Time-series spectroscopy of pulsating sdB stars – III. Line indices of PG 1605+072

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ABSTRACT

We present the detection and analysis of line index variations in the pulsating sdB star PG 1605+072. We have found a strong dependence of line index amplitude on Balmer line order, with high-order Balmer line amplitudes up to 10 times larger than Hβ. Using a simple model, we have found that the line index may not only be dependent on temperature, as is usually assumed for oscillating stars, but also on surface gravity. This information will provide another set of observables that can be used for mode identification of sdBs.

Key words: stars: individual: PG 1605+072 – stars: interiors – stars: oscillations – subdwarfs.

1 INTRODUCTION

Subdwarf B (sdB) stars are hot, core-helium burning stars, with hydrogen envelopes that are too thin to sustain nuclear fusion. The discovery of multimode pulsations in some sdBs should allow the use of asteroseismology to probe their atmospheres, and thereby help to answer the many questions remaining concerning sdB formation and evolution.

Until recently, time-series observations of pulsating sdBs have been limited to photometry. We have shown that it is possible to detect radial velocity variations of Balmer lines in the pulsating sdB star PG 1605+072 using 2-m class telescopes (O’Toole et al. 2000, 2002, hereafter Papers I and II, respectively). 4-m class telescopes have also been used to detect velocity variations in sdBs (Jeffery & Pollacco 2000; Woolf, Jeffery & Pollacco 2002). In Paper II we found closely spaced peaks in the amplitude spectrum of PG 1605+072, and amplitude variation in at least one of these peaks. In this paper we describe the analysis of line-index variations of Balmer lines in PG 1605+072. The atmospheric parameters of this sdB have been determined from high-resolution optical spectra and non-local thermodynamical equilibrium (NLTE) model atmospheres to be T\textsubscript{eff} = 32 300 ± 300 K and log g = 5.25 ± 0.05 (Heber, Reid & Werner 1999). The helium abundance was found to be subsolar, i.e. log (He/H) = −2.53 ± 0.1. The star was also found to be rotating with a projected rotational velocity of 39 km s\textsuperscript{-1}. The use of equivalent widths of Balmer lines to monitor stellar oscillations of solar-type stars was first proposed by Kjeldsen et al. (1995). The Balmer lines are very temperature sensitive – the equivalent width of these lines depends on the number of hydrogen atoms in the second level. According to Kurucz (1979), the maximum line strength of H\textalpha to H\delta is between 8500 and 9000 K at log g = 4.0. Since the temperature changes slightly with the oscillations, the equivalent width must also change. The idea was extended by Bedding et al. (1996) to include metal lines. In this paper we calculate line indices, which depend on the temperature and surface gravity sensitivity of the equivalent widths of spectral lines. This method has been used to identify modes in the δ Scuti stars FG Vir (Viskum et al. 1998) and BN Cnc (Dall et al. 2002), and to detect equivalent-width oscillations in the H\alpha line of the roAp star α Cir (Baldry et al. 1999). Here we present the first detection of line index variations in a pulsating sdB star, namely PG 1605+072, and find a dramatic dependence of line-index amplitude on the Balmer line number. We show that a simple model can qualitatively explain this effect as a combination of temperature and surface gravity fluctuations.

2 OBSERVATIONS AND REDUCTIONS

In this paper we use the spectroscopic observations described in Papers I and II. Briefly, they consist of 16 nights in 2000 May using DFOSC on the Danish 1.54-m telescope in Chile, four nights overlapping this using ALFOSC on the NOT 2.56-m telescope and, to improve frequency resolution, a further ∼1 h night\textsuperscript{-1} for a month in 2000 March–April using DFOSC. We also have 10 nights of observations using DFOSC from 1999 July using the same setup, and two nights using the coudé spectrograph mounted on the Mount Stromlo 74-in telescope in Australia. Finally, we have 12 nights of Johnson B photometry from the South African Astronomical Observatory, also taken in 1999 July (see Paper I).

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As described in Papers I and II, reductions of the spectra were performed using standard IRAF routines for bias subtraction, flat-fielding and background light subtraction, and spectra were extracted using a variance weighting algorithm. A typical spectrum is shown in Fig. 1. For details of photometric reductions see, for example, Koen et al. (1997).

