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ON THE POSSIBLE EXISTENCE OF SHORT-PERIOD *g*-MODE INSTABILITIES POWERED BY NUCLEAR-BURNING SHELLS IN POST-ASYMPTOTIC GIANT BRANCH H-DEFICIENT (PG1159-TYPE) STARS

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ABSTRACT

We present a pulsational stability analysis of hot post-asymptotic giant branch (AGB) H-deficient pre-white dwarf stars with active He-burning shells. The stellar models employed are state-of-the-art equilibrium structures representative of PG1159 stars derived from the complete evolution of the progenitor stars, through the thermally pulsing AGB phase and born-again episode. On the basis of fully nonadiabatic pulsation computations, we confirmed theoretical evidence for the existence of a separate PG1159 instability strip in the $\log T_{\rm eff}$–$\log g$ diagram characterized by short-period *g*-modes excited by the ϵ-mechanism. This instability strip partially overlaps the already known GW Vir instability strip of intermediate/long-period *g*-modes destabilized by the classical κ-mechanism acting on the partial ionization of C and/or O in the envelope of PG1159 stars. We found that PG1159 stars characterized by thick He-rich envelopes and located inside this overlapping region could exhibit both short and intermediate/long periods simultaneously. As a natural application of our results, we study the particular case of VV 47, a pulsating planetary nebula nucleus (PG1159 type) that is particularly interesting because it has been reported to exhibit a rich and complex pulsation spectrum including a series of unusually short pulsation periods. We found that the long periods exhibited by VV 47 can be readily explained by the classical κ-mechanism, while the observed short-period branch below ≈300 s could correspond to modes triggered by the He-burning shell through the ϵ-mechanism, although more observational work is needed to confirm the reality of these short-period modes. Were the existence of short-period *g*-modes in this star convincingly confirmed by future observations, VV 47 could be the first known pulsating star in which both the κ-mechanism and the ϵ-mechanism of mode driving are *simultaneously* operating.

Key words: stars: evolution – stars: individual (VV 47) – stars: interiors – stars: oscillations – white dwarfs

Online-only material: color figures

1. INTRODUCTION

At present, the study of stellar pulsations constitutes one of the most fundamental pillars on which the building of stellar astrophysics rests. Although the theory of stellar pulsations was initially elaborated to explain the existence of classical variable stars such as Cepheids and RR Lyrae, in the last few decades the study of pulsating stars has been extended to many other different kinds of stars that were previously regarded as constant stars (e.g., Unno et al. 1989; Gautschy & Saio 1995). Nowadays, new classes of pulsating stars across the HR diagram are being routinely uncovered from ground-based observations as well as space missions (e.g., *CoRoT*, *MOST*; see Aerts et al. 2008). The study of stellar pulsations through the approach of asteroseismology constitutes a powerful tool to probe the internal structure and evolution of stars.

Most of the pulsations exhibited by pulsating stars are self-excited through the classical κ-mechanism operating in a partial ionization zone near the surface of stars (Cox 1980; Unno et al. 1989). As a matter of fact, this mechanism is responsible for pulsations of the stars in the classical instability strip due to partial ionization of H and He I and/or He II. In the driving zone, the opacity perturbation increases outward so that radiative luminosity is blocked in the compression phase of pulsation. The region gains thermal energy in the compression phase and it loses thermal energy in the expansion phase.

A less common—and consequently less explored—pulsation driving mechanism in stars is the ϵ-mechanism. This mechanism is due to vibrational instability induced by thermonuclear reactions. In this case, the driving is due to the strong dependence of nuclear burning on temperature. During maximum compression, the temperature and thus the nuclear energy production rates are higher than at equilibrium. So, in the layers where nuclear reactions take place, thermal energy is gained at compression while the opposite happens during the expansion phase (Unno et al. 1989; Gautschy & Saio 1995). An excellent historical account of studies on vibrational destabilization of stars by the ϵ-mechanism, can be found in Kawaler (1988)—we refer the interested reader to that paper for details.

