Baltic Astronomy, vol. 15, 291–300, 2006.

LONG-PERIOD VARIABLE SUBDWARF B STARS: PROSPECTS FOR ASTEROSEISMOLOGY

S. K. Randall[1], G. Fontaine[1], E. M. Green[2], P. Brassard[1] and D. M. Terndrup[3]

[1] *Département de Physique, Université de Montréal, C.P. 6128, Succ. Centre-Ville, Montréal, Québec, H3C 3J7, Canada*

[2] *Steward Observatory, University of Arizona, Tucson, AZ 85721, U.S.A.*

[3] *Department of Astronomy, Ohio State University, 140 West 18th Avenue, Columbus, OH 43210, U.S.A.*

Received 2005 August 1

Abstract. We summarize the results of an extensive study aimed at quantitatively interpreting the oscillations detected in long-period variable subdwarf B stars. Our analysis is based on between 300 and 400 hours of time-series photometry obtained for each of three representative targets: PG 1627+017, PG 1338+481 and PG 0101+039. The former two were the subjects of extensive multi-site campaigns led from the 1.52 m Steward Observatory telescope on Mt. Bigelow, Arizona, while the latter was observed with the 0.15 m Canadian space telescope MOST. We find that, unlike the short-period oscillators, where asteroseismology has been successful in some instances, our understanding of the slow pulsators is somewhat limited due to both observational and conceptual challenges. In particular, the period spectra measured to date are much sparser than those anticipated from models, implying that the indices of the modes observed must be constrained from the outset if asteroseismology is to be achieved. One promising idea is the exploitation of a mode's color-amplitude dependence on its degree index ℓ through multicolor photometry. Applying that method to the PG 1338+481 data together with other constraints suggests the excitation of $\ell = 1$ modes. If confirmed, this would point to a discrepancy between the observed and predicted long-period variable subdwarf B star instability strips of around 7000 K on the blue side, although some of it could be due to incorrect spectroscopic determinations of the effective temperatures of cool sdB stars.

Key words: stars: EHB and post-EHB, variable: general – stars: subdwarfs

1. INTRODUCTION

Pulsating subdwarf B (sdB) stars can be divided into two groups: the rapidly oscillating EC 14026 stars (Kilkenny et al. 1997) and the long-period variable PG 1716 stars (Green et al. 2003). At effective temperatures between 29 000 K and 36 000 K, the rapid oscillators correspond to the hotter of the two classes and excite both radial and low-degree non-radial pressure modes with typical periods in the 80–500 s range. Their instabilities are thought to be driven by a classical kappa mechanism associated with a local overabundance of iron, which in turn depends on the competitive actions of gravitational settling and radiative levitation (Charpinet et al. 1996). Indeed, models taking into account diffusion processes and the resulting non-uniform iron abundance profile have been very successful at predicting the observed EC 14026 instability strip on the HR diagram as well as the range of periods excited for a given object (see Fontaine et al. 2006 for details). Beyond this, quantitative period matches leading to mode identification and asteroseismological estimates of key stellar parameters have been possible in a few instances (see Charpinet et al. (2006) for details).

In comparison, the study of the long-period variables is still in its infancy. Found at cooler temperatures in the 22 000 K to 29 000 K range, these stars exhibit brightness variations on a typical timescale of 1–2 hours, immediately implying high radial order gravity modes. While the driving mechanism is believed to be the same as for the EC 14026 stars (Fontaine et al. 2003), the vast majority of current PG 1716 models can excite only modes with degree indices $\ell \geq 3$, the observability of which is controversial due to cancellation effects when integrating over the visible disk of the star. However, discrepancies between the observed and predicted instability strips have been difficult to quantify due to a lack of data. Unlike the EC 14026 stars, where just a few nights of photometry can be sufficient to identify enough periods for asteroseismology, the long-period variables need to be monitored over the course of weeks or even months to yield a comparable number of periodicities. Extracting the observed frequency spectrum is further complicated by severe aliasing effects and the fact that atmospheric variations occur on a similar timescale as the stellar oscillations. These observational challenges notwithstanding, the detailed study of long-period variable subdwarf B stars could prove invaluable to our understanding of post-main sequence stellar evolution. In contrast to the shallow pressure modes observed in the EC 14026 pulsators, the slow oscillators' gravity modes probe deep within the star and are sensitive to the exact composition of the CO/He core. Successful asteroseismology of the latter would thus hold implications for the core helium burning phase not only of subdwarfs, but of other evolved stars as well.

