TIME SERIES SPECTROSCOPY OF PULSATING SUBDWARF B STARS: PG 1605+072

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ABSTRACT

We report the detection of velocity variations in the pulsating subdwarf star PG 1605+072. Oscillations are detected at the same frequencies found from photometry and have amplitudes of up to 14 km s⁻¹ for Hβ. The strongest oscillation found in previous photometric observations is not evident in our spectroscopy or photometry, and it may be absent because of the beating of closely spaced modes. Phase differences between spectroscopy and B-magnitude photometry imply that maximum brightness occurs not long after maximum radius. We have also found evidence of variation in the observed amplitudes of five Balmer lines, with a decrease in the amplitude of the strongest mode blueward from Hβ. This effect is not expected, and a longer time series will be needed to clarify it.

Subject headings: stars: interiors — stars: oscillations — subdwarfs

1. INTRODUCTION

The discovery of a class of pulsating hot subdwarfs (sdBs; Kilkenny et al. 1997) has created an interest in the asteroseismology of evolved stars. Subdwarfs are believed to lie on the extreme horizontal branch (Saffer et al. 1994), although their formation and evolution are still uncertain. Pulsations in sdB stars were predicted theoretically by Charpinet et al. (1996) just prior to their discovery, and about 20 pulsators have been discovered to date using time series photometry (see Koen et al. 1999 for a review). The stars (also known as EC 14026 stars, after the prototype) are believed to pulsate in p-modes and typically have periods of 100–200 s and semiamplitudes less than 10 mmag. Models indicate that an opacity bump associated with iron ionization may be the driving mechanism of the pulsations (Charpinet et al. 1996, 1997), although recent studies by Koen et al. (1999) find no well-defined instability strip in the (log g, T_eff)-plane.

Combining time series photometry with time series spectroscopy should help us to understand better the pulsations in these stars. We have shown the feasibility of time series spectroscopy with observations of PG 1605+072 on a 1.5 m telescope over 2 hr (O'Toole et al. 2000). Jeffery & Pollacco (2000) made similar observations of KPD 2109+4401 (5 hr) and PB 8783 (6 hr) using the 4.2 m William Herschel Telescope. In all three cases, velocity variations were detected at the published photometric frequencies. However, sdB stars are multimode pulsators, and longer time series are needed to resolve the individual modes and measure their amplitudes. We present here the first extended time series spectroscopy of a pulsating sdB star.

Our target was PG 1605+072, which has the most extreme properties of all the pulsating sdBs detected so far, with high amplitudes (up to ~25 mmag) and long periods (~500 s). Because of its low gravity (log g ~ 5.25), this star is believed to have evolved off the horizontal branch and may oscillate in g- as well as p-modes (Kilkenny et al. 1999). The power spectrum is complex, with up to 55 identifiable frequencies. PG 1605+072 displays considerable rotation (v sin i ~ 39 km s⁻¹), possibly leading to unequally spaced multiplet components (Heber, Reid, & Werner 1999). Unlike several of the pulsating sdBs, multicolor photometry gives no indication of a cool companion (Koen et al. 1998).

2. OBSERVATIONS

We obtained medium-resolution spectra of PG 1605+072 using the Danish Faint Object Spectrograph and Camera on the Danish 1.54 m telescope at La Silla, Chile, and the coude spectrograph (A grating) on the 74 inch (1.88 m) telescope at Mount Stromlo, Australia. The observations were made on seven nights over an 11 day period in 1999 July and August (see Table 1). To supplement the spectroscopy, we obtained time series photometry at the Sutherland site of the South African Astronomical Observatory (see Table 2).

The La Silla data consisted of single-order spectra projected onto a 2k Loral CCD—pixel-binning (to reduce readout noise) and windowing (to reduce readout time) gave 66 × 500 pixel spectra with a total wavelength range of 3700–5000 Å and a dispersion of 1.65 Å pixel⁻¹. The resolution was 2.8 Å, set by a slit width of 1.5. The exposure time was 46 s, with a dead time of about 15 s. The average number of photons per angstrom unit in each spectrum was about 22000.