In this paper, we explore the ϵ-mechanism in connection with pulsating PG1159 stars. These stars, also called GW Vir or DOV, are very hot H-deficient post-asymptotic giant branch (AGB) stars with surface layers rich in He, C, and O (Werner & Herwig 2006) that exhibit multiperiodic luminosity variations with periods ranging from 300 to 6000 s, attributable to nonradial *g*-modes driven by the κ-mechanism acting on the region of partial ionization of C and O (Starrfield et al. 1983, 1984, 1985; Gautschy 1997; Quirion et al. 2004; Gautschy et al. 2005; Córsico et al. 2006; Quirion et al. 2007). Some pulsating PG1159 stars are still embedded in a nebula and are called planetary nebula nuclei variable (PNNV) stars (see

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Winget & Kepler 2008 and Fontaine & Brassard 2008 for recent reviews).

Evolutionary models of PG1159 stars with thick He-rich envelopes located at the upper left portion of the HR diagram are characterized by the presence of vigorous He-burning shells. The first attempt to study the effect of the ϵ-mechanism induced by an He-burning shell in H-deficient pre-white dwarf stars was the seminal work by Kawaler et al. (1986). These authors found some g-modes excited through this mechanism with periods in the range 70–200 s. Observationally, however, no signature of these short pulsation periods was found in the surveys of planetary nebula nuclei conducted at that time (Grauer et al. 1987; Hine & Nather 1987). Later on, stability analysis on simplified PG1159 models by Saio (1996) and Gautschy (1997) also predicted unstable g-modes driven by the ϵ-mechanism with periods in the range 110–150 s.

The interest in the ϵ-mechanism in the context of H-deficient post-AGB stars has recently been renewed by the discovery of luminosity variations in the PNNV star VV 47 ($T_{\rm eff}$ = 130,000 ± 5000 K, $\log g$ = 7 ± 0.5, C/He = 1.5, and O/He = 0.4; Werner & Herwig 2006) by González Pérez et al. (2006). The most outstanding feature of VV 47 is that its period spectrum appears to include a series of unusually short pulsation periods (∼130–300 s), the shortest periods ever detected in a pulsator of its class. González Pérez et al. (2006; see also Solheim et al. 2008) speculate that these rapid oscillations could be excited by the ϵ-mechanism.

In this work, we largely extend the pioneering work by Kawaler et al. (1986), Saio (1996), and Gautschy (1997) by performing fully nonadiabatic pulsation computations on realistic PG1159 models extracted from full evolutionary sequences with a wide range of stellar masses and effective temperatures. In particular, we gather strong evidence for the existence of a new short-period g-mode instability strip of pulsating PG1159 stars due to the ϵ-mechanism. In addition, we examine the possibility that the short-period g-modes of VV 47 could be excited by this mechanism. The paper is organized as follows: in the next section, we briefly describe the input physics of the PG1159 evolutionary sequences analyzed and the nonadiabatic treatment of the pulsations. In Section 3, we describe the stability analysis. In Section 3.3, we present the application to the star VV 47, and in Section 3.4 we discuss the case of the prototypical DOV star PG1159−035 in the context of our theoretical findings. Finally, in Section 4 we summarize our main results and make some concluding remarks.

2. EVOLUTIONARY/PULSATIONAL MODELING OF PG1159 STARS

The PG1159 equilibrium models on which the present investigation rests on were extracted from the evolutionary calculations presented by Althaus et al. (2005), Miller Bertolami & Althaus (2006), and Córsico et al. (2006), who computed the complete evolution of model star sequences with initial masses on the zero-age main sequence (ZAMS) in the range 1–3.75 $M_{\odot}$. The evolutionary tracks for the H-deficient pre-white dwarf remnants are displayed in Figure 1. All of the post-AGB evolutionary sequences, computed with LPCODE (Althaus et al. 2005), were followed through the very late thermal pulse (VLTP) and the resulting born-again episode that gives rise to the H-deficient, He-, C-, and O-rich composition characteristic of PG1159 stars. For details about the input physics and evolutionary code used, and the numerical simulations performed to obtain the PG1159 evolutionary sequences employed here, we refer the interested