3 THE LINE INDEX

We measure the line index, a quantity that depends on the temperature and surface gravity sensitivity of the equivalent width. It is defined as

\[ \Lambda^l = \sum_x \frac{C_x - S_x}{C_x} W_x^l, \]

(Dall et al. 2002), where \( C_x \) is the continuum count level at pixel \( x \), \( S_x \) is the source count level and \( W_x^l \) is a Gaussian-like weighting function for the line in question. The value of \( C_x \) is found using

\[ C_x = \sum_x S_x W_x^C \sum_x W_x^C, \]

where \( W_x^C \) is a broad filter function and is also Gaussian-like. \( W_x^l \) is centred by moving an integration weight filter across the line in question. The position that maximizes the sum through this filter is taken as the line centre (Dall et al. 2002). The width of the function can be chosen arbitrarily; we have chosen the approximate full width at half maximum of each Balmer line, which means we use a different filter for each line.

Prior to calculating the line index, each spectrum was normalized to an average number of counts pixel\(^{-1}\) and divided by the local continuum. The line index was calculated by multiplying each Balmer line and the adjacent continuum by the weighting function (a super-super-Gaussian: \( e^{-x^4} \)), dividing the line by the average of the two continua, and then summing over the line. In this way, the line index can be thought of as being similar to the Strömgren H\(\beta\) index, calculated using software filters. (For a justification of the term ‘line index’ as an analogue to a colour index, see Dall et al. 2002.) The software for calculating line indices has been collected in a software package called \( x \), as described by Dall (2000).

3.1 Individual Balmer lines

We have calculated the line indices of all Balmer lines from H\(\beta\) to H\(9\). These values were normalized to a mean of zero and divided by the total mean to give the fractional change [i.e. we calculated \((\Lambda - \langle \Lambda \rangle)/\langle \Lambda \rangle\), where \(\langle \Lambda \rangle\) is the mean line index]. A sample line index curve (of H\(8\)) is shown in Fig. 2; the peak-to-peak scatter of the best quality data (from the NOT) is around 20 per cent. As in Papers I and II, the quality of the data varies from night to night, so we have weighted the Fourier transform using the internal scatter.

The amplitude spectra for the six Balmer lines from H\(\beta\) to H\(9\) is shown in Fig. 3. The left-hand column shows results for the 1999 data (Paper I), while the right-hand column shows the 2000 data (Paper II). An amplitude change is evident over the 300 d between observations, similar to that seen in velocity. Also, line-index amplitudes vary strongly with Balmer line number in both sets of observations. We now consider possible reasons for the latter effect.

3.2 Dependence of the amplitude of the Balmer-line order

Could the variation with Balmer line order seen in Fig. 3 be an artefact of our measurement technique? There are several factors we should consider.

First, in sdB stars the Balmer lines are broadened by temperature and gravity, so it is difficult to measure the continuum near high-order lines (\(n = 9–12\)), since it does not really exist in these regions. However, the amplitudes of the strongest peaks differ by approximately a factor of 3 between H\(\beta\) and He, and these lines have a good continuum, as seen in Fig. 1. Still, the wings of the Balmer lines are very broad in sdBs and are dominated by gravity effects, so we will investigate this ‘pseudo-continuum’ at high-order Balmer lines in Section 4.

A second explanation may be that the wings of the Balmer lines are oscillating out of phase with the cores. Since the wings extend out so far, they may be inadvertently sampled as part of the continuum and thereby boost the observed amplitude of line index change. We have determined the line index variation across each Balmer line at each of the frequencies in table 7 of Paper II. The phases at each frequency are constant when we examine different slices across the line, leading us to rule out this explanation.

4 A SIMPLE MODEL

To investigate the observed behaviour, we have used an H–He line-blanketed, metal-free NLTE model sdB spectra (Napiwotzki 1997) at \(\log g = 5.0, 5.25, 5.5\) and \(T_{\text{eff}} = 30 000, 32 500\) and 35 000 K. The helium abundance is fixed at \(\log (\text{He}/\text{H}) = -2.5\). A sample model is shown in Fig. 4. The calculations that follow were also carried out using metal line-blanketed LTE model sdB spectra with solar metallicity and Kurucz’ ATLAS6 opacity distribution functions (Heber,
Reid & Werner 2000), but since the basic conclusions are the same, we present only the NLTE results. A detailed discussion of NLTE versus LTE models can be found in Heber et al. (2000). In the following sections we will compare the line indices of Balmer lines in these spectra with those of our observations.

