Mem. S.A.It. Vol. 77, 59

Memorie della

Detection of long-period variations in the subdwarf B star PG 0101+039 on the basis of MOST photometry

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Abstract. We present the results of ∼ 400 hours of optical wide-band photometry for the long-period variable subdwarf B (sdB) star PG 0101+039 obtained by MOST, Canada's first orbiting space telescope, in September/October 2004. Despite the relative faintness of the target, the observations uncovered three low-amplitude periodicities between 2600 and 7250 s attributed to intrinsic stellar pulsations, as well as an ellipsoidal deformation of the subdwarf due to its close binary status. The fact that slow pulsations were detected in a target as hot as PG 0101+039 is in conflict with current non-adiabatic theory, which only predicts the excitation of more rapid oscillations that have amplitudes too small to be observable when integrating over the visible disk of the star. In light of our findings we will thus have to reconsider our models and refine their construction.

Key words. Stars: interiors – Stars: oscillations – Stars: subdwarfs

1. Introduction

Subdwarf B (sdB) stars are evolved extreme horizontal branch (EHB) objects with effective temperatures in the 20,000−40,000 K range and high surface gravities of $5.0 \leq \log g \leq 6.2$ (Saffer et al. 1994). Their progenitors are thought to have undergone substantial mass loss near the red giant tip, leaving the helium core surrounded by a hydrogen shell too thin for the stars to ascend the asymptotic giant branch. Instead, they settle on the EHB, spend around 10^8 years burning core helium as subdwarf B stars, and end their lives as low-mass white dwarfs (Bergeron et al. 1994). As a result of their evolutionary history, the masses of sdB's are believed to be tightly constrained, canonically predicted values lying in the 0.44−0.53 $M_\odot$ range (Dorman et al. 1993). However, more recent developmentary hypotheses including the merging of two white dwarfs and Roche lobe overflow in a close binary system predict a somewhat larger range of possible masses (Han et al. 2003). The thickness of the hydrogen shell depends on the exact temperature at which the star settles on the zero-age EHB and thus contains valuable information on pre-EHB conditions. Since usually neither the mass nor the exact composi-

Send offprint requests to: S.K. Randall tion of a star can be observed directly, it is their determination through asteroseismology that holds the key to a more mature understanding of these stars' evolution.

Fortunately, we know of two distinct types of oscillator among subdwarfs, each probing a different part of the stellar interior. The hotter EC 14026 stars (Kilkenny et al. 1997) exhibit rapid pulsations on a typical time scale of 100−200 s, which can be accounted for surprisingly well by a classical kappa mechanism in the presence of an iron opacity bump achieved through radiative levitation (Charpinet et al. 1997). Asteroseismological analyses invoking low-degree, low radial order pressure modes have been possible in several instances, yielding accurate estimates of the targets' masses and the thickness of their envelopes (see Charpinet et al. these proceedings for details). While these are becoming statistically significant for restricting evolutionary scenarios, the fact that pressure modes propagate primarily in the outer layers of a star means that they contain virtually no information on its inner regions. To obtain that, we need to turn to the PG 1716 stars, a second class of subdwarf B pulsator discovered only recently (Green et al. 2003). Distinctly cooler than the rapid variables, these stars exhibit periodicities between 1000 and 9000 s, which automatically implies high radial order gravity modes. The driving mechanism is believed to be the same as for the EC 14026 stars, however current models have been able to excite only modes with degree indices $\ell \geq 3$ for the majority of the spectroscopic temperature range, and modes with $\ell > 8$ for the very hottest PG 1716 stars detected (Fontaine et al. 2003). According to canonical wisdom, high degree modes should not be observable due to cancellation effects when integrating over the visible disk of the star. It thus seems that the instability strip predicted by our models is subject to some uncertainties, although these have been difficult to quantify due to a lack of data. In the present study, we address the issue by obtaining high quality photometry for one of the hottest long-period variables known, and compare the ensuing results to theoretical predictions.