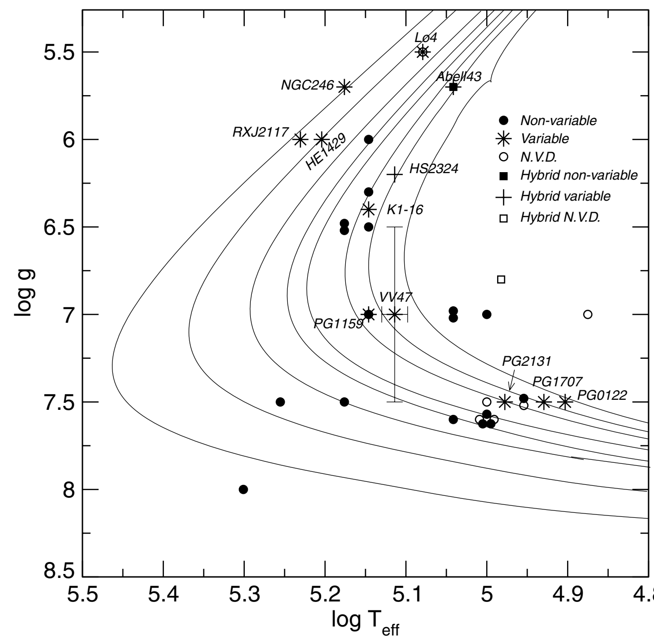

Figure 1. PG1159 evolutionary tracks of Althaus et al. (2005), Miller Bertolami & Althaus (2006), and Córsico et al. (2006), with stellar masses of (from right to left): $M_* = 0.515, 0.530, 0.542, 0.565, 0.589, 0.609, 0.664,$ and $0.741\ M_{\odot}$. Also shown is the location of known PG1159 stars. The error bars for VV 47 are displayed.

reader to the works mentioned above. One distinctive feature that is common to all of our sequences and crucial for this study is that the PG1159 models are characterized by He-rich envelopes thick enough as to sustain active He-burning shell sources during the evolutionary stages of interest. This is at variance with the nonstandard PG1159 models employed in Althaus et al. (2008) to explain the $\dot{\Pi}$ values in PG1159−035, which are characterized by thin He-rich envelopes and so they are not able to sustain an active He-burning shell.

The pulsational stability analysis presented in this work was carried out with the linear, nonradial, nonadiabatic pulsation code described in Córsico et al. (2006). The "frozen-in convection" approximation was assumed because the flux of heat carried by convection is negligible in PG1159 stars. At variance with Córsico et al. (2006), in this work we have fully taken into account the ϵ-mechanism for mode driving operating in the He-shell nuclear-burning region. Because we are interested in PG1159 stars which are H-deficient, we are only concerned with the He-burning reactions. Fortunately, because g-mode pulsation timescales are much shorter than the timescales of nucleosynthesis, possible phase delays between the temperature perturbations and the abundance variations are unimportant. Hence, they can be neglected, largely simplifying the pulsational stability analysis (Unno et al. 1989; Kawaler et al. 1986).[5]

3. NONADIABATIC RESULTS

We analyzed the stability properties of about 4000 stellar models covering a wide range of effective temperatures ($5.5 \gtrsim \log(T_{\rm eff}) \gtrsim 4.7$) and stellar masses ($0.515 \lesssim M_*/M_{\odot} \lesssim 0.741$).

[5] We note that some of our sequences have trace surface abundances of H ($X_{\rm H} \lesssim 10^{-3}$) which give rise to some H-burning. However, exhaustive test stability computations demonstrate that H-burning is very weak and extends on a extremely narrow layer, as a result of which the H-shell burning is completely irrelevant in destabilizing modes and will not be further considered in this paper.