4.1 The effect of temperature

For most oscillating stars, it is usually assumed that variations are predominantly caused by temperature changes, and that radius changes (and hence surface gravity changes) are negligible (e.g.
Kjeldsen et al. 1995). In this case, the oscillation amplitude in line index is related to the temperature fluctuations by the relation

\[ \frac{\delta \Lambda}{\Lambda} = \frac{\partial \log \Lambda}{\partial \log T} \frac{\delta T}{T}. \]  

For cool stars \( \partial \log \Lambda/\partial \log T \) is positive, but for hot stars such as sdBs, it is expected to be negative. (Note that for A stars it is approximately zero.) To investigate the behaviour of the line index with varying temperature for each Balmer line, we show in Fig. 5 both \( \Lambda \) and \( \partial \log \Lambda/\partial \log T \) as a functions of temperature. Here we have used LTE models with a larger range of effective temperatures and the surface gravity fixed at \( \log g = 5.5 \). Prior to calculating the line indices, we rebinned the model spectra to the approximate dispersion of our observed spectra and multiplied these spectra by a typical continuum from the NOT observations. We also used exactly the same parameters in our line index software for both models and observations.

Fig. 5 is similar to fig. 2 of Bedding et al. (1996), which was made for cooler main-sequence stars. An important difference is the scale of change of the line index with temperature. For cool main-sequence stars there is a factor of 3 difference over around 1000 K for H\( \beta \), while for our sDB models, the difference for H\( \beta \) is approximately a factor of 2 over 20 000 K. The line index of all Balmer lines except H9 and H10 seems to converge at approximately 40 000 K, although without modelling beyond this temperature we cannot be certain (and \( \sim 40 000 \) K is the upper limit of the sDB regime anyway). As is expected, the change in line index with temperature is negative, that is, the line index of hotter sDBs is smaller.

To investigate the 'pseudo-continuum' idea suggested in Section 3.2, we rebinned our NLTE model spectra to the approximate dispersion of our observed spectra and again multiplied the resultant spectra by a typical continuum from the NOT observations. Our goal was to use a model that was as close to the observations as possible. We calculated line indices for each of our models, once again using the same parameters as for the observations. To simulate oscillations, we took the difference between the line index of each model Balmer line at each of the different temperatures listed above. The surface gravity of the models was fixed at \( \log g = 5.5 \). The change in line index, \( \Delta \Lambda \), is approximately linearly proportional to the change in temperature \( \Delta T_{\text{eff}} \). Because of this relationship, we can scale the line index 'amplitude' to a more realistic value of \( \Delta T \). We chose \( \Delta T \sim 500 \) K, which is an order-of-magnitude estimate based on photometric amplitudes. Finally, we normalized these differences by the line index values at 32 500 K (the approximate effective temperature of PG 1605+072), allowing us to compare fractional changes directly with our observations.

The model line-index amplitude is plotted as the dashed line in Fig. 6. Also shown is the line-index amplitude of the 2742.85-\( \mu \)Hz peak from the 2000 March–May observations. Both model and observations show an upward trend moving to bluer wavelengths, but the amplitudes do not match. A similar result is seen for each of the other frequencies in table 7 of Paper II. Clearly, then, these unusual variations depend on more than just temperature, particularly for the higher-order Balmer lines. We now consider the effect of changing surface gravity and temperature.

4.2 Add gravity and stir

Here we assume that the relationship between change in surface gravity and change in line index is similar to equation (2), and that we can use the simple formula

\[ \log g = \text{...} \]

Figure 4. Model sDB spectrum with \( T_{\text{eff}} = 32500 \) K and \( \log g = 5.25 \), used to determine line index variations. The continuum is based on a typical NOT spectrum. Flux is in arbitrary units.

Figure 5. LTE model line index, \( \Lambda \) (top panel) and its derivative \( \partial \log \Lambda/\partial \log T \) (bottom panel), both as a function of effective temperature. The symbols have the following meaning: diamonds, H\( \beta \); triangles, H\( \gamma \); squares, H\( \delta \); crosses, He; open circles, H\( \delta \); stars, H9; filled circles, H10.

Figure 6. Line index of the highest peak (2742.85 \( \mu \)Hz) in the 2000 amplitude spectrum compared with a simple model with temperature variations of \( \sim 500 \) K (dashed line).
\[ \frac{\Delta \lambda}{\lambda} = \left( \frac{\Delta \lambda}{\lambda} \right)_{T_{\text{eff}}} + \left( \frac{\Delta \lambda}{\lambda} \right)_{\log g} \]  

(3)

to combine the effects of \( T_{\text{eff}} \) and \( \log g \). The first term on the right of equation (3) is the line index at fixed \( T_{\text{eff}} \), and the second term is at fixed \( \log g \). This linearity assumes that the oscillations are adiabatic, which implies that \( T_{\text{eff}} \) and \( \log g \) are in phase.