In what follows, we present the results of an ambitious observational campaign aimed at measuring and quantitatively interpreting the period spectra of three representative slowly oscillating subdwarf B stars. We begin with an account of the observing runs and the frequencies extracted before comparing our findings to qualitative non-adiabatic and quantitative adiabatic predictions. We then outline the steps taken towards asteroseismical modeling and note the implications of our preliminary results.

2. OBSERVATIONAL PROGRAM

2.1. PG 1627+017

At atmospheric parameters $T_{\rm eff} \sim 23\,700$ K and $\log g \sim 5.32$ (Green, Fontaine and Chayer, in preparation), PG 1627+017 is one of the coolest subdwarf B stars known. It was chosen as a first observational target because of its brightness ($V \sim 12.9$), relatively high-amplitude pulsations, and an equatorial location vital to the success of our multi-site collaboration. While the majority of the data were gathered at the 1.52 m Steward Observatory telescope on Mt. Bigelow, Arizona, between 2003 May 9 and 2003 June 11, the time coverage and baseline

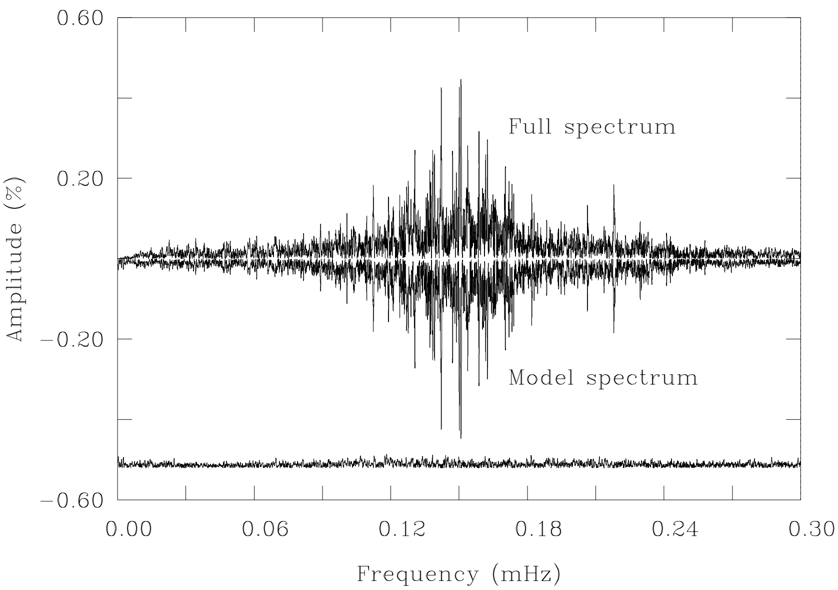

Fig. 1. Fourier transform for PG 1627+017.

were improved by simultaneous observing time granted on the 1 m telescope of the South African Astronomical Observatory and the 2.3 m telescope of the Siding Spring Observatory (Australia), as well as by weekend runs at Mt. Bigelow in the weeks leading up to the main campaign. Our efforts yielded a total of 303 hours of useful R-band photometry with a duty cycle of 33% over the five week period. Some spectroscopy was also obtained with the aim of recovering the main peaks from radial velocity shifts (see For et al. 2006 for details). The Fourier transform of the entire photometry light curve is shown in Figure 1, mirrored by a model spectrum (upside down) constructed on the basis of 23 extracted periodicities with amplitudes of at least three times the noise level. The residual between the observed and modeled spectra is displayed at the bottom of the figure.