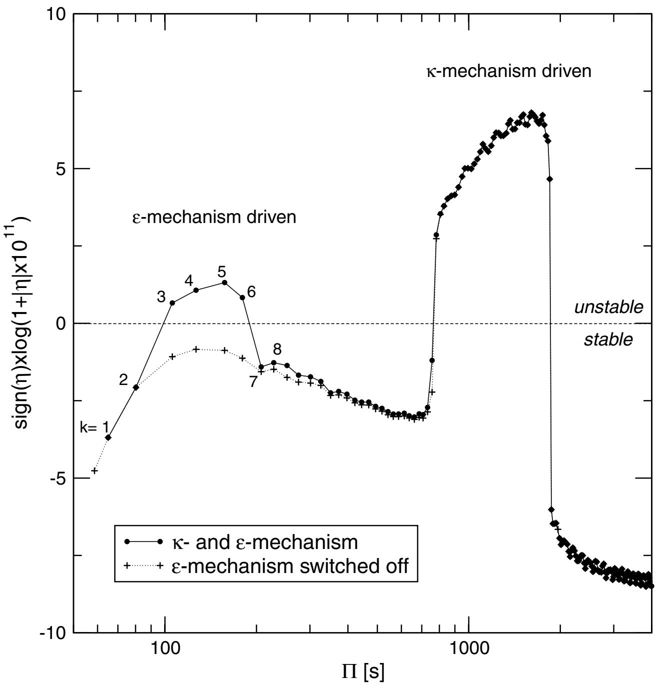

Figure 2. Dipole ($\ell = 1$) normalized growth rates η (black dots connected with continuous lines) in terms of the pulsation periods for a 0.530 $M_\odot$ PG1159 template model located before the evolutionary knee ($T_{\rm eff} = 138{,}400$ K, $\log(L_*/L_\odot) = 3.14$). Numbers indicate the radial order k for low-order modes. The large numerical range spanned by η is appropriately scaled for a better graphical representation. The two ranges of overstable g-modes—one due to the κ-mechanism and the other induced by the ϵ-mechanism—are clearly discernible. Plus symbols connected with dotted lines correspond to the case where the ϵ-mechanism is explicitly suppressed in the stability calculations.

For each model, we restricted our study to $\ell = 1 g$-modes with periods in the range 50–7000 s.

3.1. A Single Template Model

We start our description by focusing on a 0.530 $M_\odot$ PG1159 template model with $T_{\rm eff} = 138{,}400$ K and $\log(L_*/L_\odot) = 3.14$ located before the evolutionary knee in Figure 1. The surface chemical composition of the model is $X(^4{\rm He}) = 0.33$, $X(^{12}{\rm C}) = 0.39$, $X(^{13}{\rm C}) = 0.05$, $X(^{14}{\rm N}) = 0.02$, and $X(^{16}{\rm O}) = 0.17$. Figure 2 displays the normalized $\ell = 1$ growth rates $\eta = -\Re(\sigma)/\Im(\sigma)$ (where $\Re(\sigma)$ and $\Im(\sigma)$ are the real and the imaginary parts, respectively, of the complex eigenfrequency σ) in terms of the pulsation periods (Π) corresponding to our template model. In the interests of a better graphical representation, the huge numerical range spanned by η is appropriately scaled (see Gautschy 1997). The sign function allows to discriminate between stable and unstable modes. The presence of two well defined families of overstable g-modes, one at the intermediate- and long-period regime, and the other one at the short-period regime, is apparent. The first group of periods (≈750–1800 s) corresponds to modes driven by the well known κ-mechanism operating at the region of the opacity bump due to partial ionization of C and O, centered at $\log T \approx 6.2$ (Gautschy et al. 2005; Córsico et al. 2006). The second group of periods, which are associated to low radial order g-modes, are destabilized by the action of the vigorous He-shell burning through the ϵ-mechanism.

The short-period instabilities uncovered here are of the same nature than those found by Kawaler et al. (1986) in the context of H-deficient hot central stars of planetary nebulae. Here, as in that work, the ϵ-mechanism induced by the He-shell burning constitutes the source of driving. In absence of this destabilizing agent, the overstable modes with periods in the range (≈100–180 s) turn out to be stable, while the remainder modes of the pulsation spectrum remain unchanged. This is vividly displayed in Figure 2 that shows with plus symbols the results of additional stability computations in which the nuclear energy production rate, ϵ, and the logarithmic derivatives $\epsilon_T = \left(\frac{\partial \ln \epsilon}{\partial \ln T}\right)_\rho$ and $\epsilon_\rho = \left(\frac{\partial \ln \epsilon}{\partial \ln \rho}\right)_T$, are forced to be zero in the pulsation equations. It is worth emphasizing that in the present effort we are able to obtain destabilization of g-modes through both the κ-mechanism *and* the ϵ-mechanism in the same PG1159 equilibrium model. This is at variance with the study by Kawaler et al. (1986), who reported only ϵ-destabilized modes.