We show \( \lambda \) and \( \partial \log \lambda / \partial \log g \) as functions of \( \log g \) in Fig. 7. The important thing to note concerning this figure is that the line index of low-order Balmer lines stays roughly constant with \( \log g \), while for the higher-order lines the line index decreases dramatically. This is related to the pseudo-continuum effect discussed earlier. The implication of Figs 5 and 7 is that line index amplitudes should be highest for higher-order Balmer lines, which is what we see. We can now try to quantify this effect.

Using a similar method to that used for temperature changes above, but keeping \( T_{\text{eff}} \) fixed at 32 500 K, we have calculated the approximate effect of changing \( \log g \). To fit the combination of these effects, we minimized the rms scatter of the difference between observations and the model. The best-fitting combination of the temperature and surface gravity effects is shown in Fig. 8. The fit appears to be, in general, very good, although there is some discrepancy at H10. For this frequency, we find that \( \Delta T \sim 372 \text{ K} \) and \( \Delta \log g \sim 0.047 \). Whether or not these values are reasonable will be discussed in the next section.

Assuming that this method is valid, we have determined the temperature and surface gravity changes for each frequency in table 6 of Paper II, and the frequencies measured from the 1999 observations (table 5 of Paper II), and these are shown in Table 1. The velocity amplitudes derived in Paper II are shown in the final column. The uncertainties in both \( \Delta T_{\text{eff}} \) and \( \Delta \log g \) were found by fixing one of the \( (\delta \lambda / \lambda) \), and changing the other until the rms increased by the mean error of the measured line index amplitudes. We have reperformed our calculations, including the effects of rotation (\( v \sin i = 39 \text{ km s}^{-1} \) for PG 1605+072; Heber et al. 1999), and find that the values in Table 1 remain the same to within 0.1 per cent.

In Fig. 9 we show \( \Delta T \) as a function of \( \Delta \log g \) for both sets of observations, with 1σ error ellipses determined from linear regression. Most of the points lie on or near the straight line. The slope of the line is 8471 K dex\(^{-1}\). This can be compared with future models. If there is linearity, it would be consistent with all modes having the same \( l \) value. Modelling by Kawaler (1999) found four modes to be \( l = 1 \) and one to be \( l = 2 \). We have detected four of the five modes predicted by Kawaler, including the mode predicted to be \( l = 2 \) (around 2102 \( \mu \text{Hz} \)). In Fig. 9, this mode appears to lie on the same line as the other modes. Further modelling is required to determine whether this is inconsistent with Kawaler’s model.

## 5 DISCUSSION

While the model of line index oscillations we have presented here is crude, it appears to explain the observations quite well. We now must consider whether the changes in temperature and surface gravity we determined are reasonable.

### 5.1 Temperature changes

We can use the Johnson \( B \) photometry presented in Paper I to test the plausibility of the temperature changes we have calculated.
The amplitude is 3.2 per cent, implying that ($\sim$) (Paper I). The radius change is 0.9 per cent: +0.72, assuming radial modes, the radius change is 0.1 per cent. PG 1605 is consistent with the value of 560 K shown at the bottom of Table 1. This leads to a temperature change of +490 K, which is roughly equal to 30 per cent larger than those calculated from velocity by at least a factor of 5.

\[ \frac{\delta L}{L} = \frac{\delta L}{L} \lambda \lambda_{bol}, \]  
\[ \lambda_{bol} = \frac{hc}{kT_{bol}}. \]

Equation (4) is a linearized expression, assuming the star is radiating as a blackbody. We have derived the exact form of this equation, where we also allow for the radius change in the star (in PG 1605+072, assuming radial modes, the radius change is 0.1–0.9 per cent): 

\[ \frac{\delta L}{L} = \left[ \frac{\delta L}{L} \lambda - \frac{2\delta R}{R} \right] \lambda (1 - e^{-\lambda_{bol}/\lambda}) + 2 \frac{\delta R}{R}. \]

As an example, consider the 2102.15-µHz mode in our 1999 data (Paper I). The radius change is $\sim$0.9 per cent and the photometric amplitude is 3.2 per cent, implying that ($\delta L/L_{bol}$) $\sim$ 10 per cent. This leads to a temperature change of $\sim$ 490 K, which is roughly consistent with the value of 560 K shown at the bottom of Table 1. The temperature changes from photometry for the other modes from Table 1 are also of approximately the same order of magnitude as those determined from the line index. We conclude from this that the temperature values we have derived are the correct order of magnitude.