All 23 periods detected in the light curve of PG 1627+017 lie in the 4500-9000 s range and have R-band amplitudes between 0.3 and 0.5 % of the star's mean brightness. Note that their distribution in frequency space is non-uniform, with the most powerful oscillations clustering between 6300–7050 s and several very closely spaced doublets and triplets occurring throughout the period spectrum. The latter may partially be explained by rotational splitting. PG 1627+017 forms part of a close binary system and, assuming a binary-synchronous rotation rate, spins on its axis with a period of $P_{\rm rot} = P_{\rm bin} \sim 0.83$ days (Morales-Rueda et al. 2003). The resulting break in spherical symmetry lifts the $(2\ell+1)$-fold degeneracy of a mode with given radial order k and degree index ℓ, introducing a dependence on the azimuthal index m. To first order, the components of a (k,l) mode with adjacent values of m are then separated by a frequency spacing $\Delta f = (1 - C_{k\ell})/P_{\rm rot}$, where for the high radial order gravity modes encountered in PG 1716 stars $C_{k\ell} \sim 1/(\ell(\ell+1))$. These equations imply that, in theory, rotational splitting can be exploited to determine the degree indices of the modes observed. However, in the case of PG 1627+017 the frequency spectrum uncovered is too dense to allow the unambiguous identification of a given peak, as is shown in Figure 2. While

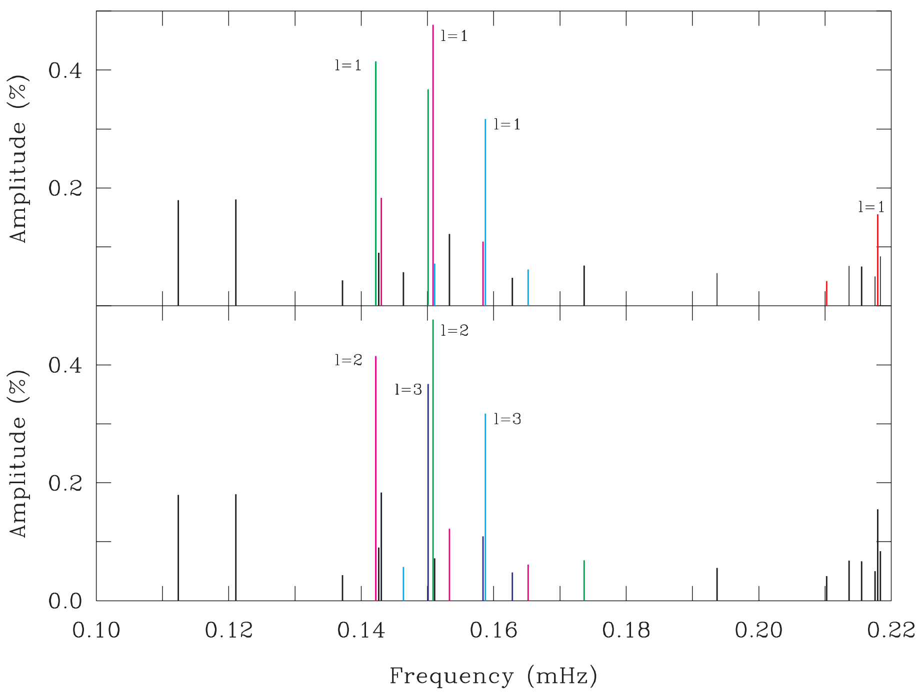

Fig. 2. Two possible manifestations of rotational splitting for PG 1627+017, depending on the degree indices invoked. Peaks illustrated in the same color refer to modes with the same values of ℓ and k but different m. The values of ℓ shown are derived from the frequency spacing between split components.

the scenario invoking modes with $\ell = 1$ (upper panel) seems more convincing, the possibility of explaining the observed period distribution in terms of $\ell = 2$ and $\ell = 3$ modes (lower panel) cannot be ruled out. It is thus unclear not only what degree indices the modes observed are associated with, but also which of the peaks detected are independent stellar pulsations, and which are rotational in nature. This makes asteroseismology and mode identification challenging, if not impossible.

