New results on the sdB star PG 0014+067

P Brassard and G Fontaine
Département de Physique, Université de Montréal, C.P. 6128, Succ. Centre-Ville, Montréal, Québec, Canada H3C 3J7
E-mail: brassard@astro.umontreal.ca, fontaine@astro.umontreal.ca

Abstract. We present here our third generation of sdB star models geared for asteroseismology. As a test of these new models, we return to a thorough analysis of the pulsating sdB PG 0014+067. We also provide a new treatment of the observed data. Many possible working hypotheses for the mode identification have been tested. In an outcome that may seem surprising to some, we found that almost all of them seem to produce very similar seismic models.

1. Observations

From the discovery of its variability in 1998, PG 0014+067 has been the subject of four important observational missions to decipher its period structure. The first one, that established the variability of the star, provided 9.6 hours of observations at the CFH Telescope (Brassard et al. 2001, hereafter referred to as CFTH1) in June 1998. A follow-up mission, again at the CFHT in August 1999, provided us with another 16.2 hours of observations (Charpinet et al. 2005, hereafter referred to as CFHT2). After that, 29.5 hours where obtained at the WHT in August 2004 with the Ultracam photometer (Jeffery et al. 2005, hereafter referred to as the WHT run) and ~ 180 hours with the WET in October 2004 (Vučković et al. 2006, hereafter referred to as the WET run).

For our experiments, we have used the periods extracted from the combined run CFHT1 and CFHT2. In spite of the rather large time gap between to the two runs, we were able to extract 19 periodicities from the joint data, thanks to the very low noise level obtained at the CFHT. We recovered all of the 10 periodicities found in the WET data. We also recovered 13 of the 19 from the WHT. For the asteroseismic analysis, we have kept only the central component of the multiplets. This left us with 10 observed periods, one more (154.72 s) and one less (130.37 s) than those used by CFTH2 and Brassard et al. (2008). Values are given in Table 1.

2. Models

Along with our previous generation of envelope models which incorporate iron profiles that take into account the effects of radiative levitation, we are now able to complete the structure of our models with a nucleus that include the description of the nuclear burning and neutrinos effects. We have used the updated nuclear reaction rates of Caughlan & Fowler (1988) available at http://www.phy.orl.gov/astrophysics/data/cf88/ and the neutrinos rates from N. Itoh and collaborators. These are static models built under the assumption of mechanical and thermal equilibrium.
Table 1. Observed Periods in PG0014+067.

| P (s)  | A (%) | P (s)  | A (%) | P (s)  | A (%) |
|--------|-------|--------|-------|--------|-------|
| 100.293  | 0.104 | 141.065  | 0.252 | 154.947  | 0.064 |
| 116.928  | 0.030 | 146.495  | 0.207 | 154.974  | 0.068 |
| 126.308  | 0.039 | 150.744  | 0.054 | 161.421  | 0.027 |
| 139.167  | 0.071 | 150.762  | 0.128 | 161.467  | 0.048 |
| 139.193  | 0.033 | 150.784  | 0.087 | 168.830  | 0.057 |
| 141.016  | 0.166 | 154.552  | 0.065 | 168.926  | 0.047 |
| 141.033  | 0.109 |

The basic input parameters used to build our models are the mass of the star \(M_\star/M_\odot\), the mass of the envelope \(M_{\text{env}}/M_\star\), the mass of the convective core \(M_{\text{core}}/M_\star\) along with its He/C/O mixture composition. The non-convective part of the core is assumed to be pure He. The envelope is the same than in our previous generation of models, i.e., almost pure H with traces of Fe in radiative levitation.

One can note here that the surface gravity \((\log g)\) and the effective temperature \((T_{\text{eff}})\) of a given model are obtained after the computation of the model. This can complicate the direct comparison with observations and does explain the approach used in the next section.