The Mount Stromlo data consisted of single-order spectra projected onto a SiTe 2k × 4k CCD, with a wavelength range of 3800–5000 Å. The slit width was ~4", and the dispersion was 0.60 Å pixels⁻¹, leading to a resolution similar to that of the La Silla data. The exposure time was 50 s, with a dead time of around 25 s.

The photometry from Sutherland was taken using the Modular Photometer with a Johnson B filter and exposure times of 20 s. The GaAs photomultiplier tube in this photometer has a good red sensitivity, and using the blue filter causes the pass-

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1 Based on observations made with the Danish 1.54 m telescope at ESO, La Silla, Chile, from the South African Astronomical Observatory, and from Mount Stromlo Observatory, Australia.
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band to resemble that of a blue-sensitive photomultiplier tube (O’Donoghue et al. 1998).

3. REDUCTIONS

Standard methods for bias subtraction, flat-fielding, and background-scattered light subtraction were used. Nonlinearities on the CCD image were only important in the Mount Stromlo data and were corrected immediately after bias subtraction (see Baldry et al. 1998). One-dimensional spectra were extracted using the optimal extraction method (Horne 1986), a variance weighting system for CCD columns. A third-order polynomial was fitted to the continuum level in both data sets, and the spectra were normalized to a continuum value of unity.

The spectrum of PG 1605+072 is dominated by Balmer lines (see, e.g., Fig. 9 of Koen et al. 1998). A cross-correlation technique was used to determine the Doppler shift for five Balmer lines (Hβ, Hγ, Hδ, Hε, and H8), relative to a template spectrum (the average of 20 high-quality spectra). The spectra and template were prepared in the manner described by Baldry et al. (1998). It should be noted that the time series for Hγ does not contain any Mount Stromlo data because that line was contaminated by a bad CCD column.

Several jumps were found in each time series, particularly in the La Silla data, occurring every 30–40 observations, corresponding to breaks in which the He + Ne calibration spectra

| UT Date   | Site | Number of Hours | Number of Spectra |
|-----------|------|-----------------|-------------------|
| Jul 23–4  | LS   | 4.01            | 210               |
| Jul 24–5  | LS   | 1.91            | 105               |
| Jul 25–6  | LS   | 5.46            | 280               |
| Jul 26–7  | LS   | 5.12            | 280               |
| Jul 30–1  | LS   | 5.09            | 260               |
| Jul 31    | LS   | 5.23            | 280               |
| Aug 1     | MS   | 3.30            | 155               |
| Aug 1–2   | LS   | 4.92            | 280               |
| Total     |      | 38.65           | 2018              |

a LS = La Silla; MS = Mount Stromlo.

Fig. 1.—Combined raw Hβ velocity and Johnson B light curve for PG 1605+072. The velocity points (in units of kilometers per second) are denoted by large dots, while the photometry points are denoted small dots. Photometry in this Letter is presented in “millimodulation units” (mmu), where the light curve is normalized by its own mean level (see Kilkenny et al. 1999). Observations were made on JD 2,451,380–2,451,393 (see Tables 1 and 2). Note that positive velocity is redshifted by definition.
TABLE 2
Photometric Observations of PG1605+072 Taken at the Sutherland Site

| UT Date (1999) | Number of Hours | Number of Observations |
|---------------|-----------------|------------------------|
| Jul 20        | 3.93            | 666                    |
| Jul 21        | 1.07            | 182                    |
| Jul 23        | 4.17            | 679                    |
| Jul 24        | 1.27            | 211                    |
| Jul 28        | 3.77            | 597                    |
| Jul 29        | 1.19            | 199                    |
| Jul 31        | 1.24            | 210                    |
| Aug 1         | 2.80            | 454                    |
| Total         | 19.44           | 3198                   |

were taken. We decided to process each of these groups separately with a template spectrum created for each group. In removing the jumps, we have effectively high-pass–filtered the data set, thus removing any instrumental drifts present.

The photometric data were reduced by subtracting the sky background, correcting for atmospheric extinction, and normalizing to the mean intensity of the run, following a method similar to O’Donoghue et al. (1997, 1998). Slow drifts were not corrected for in the photometry.