The ϵ-mechanism behaves as an efficient filter of modes that destabilizes only those g-modes that have their largest maximum of the temperature perturbation ($\delta T/T$) in the narrow region of the He-burning shell (see Kawaler et al. 1986). In the specific case of our template model, only the g-modes with $k = 3, 4, 5$, and 6 meet such a condition and, as a result, they are ϵ-destabilized. For $k = 1$ and 2, the largest maximum of $\delta T/T$ lies at inner layers with respect to the He-burning shell. Thus, these modes are stable. For modes with $k \geqslant 7$, the opposite is true and these modes also are stable.

Test stability calculations with $\ell = 2$ for our template model indicate that there exists only one quadrupole ϵ-destabilized g-mode which corresponds to $k = 5$ with a period $\Pi \sim 95$ s, about 40% shorter than the corresponding $k = 5$ mode with $\ell = 1$ ($\Pi \sim 157$ s). Hence, in general, a narrower range of shorter periods is expected to be associated with ϵ-destabilized g-modes with $\ell = 2$ as compared with the case of $\ell = 1$.

3.2. A New PG1159 Instability Strip

Having described our results for a single template model, we now are in conditions to examine the location and extension of the complete unstable domain associated with the ϵ-mechanism. Our results are depicted in Figure 3, which displays the instability strip of ϵ-destabilized modes in the $\log T_{\rm eff}$–$\log g$ drawn with thick black curves along the PG1159 evolutionary tracks. In addition, the GW Vir instability domain of κ-destabilized modes (see Córsico et al. 2006) is depicted with red (gray) lines along the tracks. Note that the instability strip for ϵ-destabilized modes partially overlaps the domain of κ-destabilized modes. So, our results indicate the existence of three well defined instability regimes in the $\log T_{\rm eff}$–$\log g$ plane: a regime—split into two regions, one at low gravity and the other at high gravity—in which stellar models harbor intermediate/long-period g-modes excited by the κ-mechanism only; another region corresponding to short-period modes destabilized by the ϵ-mechanism only; and finally a region in which models experience pulsational destabilization by the κ-mechanism and the ϵ-mechanism of driving simultaneously. Notably, only the region corresponding to the ϵ-mechanism is not occupied by any known PG1159 star (see Figure 3).

We stress that in previous works (Kawaler et al. 1986; Saio 1996; Gautschy 1997) only *some* short-period g-modes were found to be destabilized by the ϵ-mechanism. Needless to say, due to the very few ϵ-destabilized modes found in those exploratory works, no clear extension and location of the ϵ-mechanism instability domain were obtained, thus hampering those authors from making further consideration of such modes. At variance with those works, in the present study we are able to find a *complete* instability strip of ϵ-destabilized modes.