3. Methodology

Beforehand, we have built a huge grid of nearly 3,750,000 stellar models and computed their pulsation periods. Such a grid is useful in many ways. First, we can select models with specified \(\log g\) and \(T_{\text{eff}}\) (within any given ranges). Then, we can rapidly test various hypotheses on the mode identifications (all the hard work having already been done). Also, the grid resolution is sufficient to ensure that we have a global minimum instead of a local one. Finally, the grid can be reused to analyze other stars.

Our analysis is made in two steps. First we select all models within \(2\sigma\) in the observed \(T_{\text{eff}}\) and \(\log g\) of the star in our pre-built grid. Then we minimize the quantity \(S^2 = \sum (P_{\text{obs}} - P_{\text{th}})^2\) using a matching algorithm. The matching can be done under different hypotheses for the modes identification. In a second step, best-matching models are refined using a finer resolution in the basic parameters.

4. Observational Constraints

A first constraint arises from the analysis of the multi-color data of the WHT run made by Tremblay et al. (2006). They show that the modes at 141.033 s and 146.496 s can only be identified with \(\ell = 0, 1\) or \(2\). If we look at Table 1, only 4 periods can be candidate for a \(\ell = 0\) mode. Also, if we restrict ourselves to high amplitude modes, we are left with only two possibilities: 100.29 s and 146.496 s. If we look at the CFHT1 and CFHT2 runs individually, we find that the 100.29 s is very stable in frequency and amplitude. This is not the case with the mode at 146.496 s. Indeed, there is a possibility for a mode at 146.475 s. This mode was not selected in Table 1 because it falls short on our selection criterion (amplitude slightly under the \(3\sigma\) noise level). Another constraint arises from the paper of Randall et al. (2005) in which the authors clearly show that \(\ell = 3\) modes are difficult to observe in sdB stars.
Table 2. Solutions near 34,130 K

| Mode ID | Hypothesis 1 | Hypothesis 2 |
|---------|--------------|--------------|
|         | $P_{\text{th}}$ (s) | $P_{\text{obs}}$ (s) | $P_{\text{th}}$ (s) | $P_{\text{obs}}$ (s) |
| 0 5     | 99.333       | 98.666       |                |                |
| 0 4     | 113.313      | 113.173      |                |                |
| 0 3     | 123.572      | 124.141      |                |                |
| 0 2     | 150.008      | 149.068      | 146.50         |                |
| 0 1     | 162.845      | 163.318      |                |                |
| 0 0     | 188.940      | 187.511      |                |                |
| 1 6     | 95.376       | 95.078       |                |                |
| 1 5     | 104.612      | 104.475      |                |                |
| 1 4     | 119.980      | 119.159      |                |                |
| 1 3     | 141.743      | 141.04       | 141.809        | 141.04         |
| 1 2     | 154.802      | 154.72       | 154.111        | 154.72         |
| 1 1     | 188.343      | 186.892      |                |                |
| 2 6     | 89.119       | 89.065       |                |                |
| 2 5     | 100.096      | 100.29       | 99.464         | 100.29         |
| 2 4     | 115.939      | 116.93       | 115.453        | 116.93         |
| 2 3     | 126.772      | 126.31       | 126.724        | 126.31         |
| 2 2     | 151.061      | 150.77       | 149.981        | 150.77         |
| 2 1     | 168.863      | 168.88       | 169.238        | 168.88         |
| 2 0     | 187.872      | 186.482      |                |                |
| 4 5     | 95.179       | 94.802       |                |                |
| 4 4     | 105.146      | 105.062      |                |                |
| 4 3     | 119.694      | 118.932      |                |                |
| 4 2     | 139.736      | 139.18       | 139.077        | 139.18         |
| 4 1     | 146.583      | 145.662      |                |                |
| 4 0     | 160.394      | 161.45       | 160.366        | 161.45         |
| 4 1     | 186.440      | 185.196      |                |                |