2.2. PG 1338+481

Our second target, PG 1338+481 (V ∼13.6), is a much more typical long-period variable in terms of atmospheric parameters at $T_{\rm eff} \sim 28\,400$ K and $\log g \sim 5.40$ (Green, Fontaine and Chayer, in preparation). It was chosen for its representative qualities as well as the fact that it is a single, and thus probably slowly rotating, star. Observational efforts were conducted between 2004 March 15 and May 3 and focussed on just two sites: the 1.52 m Steward Observatory telescope employed during the previous campaign and the 1.3 m MDM telescope at Kitt Peak. In total, we obtained ∼250 hours of simultaneous U- and R-band photometry, as well as an additional ∼70 hours of R-band data. The resulting Fourier transforms are displayed in Figure 3 for both the U (blue) and the R (red) light curves. It is evident that, while the amplitudes in the U are significantly higher than those in the R, the oscillations are locked in frequency and phase. This

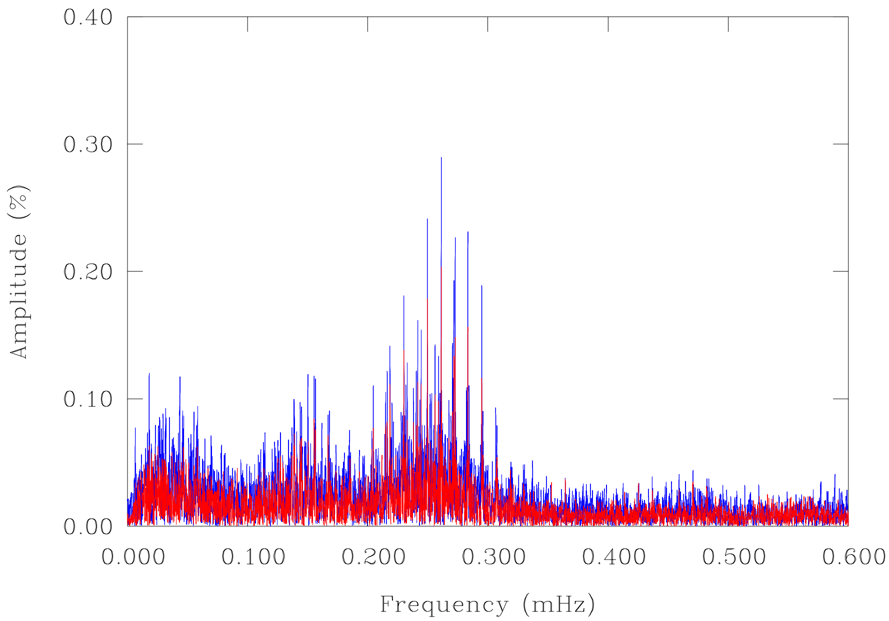

Fig. 3. U (blue) and R (red) band Fourier transforms for PG 1338+481.

is confirmed during the pre-whitening process, where the periods determined in the two colors are generally found to lie within 0.5 s of each other. Adopting a threshold of three times the local noise level, we were able to extract 13 periods in the 2100 s to 7200 s range with amplitudes up to 0.3 % and 0.2 % of the mean brightness in the U and R passbands respectively.

The decision to observe PG 1338+481 in two wavebands was based on a theoretical study exploiting the dependence of a mode's color-amplitude behavior on its degree index ℓ (Randall et al. 2005). Put simply, the ratio of a pulsation peak's amplitudes as measured in two well-separated passbands can be used to directly infer the associated mode's degree index provided the star's atmospheric parameters are known. We list, in Table 1, the U/R amplitude ratios for the five most convincing periodicities extracted from the data. Note that these all correspond to peaks with amplitudes of at least four times the local noise level. It is obvious from the table that the amplitude ratios of all five peaks are consistent within the error margins, which may imply that the corresponding modes have the same degree index. That possibility is supported by the fact that the oscillations are relatively evenly spaced in period, neighboring peaks being separated by 257 s $\leq \Delta P \leq$ 298 s. According to asymptotic theory, this is precisely what would be expected for high radial order modes with consecutive values of k and constant degree index ℓ. While the matter remains to be investigated in more detail, the

Table 1. U/R amplitude ratios for the five dominant peaks detected in the light curves of PG 1338+481.