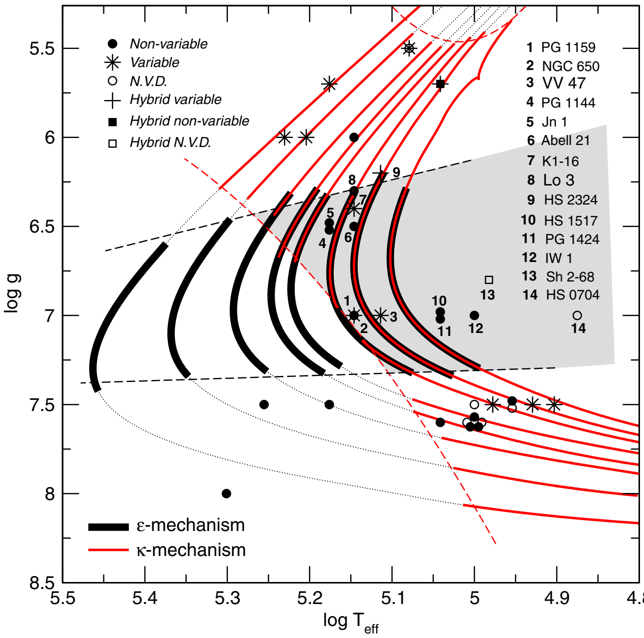

Figure 3. Same as Figure 1, but including the loci of models having $\ell = 1$ (dipole) κ-destabilized modes with solid red (gray) curves along the tracks, and models harboring short-period ϵ-destabilized modes according to the present study. Superposition of both types of curves corresponds to stellar models with both ϵ- and κ-destabilized modes (shaded area). The location and designation of relevant PG1159 stars is also shown.

(A color version of this figure is available in the online journal.)

The degree of driving and the place that it might occur in the $\log T_{\rm eff}$–$\log g$ diagram is sensitive to the stellar mass, previous evolutionary history, and so on. Thus, due to the uncertainties in the stellar evolution modeling (overshooting, nuclear reaction rates, etc.), the surface and internal composition of PG1159 stars are not known in detail, and so a clear instability domain for ϵ-destabilized pulsations is difficult to drawn. So, what is shown in Figure 3 is the shape and location of the ϵ-mechanism instability strip obtained by us under the particular assumptions adopted in the construction of the PG1159 evolutionary models of Miller Bertolami & Althaus (2006). The extension and location of this instability domain might change if other assumptions for the evolutionary history of the progenitor stars were adopted.

All of the overstable ϵ-destabilized modes computed in this work are characterized by very tiny (10^{-9} to 10^{-12}) linear growth rates η, by far smaller than those characterizing overstable modes excited by the κ-mechanism ($10^{-8} \lesssim \eta \lesssim 10^{-4}$). So, the question rises about what would be the chance for a given ϵ-destabilized mode to have plenty of time for developing observable amplitudes. To analyze this question, we consider the time interval that the models spend crossing the instability strip of ϵ-destabilized modes, Δt, and the maximum and minimum e-folding times, $\tau_e^{\rm max}$ and $\tau_e^{\rm min}$, of the unstable modes for a given stellar mass. The e-folding times are defined as $\tau_e \equiv 1/|\Im(\sigma)|$, such that the time dependence of the amplitude of the pulsations is given by $\xi(t) \propto e^{i\sigma t}$, and $\Im(\sigma) < 0$ for overstable modes.

The values of Δt, $\tau_e^{\rm min}$, and $\tau_e^{\rm max}$ are provided in Table 1 for each value of the stellar mass. Note that the three timescales monotonically decrease for increasing stellar mass. For all of our PG1159 sequences, we found that the most unstable modes—those with the smaller values of τ_e—are found near the low-gravity (high-luminosity) boundary of the instability domain (upper black dashed line in Figure 3), when the models

Table 1
Minimum and Maximum e-Folding Times (in yr), and the Time (in yr) that PG1159 Models Spend within the Instability Strip of ϵ-destabilized Modes

$M_*/M_\odot$	$\tau_e^{\rm min}$	$\tau_e^{\rm max}$	Δt
0.515	3410	1.5×10^6	1.60×10^5
0.530	2580	1.0×10^6	1.01×10^5
0.542	1610	3.8×10^5	5.95×10^4
0.565	1400	1.3×10^5	2.78×10^4
0.589	1160	1.0×10^5	2.47×10^4
0.609	742	4.7×10^4	1.26×10^4
0.664	361	1.8×10^4	4830
0.741	180	7000	1570

are still evolving to the blue before reaching the evolutionary knee. In contrast, when models are already evolving toward the white dwarf cooling track, the ϵ-destabilized modes are only marginally unstable, and so they are characterized by large e-folding times.