2. Observations and Analysis

The slow oscillator PG 0101+039 has atmospheric parameters $T_{\rm eff} \sim 28{,}300$ K and $\log g \sim 5.52$ (Green, Fontaine, & Chayer, in preparation) and forms one half of a short-period binary system with $P_{\rm bin} \sim 0.57$ d (Moran et al. 1999). As one of the brightest subdwarfs at $V = 12.06$, it was considered an ideal exploratory target for the Canadian space telescope MOST ('Microvariability and Oscillations of STars; see Matthews et al. in these proceedings). After encountering severe problems with daily aliasing and atmospheric extinction during ground-based campaigns on PG 1716 stars, we had come to the conclusion that a detailed frequency analysis would be greatly facilitated by observations from space. Currently the only satellite dedicated to asteroseismology, MOST was the obvious choice. However, it was not clear from the outset whether the 15-cm aperture telescope, primarily designed to monitor targets brighter than $V = 6$, would be able to achieve sufficient precision to detect low-amplitude oscillations in the relatively faint long-period variable subdwarfs. Besides constituting a scientific study in its own right, the trial run reported here was therefore intended to assess the feasibility of observing slowly oscillating subdwarfs with MOST.

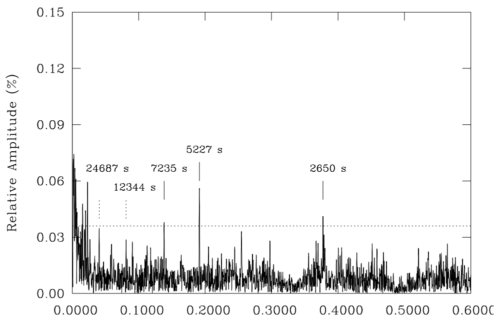

Fig. 1. Fourier transform of the entire light curve obtained for PG 0101+039 with MOST. Continuous line segments indicate periodicities believed to constitute stellar oscillations, while peaks associated with the ellipsoidal variation of the subdwarf during its binary orbit are marked by dotted lines.

Broadband photometry of PG 0101+039 was gathered nearly continuously from 28 September to 15 October 2004, with only one major gap of about 14 hours occuring near the beginning of the run. This implies around 400 hours of data with a net duty cycle of 96.5 %, significantly higher than anything achievable from the ground. The Fourier transform (FT) of the entire reduced light curve is illustrated in Figure 1. Note that it shows no visible signs of aliasing and boasts a noise level similar to that achieved for other PG 1716 stars after 3−5 weeks of observation from ground-based telescopes in the 1−2-m class. Adopting a threshold of four times the mean noise level (indicated by the horizontal dotted line), we were able to extract three frequencies attributed to stellar oscillation, indicated by continuous line segments. They are asociated with periods of 2650 s, 5227 s and 7235 s and have relatively low amplitudes of less than 0.06 % of the star's mean brightness. In addition, we found two weaker peaks corresponding to half the binary frequency and its first harmonic, probably indicating an ellipsoidal deformation of the subdwarf due to the gravitational pull of its companion. While interesting from the point of view of binary studies, the latter periodicities are not related to an intrinsic pulsation mechanism and will not be discussed in the what follows.

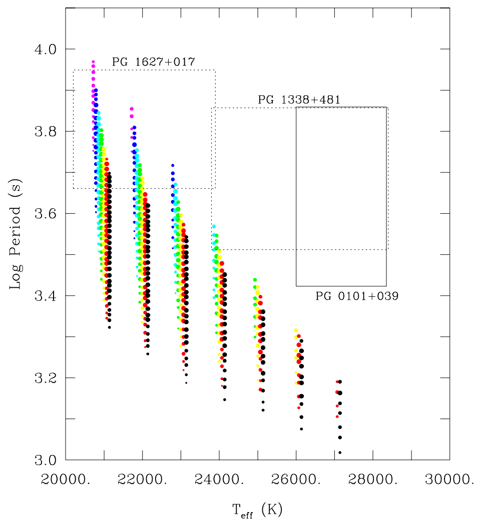

Fig. 2. Periodicities predicted to be excited from a sequence of PG 1716 star models. Individual modes are colour-coded in magenta (ℓ = 2), blue (ℓ = 3), cyan (ℓ = 4), green (ℓ = 5), yellow (ℓ = 6), red (ℓ = 7) and black (ℓ = 8). The superposed boxes refer to the period range observed in the vertical direction and the temperature uncertainty from spectroscopy in the horizontal direction. Values for PG 0101+039 are indicated together with those for previous targets PG 1627+017 (Randall et al. 2006) and PG 1338+481 (Randall et al. in preparation). *See the electronic edition of this manuscript for a color coded figure.*