The Hβ velocity curves and B-magnitude light curves for each night of observations are shown in Figure 1. Oscillations are not as evident in our velocity curve as they are in the light curve since the signal-to-noise ratio per measurement is lower.

As is common with time series measurements, the quality of the data varies considerably through the data set. We therefore performed the frequency analysis using a weighted Fourier transform, in which the weights were assigned according to the local rms scatter (Kjeldsen & Frandsen 1992).

4. RESULTS AND DISCUSSION

The amplitude spectra of Hβ and Hγ are shown in the top two left panels of Figure 2. The white-noise level is 1.07 km s\(^{-1}\) for Hβ and 0.93 km s\(^{-1}\) for Hγ. Oscillations are clearly visible at 2102 and 2743 \(\mu\)Hz (2742.72 \(\mu\)Hz in Kilkenny et al. 1999) in both lines but at 1891 \(\mu\)Hz (1891.42 \(\mu\)Hz) only in Hγ. Because of possible beating between closely spaced modes, it is unclear whether this last effect is due to the low amplitude of the mode in Hβ. The bottom two left panels of Figure 1 show our B-magnitude and white-light amplitude spectra (from a 15 day multisite campaign by Kilkenny et al. 1999 in 1997 May; white-light observations were obtained using a CuSO\(_4\) filter), respectively, and are included for comparison. The three modes previously mentioned are all present in the B-magnitude spectrum. We believe that the highest amplitude peak (14 km s\(^{-1}\) for Hβ) at 2102 \(\mu\)Hz may be a combination of the 2101.65
and 2103.28 $\mu$Hz frequencies found by Kilkenny et al.—a longer time series is needed to clarify this.

The panels on the right in Figure 2 show the 2050–2150 $\mu$Hz region in greater detail. The highest amplitude mode found by Kilkenny et al. at 2075.76 $\mu$Hz is not present in any of our observations. It is not clear whether this is due to the variation in amplitudes over the 2.2 yr between observations or to the beating between very closely spaced modes.

The $B$-magnitude and white-light amplitudes differ by around 40%, which is to be expected in such hot blue stars, considering that the effective wavelength of white light is redder than the $B$ band. If the oscillation phase is wavelength-dependent, then this would also reduce the amplitude in white light (which is a much broader “band” than $B$).

4.1. Oscillation Amplitudes

In this Letter, we present a qualitative comparison of luminosity and velocity amplitudes. All amplitudes were measured by the height of their peak. A more detailed quantitative study will be the subject of a subsequent paper.

Kjeldsen & Bedding (1995) derived a relationship between luminosity amplitude at a given wavelength and velocity amplitude for classical and solar-like oscillations. Using their scaling law, which assumes a blackbody spectrum and adiabatic oscillations, we find that the velocity amplitudes in PG 1605+072 are 2–3 times lower than expected. However, a blackbody and adiabatic assumption is far from valid in such a hot star when one is considering visual amplitudes. In a pure adiabatic assumption, there is a 180° phase difference between temperature and stellar radius (with maximum brightness coinciding with minimum radius). For the mode at 2.742 mHz (which does not appear to be contaminated by closely spaced modes), we find a phase difference of $-75^\circ \pm 10^\circ$, which implies that the maximum brightness comes slightly after the maximum radius. More data are needed to clarify this result.

There is evidence to suggest that the velocity amplitude is wavelength-dependent. Figure 3 shows that the amplitude of oscillations at two frequencies decreases blueward of H$\beta$. The amplitude of H$\beta$ is almost 25% smaller than that of H$\beta$. If confirmed, this would be puzzling, given that all the Balmer lines are formed in the same part of the atmosphere.

5. CONCLUSIONS

The results presented here show that times series spectroscopy of sdBs can be done using a medium-size (1.5 m) telescope. We have detected oscillations in velocity at previously published photometric frequencies. A longer times series would allow most of the closely spaced modes in PG 1605+072 to be resolved and thus would help us to confirm the variation of velocity amplitude with wavelength. Further studies may also determine whether the amplitudes of modes in this star are variable over time or whether the apparent shift in primary pulsation mode is due to beating. We will also examine the behavior of the equivalent width and other line profile variations.

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