Period (s)	U/R amplitude
3530	1.49±0.29
3828	1.42±0.22
4090	1.39±0.40
4347	1.27±0.30
4625	1.55±0.51

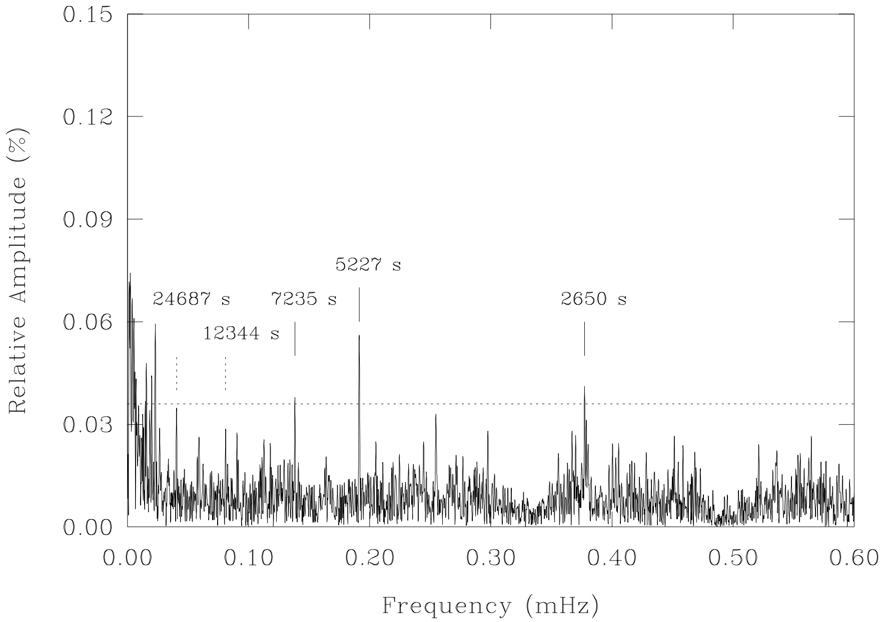

Fig. 4. Fourier transform for PG 0101+039.

resulting constraint on mode identification makes PG 1338+481 a prime target for asteroseismological studies.

2.3. PG 0101+039

PG 0101+039 was observed with the Canadian space telescope MOST (Walker et al. 2003) from 2004 September 28 to October 15 in a trial run for potential future missions. Since the effects of daily aliasing and atmospheric variation had undermined the extraction of periodicities for both of the previously studied targets, we had concluded that the successful asteroseismology of long-period variable subdwarf B stars would be facilitated by space-based observations. However, it was not clear from the outset whether the 15 cm aperture MOST telescope, currently the only satellite dedicated to asteroseismology, would be able to achieve sufficient precision for detecting pulsations in the relatively faint subdwarfs. It was therefore imperative to select a bright target like PG 0101+039 ($V \sim 12.1$), regardless of its other characteristics such as atmospheric parameters ($T_{\rm eff} \sim 28\,300$ K and $\log g \sim 5.52$ according to Green, Fontaine and Chayer, in preparation), or the fact that it forms part of a short-period binary system ($P_{\rm bin} \sim 0.57$ days from Moran et al. 1999).

