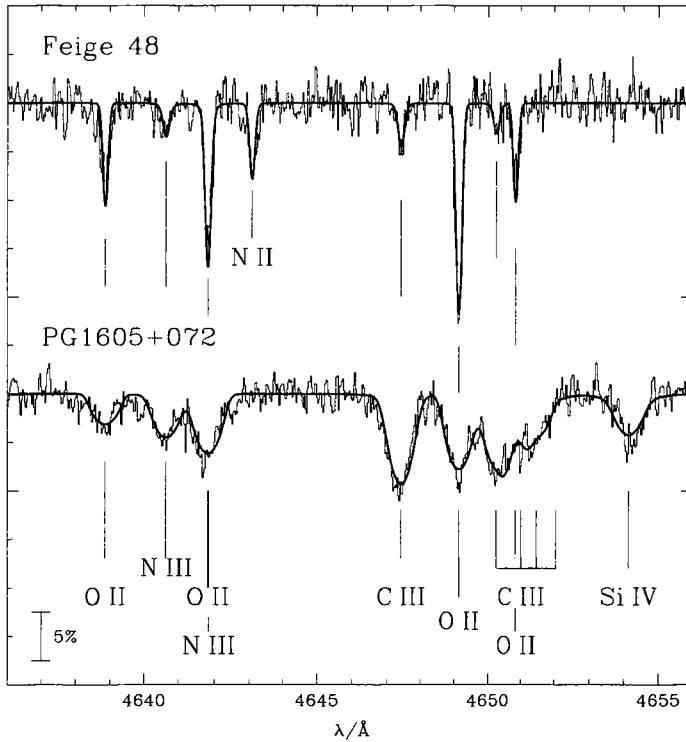


Fig. 5. Fit of a section of the metal-line spectrum of PG 1605+072, (bottom, $v \sin i < 39$ km/s) compared to that of Feige 48 (top, no rotation).

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 mostly very slow rotators (e.g. Heber et al. 1997, Koester et al. 1998).

ACKNOWLEDGMENT.

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