Nonadiabatic Asteroseismology of GW Vir Stars

Pierre-Olivier Quirion¹, Gilles Fontaine² and Pierre Brassard²

¹Institut for Fysik og Astronomi, Aarhus Universitet Ny Munkegade, Bygn. 1520, 8000 Århus-C
²Département de physique Université de Montréal, C.P. 6128, Succ. centre-ville, Montréal (Québec) H3C 3J7
E-mail: olivier@phys.au.dk

Abstract. We present results from nonadiabatic stability calculation to determine the position of the GW Vir band in the log \(g\) – \(T_{\text{eff}}\) diagram. With this method, we calculate the position of seven GW Vir stars. The results are consistent with and complementary to the spectroscopic determination of atmospheric parameters and the chemical compositions of these stars except for the newly discover GW Vir star VV 47. This discrepancy is discussed.

1. Astrophysical Context

The GW Vir stars are extremely hot, compact stars that pulsate in gravity modes. They include at least two different spectral types: the hot H-deficient Wolf-Rayet central stars of planetary nebulae or [WCE] stars, and their descendants, the PG 1159 stars. The multiperiodic luminosity variations observed in GW Vir stars are due to a classic \(\kappa\)-mechanism associated with the ionization of the K-shell electrons of carbon and oxygen, two of the main atmospheric/envelope constituents in these objects.

Quantitative spectroscopy, based on detailed Non-LTE model atmospheres and synthetic spectra, has revealed that GW Vir stars occupy a wide domain in the surface gravity–effective temperature plane, with objects in the ranges \(5.5 \leq \log g \leq 7.5\) and \(80,000 \, \text{K} \leq T_{\text{eff}} \leq 170,000 \, \text{K}\). In addition, the inferred atmospheric abundances vary largely from one star to another, and the main atmospheric constituents are found in the intervals, \(0.33 \leq X(\text{He}) \leq 0.76\), \(0.16 \leq X(\text{C}) \leq 0.55\), and \(0.00 \leq X(\text{O}) \leq 0.17\). We refer the reader to the excellent review by Werner & Herwig (2006) for more details on the chemical compositions of these stars. Unfortunately, at the very high \(T_{\text{eff}}\) of the GW Vir regime, the uncertainties on the derived values of \(T_{\text{eff}}\) and \(\log g\) remain relatively large with typical values of 5 to 10% for \(T_{\text{eff}}\), and 0.5 dex for \(\log g\). We argue here that it is possible to infer the atmospheric parameters of GW Vir pulsators with a higher accuracy by exploiting nonadiabatic asteroseismology. This is based on a comparison of the observed ranges of excited periods with ranges predicted from nonadiabatic models.

2. Models and Results

We know that the instability band of GW Vir stars is strongly correlated with its location in the log \(g\) – \(T_{\text{eff}}\) diagram (Quirion et al. 2007). The range of the instability bands depend mainly on surface gravity for the “fluffy” stars of lower gravities and is a function of temperature and gravity for the more compact/evolved objects of higher gravities. We thus expect an especially
Table 1. Comparison between spectroscopic results, our nonadiabatic asteroseismology calculation and the observations.

| Star            | log $g$ | $T_{\text{eff}}$ [kK] | Periods [s] | log $g$ | $T_{\text{eff}}$ [kK] | Periods [s] | Observable Periods [s] |
|-----------------|---------|------------------------|-------------|---------|------------------------|-------------|------------------------|
| NGC 246         | 5.70    | 150                    | 514−11453   | ~ 5.75  | ~                      | 604−4477    | 1464−1842              |
| RX J2117.1+3412 | 6.00    | 170                    | 635−2202    | ~ 6.10  | 180 ± 10               | 178−779     | 694−1530               |
| PG 1159−035     | 7.00    | 140                    | 247−623     | 6.80 ± 0.5 | 142 ± 3             | 336−987     | 339−982                |
| VV 47           | 7.00    | 130                    | 216−891     | 6.10 ± 10 | 130 ± 20             | 235−3531    | 261−4310               |
| PG 2131+066     | 7.50    | 95                     | 197−650     | 7.25 ± 0.25 |                   | 118−508     | 339−508                |
| PG 1707+427     | 7.50    | 85                     | 188−765     | 7.35 ± 0.05 | 81 ± 5              | 224−960     | 336−942                |
| PG 0122+200     | 7.50    | 80                     | 198−847     | 7.50 ± 0.30 |                   | 330−602     | 336−612                |

good constraint on surface gravity for GW Vir stars of low gravity, and both good fit on gravity and temperature for the more compact object.