The $\sim$400 hours of broad-band photometry gathered by MOST boast a duty cycle of 96.5 % and a noise level similar to that achieved for PG 1338+481 after seven weeks of ground-based observations. It is thus beyond doubt that, given the appropriate observing time, data from MOST can surpass anything obtainable from the ground in terms of time coverage. And indeed, the Fourier transform illustrated in Figure 4 shows no visible signs of aliasing. Adopting a threshold of four times the mean noise level, we were able to extract three convincing periodicities attributed to stellar oscillation (continuous line segments). Note that

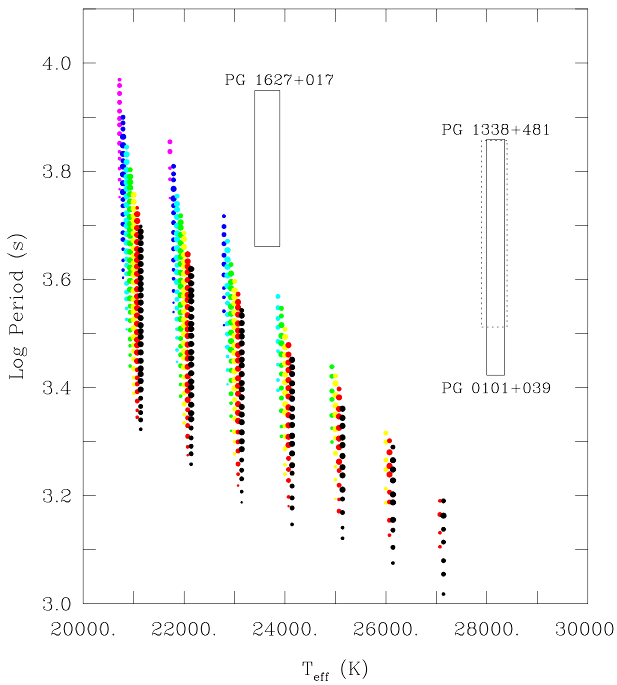

Fig. 5. Comparison between the range of periods predicted from a sequence of PG 1716 models (color-coded dots) and those observed for PG 1627+017, PG 1338+481 and PG 0101+039 (boxes). See text for further details.

their amplitudes are significantly lower than those detected for either of the previous targets, which could well be due to PG 0101+039's higher surface gravity. In addition, we found two lower amplitude peaks (dotted line segments) that are probably caused by an ellipsoidal deformation of the subdwarf due to the gravitational pull of its companion, and would imply a binary-synchronous rotation rate. Unfortunately, the fact that only three pulsations were identified makes this star unsuitable for asteroseismology for the time being.

3. QUALITATIVE COMPARISON WITH NON-ADIABATIC THEORY

In order to compare the ranges of periods observed for PG 1627+017, PG 1338 +481 and PG 0101+019 to those predicted by non-adiabatic theory, we computed a short sequence of sdB models in the appropriate temperature range. Constituting an updated version of the numerical tools employed by Charpinet et al. (1996) to explain the EC 14026 phenomenon, these models incorporate radiative levitation and are characterized by five free parameters: effective temperature $T_{\rm eff}$, surface gravity $\log g$, total stellar mass M_*, logarithmic depth of the transition between the hydrogen-rich envelope and the helium core $\log q(\rm H)$, and logarithmic depth of the extent of the inner carbon-oxygen core $\log q(\rm He)$. Note that, while M_* and $\log q(\rm He)$ were kept at constant representative values over the entire sequence, $\log q(\rm H)$ and $\log g$ were changed with $T_{\rm eff}$ so as to keep all of the structures parallel to the zero-age extreme horizontal branch (for precise values see Randall et al.

2005). Each model was then subjected to adiabatic and non-adiabatic pulsation calculations, the former estimating the periods of modes present, and the latter computing their stability. Figure 5 illustrates the periodicities predicted to be excited over the sequence for modes with $\ell = 2$ (magenta), $\ell = 3$ (blue), $\ell = 4$ (cyan), $\ell = 5$ (green), $\ell = 6$ (yellow), $\ell = 7$ (red) and $\ell = 8$ (black). Superposed on this theoretical instability strip are the ranges of periods observed for our three targets. It can be seen that the general trend of the unstable period range decreasing with increasing temperature is recovered by the models, however on an absolute scale the periods observed are longer than those predicted. Moreover, the modes excited by models hotter than 23 000 K are associated with degree indices $\ell \geq 4$, and the structure representative of PG 1338+481 and PG 0101+039 at $T_{\rm eff}$ = 28 000 K drives no modes with $\ell \leq 8$ whatsoever. It is thus clear that our models are subject to important deficiencies that have yet to be determined and addressed. Given the similarities that exist between the theoretical instability strip and that observed, we nevertheless believe that the driving mechanism identified for the long-period variable subdwarfs lies at the origin of the oscillations detected and will be able to account for them quantitatively when more realistic models become available.