Table 3. Properties of PG 0014+067

| Quantity | Spectroscopy | Hypothesis 1 | Hypothesis 2 |
|----------|--------------|--------------|--------------|
| log $g$  | 5.77         | 5.751        | 5.754        |
| $T_{\text{eff}}$ (K) | 34,130       | 34,124       | 34,172       |
| $M_{\star}/M_\odot$ | 0.450        | 0.451        |              |
| log($M_{\text{env}}/M_\star$) | -3.941       | -3.975       |              |
| log($M_{\text{core}}/M_\star$) | -0.328       | -0.310       |              |
| $X$(C)   | 0.469        | 0.467        |              |
| $X$(O)   | 0.468        | 0.466        |              |
| $S^2$ (Hyp. 1) | 3.254        | 6.599        |              |
| $S^2$ (Hyp. 2) | 15.687       | 12.628       |              |
5. Results
We have tested many hypotheses for the mode identification for PG 0014+067. Each of these hypotheses were tested with the 10 pulsation modes extracted from Table 1 and also with the subset of the 5 modes with the highest observed amplitudes. Detailed results will be produced elsewhere, but we summarize the main results here.

First, there is only one solution assuming that all the modes have $\ell \leq 2$. This solution have the modes at 139.27 s and 150.76 s with a $\ell = 0$ index. This is clearly in contradiction with the observations. It follows that we reassert the result of CFHT1 that the light curve of PG0014+067 can only be deciphered if we allow the presence of modes with $\ell \geq 3$. Second, with the notable exception of the hypothesis that the modes can have any values with $\ell \leq 4$, we find that all our hypotheses produce very similar models with $-3.9 \leq \log(M_{\text{env}}/M_\star) \leq -4.0$ (for the general case with $\ell \leq 4$, numerous solutions are possible in the range $-3.75 \leq \log(M_{\text{env}}/M_\star) \leq -4.45$).

Third, we do not find unique solutions, but instead a family of solutions that produces essentially the same fit but at various masses for the star. Fortunately the observed quantity $T_{\text{eff}}$ can be used to pinpoint a solution fully consistent with the observations.

For the rest of the paper we take a closer look at two interesting possibilities consistent with the observational constraints.

Hypothesis 1: We exclude modes with $\ell = 0$ and try to obtain solutions with $\ell = 1, 2$ and 4 only. The member of the family of solution with $T_{\text{eff}}$ near the observed effective temperature of 34,130 K that produce the best fit is given in Table 2 and Table 3. This is a very interesting solution from a strict theoretical point of view since all the modes have consecutives $k$ values. This solution can also accommodate the possibility that the 100.3 s observed period is a $\ell = 0$ mode because there is a nearby $\ell = 0$ mode with 99.3 s in the model. The only problem with this model is that the condition that the 146.50 s must have $\ell = 0, 1$ or 2 is not respected.

Hypothesis 2: The mode at 146.50 s may have $\ell = 0, 1$ or 2, the mode at 141.04 s may have $\ell = 1$ or 2, and the other observed modes may have $\ell = 1, 2$ or 4. In this case, we have a solution fully consistent with observational constraints. What is interesting here, is that this new solution is essentially the same than the previous one! The mode at 146.50 s as simply moved from $\ell = 3$ to $\ell = 0$.

6. Conclusions
We thus found another case for which a priori partial mode identification seems to be immaterial for defining the optimal seismic model in sdB asteroseismology. This may seem surprising, even “heretic” to many, but it can be readily explained by the particular period structure found in sdB pulsators. Modes with the same radial order but different values of the degree index tend to have very similar periods. At the present level of accuracy with which observed periods can be matched with our models of sdB stars, a priori mode identification does not seem necessary. This is a good thing because pulsating sdB stars are relatively faint, and constraints on the values of the modal degree from multicolor photometry and/or time-resolved spectroscopy are likely to be limited to the brighter members of the class.

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