### 5.2 Surface gravity variations

It is possible that we are measuring changes in the effective surface gravity rather than the true surface gravity. The effective surface gravity is a combination of the true surface gravity and other forces acting on the stellar photosphere. In order to test whether we are measuring true surface gravity variations, we have calculated the radius change expected from the best-fitting variation in surface gravity at each frequency. These changes are shown in Table 2, along with the radius changes calculated from velocity amplitudes, assuming all modes are radial. The difference between the radius change for a radial and non-radial mode is a scaling factor that is dependent on the inclination angle and limb darkening. For example, with no limb darkening and with the star pole on, an $l = 1$, $m = 0$ mode will have an apparent radius change $\sim$30 per cent larger than an $l = 0$ mode with the same frequency, while an $l = 2$, $m = 0$ mode will have a radius change $\sim$10 per cent smaller (Christensen-Dalsgaard 1994). Bedding et al. (1996) presented an analysis for solar-like stars that also considered limb darkening. They found that the mode sensitivity of the line index of Balmer lines is similar to that of Balmer-line velocity.

All of the values of $\Delta R/R$ calculated from the log g changes are larger than those calculated from velocity by at least a factor of 5. A more realistic interpretation of the line index measurements requires sophisticated models. Phase-dependent synthetic spectra need to be calculated that also account for limb darkening and rotation. As a prerequisite for such model spectra, the time-dependent surface distribution of $T_{bol}$, log g and the velocity field have to be determined. Townsend (1997) has developed such a program (BRUCE) for the analysis of pulsations in rotating hot massive stars. Falter (2001) recently wrote a program for modelling synthetic spectra of sdB stars from BRUCE output that shall be used to analyse the line index variations. A much larger data set has been acquired in 2002 May/June by a spectroscopic and photometric multisite campaign, which became known as the MultiSite spectroscopic telescope (MSST, Heber et al. 2003). We will use the more detailed modelling when we analyse this much larger data set.

However, we may also have to check the validity of the hydrostatic approximation. Jeffery, Wolff & Pollacco (2001) encountered a similar problem in the analysis of the extreme helium star V652 Her; for this radially pulsating star the discrepancy between radii derived from surface gravity and spectrophotometry is approximately a factor of 2. They found that at least for 10 per cent of the pulsation cycle of this star the assumption of hydrostatic equilibrium is not valid, owing to shocks moving through the atmosphere. For PG 1605+072 the speed of sound is more than twice as large as for V652 Her owing to its different chemical composition. A study of such effects is beyond the scope of this paper and should be performed after the more detailed hydrostatic spectral analysis outlined above has been carried out.

| Year | Frequency (µHz) | ($\Delta R/R$)$_{\log g}$ (per cent) | ($\Delta R/R$)$_{vel}$ (per cent) |
|------|----------------|------------------------------------|-----------------------------------|
| 2000 | 2742.85        | 5.41                               | 0.44                              |
|      | 2742.47        | 3.22                               | 0.27                              |
|      | 2102.83        | 2.07                               | 0.29                              |
|      | 2102.48        | 4.84                               | 0.68                              |
|      | 2101.57        | 1.27                               | 0.27                              |
|      | 2075.72        | 2.65                               | 0.35                              |
|      | 1985.75        | 1.50                               | 0.35                              |
|      | 1891.01        | 1.04                               | 0.18                              |
| 1999 | 2742.63        | 5.87                               | 0.36                              |
|      | 2102.15        | 7.14                               | 0.90                              |
|      | 2075.29        | 2.07                               | 0.20                              |
|      | 1890.98        | 0.35                               | 0.28                              |
6 CONCLUSIONS

We have detected line index variations in the pulsating sdB star PG 1605+072. There is a strong dependence of the line-index oscillation amplitude on the Balmer line. We have developed a simple model, assuming hydrostatic equilibrium, where we use model spectra at as close to the same resolution and sampling of the observations as possible. Using this model, we have shown that despite not measuring true equivalent width variations, we can use the observables to infer effective temperature and effective surface gravity variations in PG 1605+072.

Using more detailed models, we should be able to measure the $\Delta T$ and $\Delta \log g$ independently of photometry and velocity measurements. With this information, we will have another set of amplitudes that we can use for mode identification of sdB stars.

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