4. QUANTITATIVE COMPARISON WITH ADIABATIC THEORY

In a first attempt to quantitatively explain the period spectra uncovered in long-period variable subdwarf B stars we focus primarily on PG 1338+481, the most promising object observed so far. One thing that the photometry for all our targets have in common is a strong deficiency in periodicities observed compared to those predicted in the same range. While this could be partly alleviated by more sensitive measurements, it is obvious that asteroseismology will only be achieved if there is some constraint on mode identification from the outset. Possible methods of determining the degree index ℓ of a mode observed include the exploitation of rotational splitting (e.g., Charpinet et al. 2005), line-profile variations from time-series spectroscopy (see Schoenaers & Lynas-Gray 2006) and multicolor photometry (e.g., Randall et al. 2005). Since our observations do not include high-resolution spectroscopy and rotational

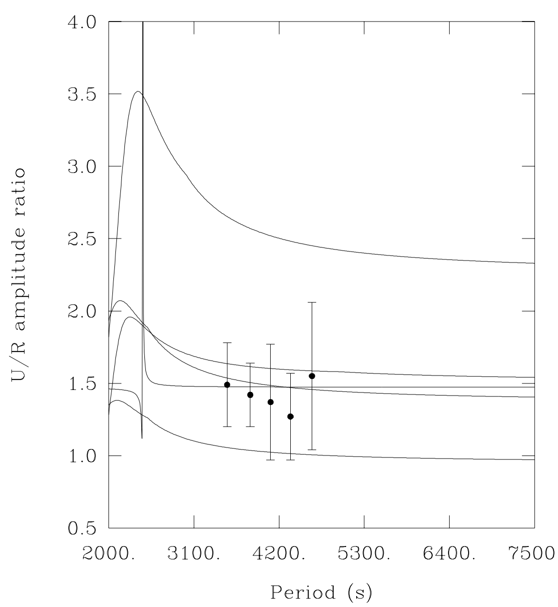

Fig. 6. U/R amplitude ratios predicted for a representative PG 1338+481 model for degree indices $\ell = 3$, 2, 1, 4 and 5 from top to bottom on the right-hand side. The amplitude ratios measured for PG 1338+481 are also indicated.

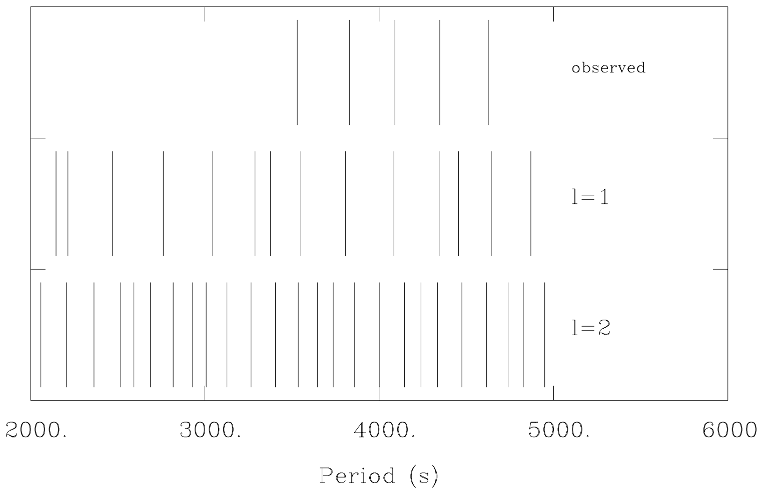

Fig. 7. Period spectrum predicted for a model with $T_{\rm eff}$ = 28 600 K, $\log g$ = 5.22, $M_* = 0.45\ M_\odot$, $\log q({\rm H}) = -2.68$ and $\log q({\rm He}) = -0.24$. The five highest amplitude periodicities observed for PG 1338+481 are also illustrated.