3. Comparison with non-adiabatic theory

We qualitatively compare the pulsational periods extracted to those predicted from theory with the aid of a short sequence of PG 1716 star models (see Charpinet et al. 1997 and Fontaine et al. 2003 for details on these models). Designed so as to lie parallel to the zero-age EHB, the sequence covers the entire temperature range where long-period variables are observed. Figure 2 illustrates the periodicities predicted to be unstable on the basis of the kappa mechanism for each model. The points are colour-coded according to the degree index of the mode in question (see figure caption for details). Superposed on the period sequence are the ranges of periods extracted for PG 0101+039 as well as two previously observed slow oscillators as a function of their effective temperature. Note that, for each target, the widths of the boxes give the temperature uncertainties based on two different sources (U. Heber, private communication, and Green, Fontaine & Chayer, in preparation) rather than the formal errors obtained from one spectral fit. As such, they are indicative of the significant discrepancies that still exist for cool sdB stars between atmospheric parameters derived from different sets of model atmospheres. In all likelyhood, the true values lie somewhere in between, however we belive it is safest to adopt conservative uncertainty estimates until the issue has been resolved.

Figure 2 clearly shows that, while the tendency for hotter stars to exhibit shorter periods is recovered by the models, there are discrepancies at the quantitative level. This is particularly obvious for the two hotter targets, where the periods observed are significantly longer than those predicted. Moreover, the frequencies predicted to be excited correspond to modes with relatively high degree indices, particularly in the models representative of PG 0101+039 (which, for the most part, are not able to drive modes with $\ell < 6$). Whereas there is some overlap between the theoretical and experimental instability regions for the other two stars, the more stringent constraints on the effective temperature of PG 0101+039 eliminate any hope of recreating the observed period spectrum with current models. It is thus clear that the latter are subject to deficiencies, at least at the non-adiabatic level, that have not yet been identified. Since it is probable that structural improvements made to the models would quantitatively affect the adiabatic period spectrum as well as the instability calculations, the inaccuracies will have to be addressed if meaningful asteroseismological fits are to be achieved for long-period variable subdwarf B stars.

4. Conclusion

The quality of the photometry obtained for PG 0101+039 conclusively shows that MOST is ideally suited to the monitoring of long-period variable subdwarf B stars. Indeed, the data obtained are far superior to anything achievable from the ground as far as time coverage is concerned, making space-based observations the obvious choice for future missions. While the number of periodicities detected for PG 0101+039 is too small to contemplate asteroseismology, we are hopeful that a MOST observing run of longer duration could uncover many more oscillations for other long-period variables, particularly those exhibiting higher amplitude pulsations. However, the successful use of these observed frequencies to infer the structural parameters of long-period variable subdwarfs depends on the identification and correction of deficiencies in our current models. We are in the process of addressing this issue and hope to solve the problem in the near future.

References

Bergeron, P., Wesemael, F., Beauchamp, A. et al. 1994, ApJ, 432, 305

Charpinet, S., Fontaine, G., Brassard, P. et al. 1997, ApJ, 483, L123

Dorman, B., Rood, R. T., & O'Connell, R. W. 1993 ApJ, 419, 596

Fontaine, G., Brassard, P., Charpinet, S. et al. 2003, ApJ, 597, 518

Green, E. M. , Fontaine, G., Reed, M. D. et al. 2003, ApJ, 583, L31

Han, Z., Podsialowski, P., Maxted, P. F. L., & Marsh, T. R. 2003, MNRAS, 341, 669

Kilkenny, D., Koen, C., O'Donogue, D., & Stobie, R. S. 1997, MNRAS, 285, 640

Moran, C., Maxted, P., Marsh, T. R. et al. 1999, MNRAS, 304, 535

Randall, S.K., Fontaine, G., Green, E.M. et al. 2006, ApJ, submitted

Saffer, R., Bergeron, P., Koester, D., & Liebert, J. 1994, ApJ, 432, 351