We use the test function $S$, which depends on $P_{\text{min}}$ and $P_{\text{max}}$, the shortest and longest excited periods, to measure the goodness of our fit and to find the best matching model for the observed GW Vir stars.

$$S^2 = \left( \frac{P_{\text{obs}} - P_{\text{mod}}}{\sigma_{\text{max}}} \right)^2 + \left( \frac{P_{\text{obs}} - P_{\text{mod}}}{\sigma_{\text{min}}} \right)^2$$

(1)

where the weight $\sigma_i = 1\% P_{\text{obs}}$ is chosen to be proportional to the observed period boundaries.

An other important parameter fixing the instability band is the chemical composition in the envelope of the star. The composition used for our nonadiabatic calculation are taken from the spectroscopic measurements. In that sense the results shown here are a consistency check between spectroscopic and photometric measurements. A correct interpretation our calculations should help us understanding if photometric or spectroscopic results need to be revisited.

We explicitly show our results for two stars. One which gives perfect agreement, PG 1707+427, and one where there is no consistency between the spectroscopy and the photometry, VV 47. We also present in Table 1 results for other stars.

The consistency check for PG 1707+427 (Figure 1) is perfect. In addition, asteroseismology provides a better constraint on both the gravity and the effective temperature (see Table 1). Nonadiabatic calculation finds the best fit at log $g = 7.4$ and $T_{\text{eff}} = 79,000$ K. The test function $S$ reaches a minimum value of 0.3. At that point, the instability band of the model extends from 224 s to 960 s. This GW Vir is compact enough to let the effective temperature have a significant effect on the instability band. In this high gravity regime, we can also improve the determination of log $g$. The analysis of that star is a spectroscopic and photometric success!

For VV 47, if we calculate the instability range at the spectroscopic value (log $g = 7.00$ and $T_{\text{eff}} = 130,000$ K) we find a band of 216 s to 891 s. However, find a better fit outside the estimated spectroscopy error, at log $g = 6.3$ and $T_{\text{eff}} = 103,000$ K (Figure 2). At this point, the instability band of the model extends from 235 s to 3531 s. The ”best fit valley” of the $S$ function around log $g = 6.0$ is quite far from the spectroscopic value. This inconsistency is a hint that the composition ratio and/or the temperature of VV 47 is to be revised. This poor correspondence between spectroscopy results and nonadiabatic asteroseismology is not really surprising when one consider that in their spectroscopic analysis, Rauch & Werner (1995) stress that their analysis of VV 47 was uncertain. We hope that the recent discovery of pulsation in
Figure 1. Position of PG 1707+427 in the log $g - T_{\text{eff}}$ diagram as fixed by spectroscopy is shown by the black dot. The error range is depicted by the black rectangle.

VV 47 and the inconsistency shown in Figure 2 will revive the interest in what looked, in 1995, to be one of the most compact PG 1159 star with a planetary. We notice that the value of log $g$ obtained with nonadiabatic calculations would replace VV 47 along with the other PG 1159 and [WCE] stars which display a planetary nebulae.

If we examine results of Table 1 we see that nonadiabatic asteroseismology calculation do not always constrain temperature, this can be caused by the model intrinsic low dependency on temperature or by unresolved photometric features. For all star, nonadiabatic asteroseismology gives values of the surface gravity that is equivalent or more precise than what is achieved by spectroscopy alone.
3. Conclusion
Nonadiabatic asteroseismology is more than a consistency check over different GW Vir analysis techniques. It gives a significant improvement to GW Vir stars surface gravity, and in some cases their effective temperature. This helps us establish these stars absolute luminosity and boost the understanding of physical processes leading from the post-AGB to the white dwarf track.

References
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Figure 2. Position of VV 47 in the log $g - T_{\text{eff}}$ diagram (black dot) as fixed by spectroscopy with canonical GW Vir error bars (black rectangle).