splitting was found to yield ambiguous results when it was detected (see section 2.1), the simultaneous U/R photometry of PG 1338+481 is our best option. Figure 6 illustrates the period-dependent U/R amplitude ratios calculated from a model with $T_{\rm eff}$ = 28 200 K and $\log g = 5.38$ for degree indices ℓ = 3, 2, 1, 4 and 5 (from top to bottom on the right-hand side). Superposed on this are the amplitude ratios observed for the five dominant pulsations of PG 1338+481 (see Table 1). Considering the measurement errors, only modes with $\ell = 3$ and $\ell = 5$ can be excluded with any confidence, although the $\ell = 1$ and $\ell = 4$ curves do represent better matches to the data than that for $\ell = 2$.

Another feature that makes the PG 1338+481 data stand out is the nearly equal period spacing of the five highest amplitude pulsations. As discussed in section 2.2, this could well imply that they are all associated with the same degree index, which in light of the multicolor findings would correspond to ℓ = 1, 4 or possibly 2. Since the brightness variation caused by an oscillation of given intrinsic amplitude strongly decreases with increasing ℓ-value when integrating over the visible disk of a star, the detection of ℓ = 1 or 2 modes is naturally favored compared to that of $\ell = 4$ modes. Indeed, all main sequence g-mode pulsators with good empirical mode identification show $\ell = 1$ modes only. A similar scenario holds true for white dwarfs, which do exhibit the occasional $\ell = 2$ mode, but primarily excite dipole modes. As subdwarf B stars lie in between the two regimes, we would expect their case to be no different. In addition to this, the average period spacing between the five peaks ($\langle \Delta P \rangle \simeq 274$ s) is very close to that expected for $\ell = 1$ modes in a representative PG 1338+481 model, as can be seen in Figure 7. $\langle \Delta P \rangle$ decreases significantly with increasing degree index, implying that the observed period spectrum could be matched to that predicted for $\ell = 2$ or higher only if a significant fraction of the theoretical periodicities were not excited to appreciable amplitudes. Since we find no convincing reason why this should be the case, we believe these modes to have degree indices of $\ell = 1$.

5. CONCLUSION

The observational campaign described in these Proceedings constitutes the first serious attempt at quantitatively interpreting the period spectra excited in long-period variable subdwarf B stars. It has revealed that even the most sensitive measurements available yield an observed period spectrum far sparser than that expected from theory. Consequently, mode identification must be constrained from the outset if asteroseismology is to be possible. One way of doing this is the exploitation of multicolor photometry, which we attempted for the case of PG 1338+481. Together with mode visibility and period spacing considerations, the results point to the excitation of $\ell = 1$ modes in that star. If confirmed, this would aggravate the discrepancy between the computed and the observed instability strip compared to the detection of $\ell = 3$ or 4 modes. Indeed, none of the models shown in Figure 5 are able to excite dipole modes. These are predicted only for models cooler than 21 000 K, implying a difference of 7000 K between the theoretical and observed blue edge. While this clearly indicates shortcomings in our models that have yet to be addressed (the spectroscopic determinations may also be partly at fault), qualitative similarities between the observed and predicted instability strips nevertheless point to the identification of the correct driving mechanism. Beyond this, we feel that the constraints placed on the mode identification for PG 1338+481 have opened this star up to asteroseismology, a possibility we are still in the process of investigating.

ACKNOWLEDGMENTS. We would like to thank for their contribution to the observations: T. Bedding, N. Brown, O. Cordes, L. Crause, A. Daane, M. Fontaine, B.-Q. For, A. Jacob, D. Kilkenny, L. Kiss, R. Kuschnig, J. Matthews, S. O'Toole, P.-O. Quirion, J. Rowe and P. Zacharias.

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