Table 1 shows that $\tau_e^{\rm min} \ll \Delta t$ for all of our sequences. This means that g-modes that are destabilized at epochs before the evolutionary knee, characterized by short e-folding times, have time enough to reach observable amplitudes before the star leaves the instability strip. On the other hand, it is apparent that $\tau_e^{\rm max} \gtrsim \Delta t$. Thus, the g-modes that are destabilized in models close to the high-gravity limit (low-luminosity) of the instability strip (lower black dashed line in Figure 3) have little—or even null—chances to develop observable amplitude before the model abandons the instability domain.

In summary, our computations predict that some g-modes (those with short τ_e) could have plenty of time to grow and finally develop observable amplitudes. We caution, however, that this prediction is based on a *linear* stability analysis, and that the last word should came from a detailed nonlinear description of nonadiabatic pulsations. Such a nonlinear treatment is not available at the present stage. Also, there are other effects (stellar winds, diffusion, etc.) suspected to be present in real stars that could be affecting the growth of pulsations. The assessment of their effects on the modes that are predicted to be unstable in the frame of our analysis is beyond the scope of the present study.

The next step in our analysis is to derive the range of periods (Π) of overstable ϵ-destabilized modes. Figure 4 displays the regions of the κ-mechanism instability domains in the $\log T_{\rm eff}$–Π diagram, depicted with lines of different colors for the various stellar masses. Notably, the figure also shows the presence of a separate, well defined instability domain for a broad range of effective temperatures ($5.46 \gtrsim \log T_{\rm eff} \gtrsim 4.99$) and pulsation periods in the interval 55 s $\lesssim \Pi \lesssim$ 200 s, associated with ϵ-destabilized g-modes with radial orders ranging from 2 to 5 for $M_* = 0.515\,M_\odot$ and from 3 to 8 for $M_* = 0.741\,M_\odot$. The stages corresponding to phases before (after) the evolutionary knee are depicted with small dot (plus) symbols. A close inspection of the figure reveals that for the low-mass models, most of modes are destabilized after the evolutionary knee. For the high-mass models the situation is reversed, that is, most of overstable modes are destabilized before the evolutionary knee. The existence of this new instability domain of short-period g-modes in stellar models representative of PG1159 stars is the main result of our study.

In particular, it is worth emphasizing that the ϵ-mechanism should be active in a PG1159 star irrespective of the precise abundances of He, C, and O at the surface, because in this case the mode excitation takes place at deep layers in the star. This is at variance with the κ-mechanism, which is strongly dependent

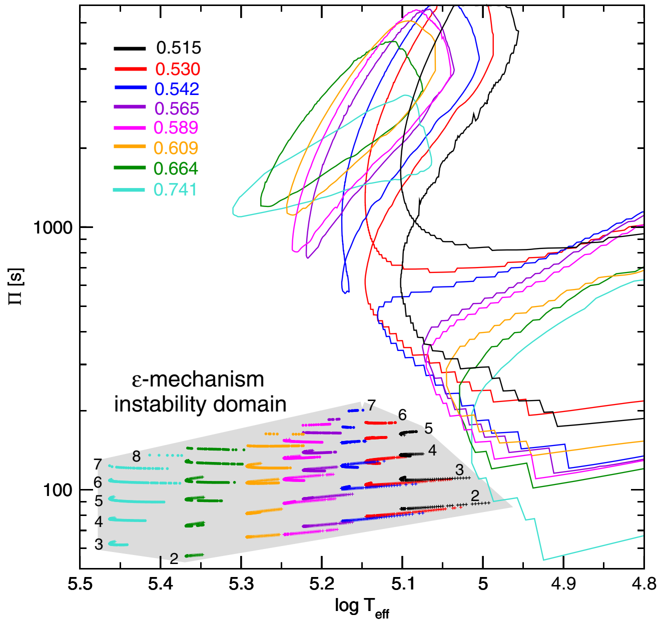

Figure 4. Dipole ($\ell = 1$) instability domains for overstable κ-destabilized g-modes, shown with thin lines of different colors for the various stellar masses. The ϵ-mechanism instability domain is emphasized with a shaded area. Short-period dipole unstable ϵ-destabilized g-modes are depicted with dot (plus) symbols for stages before (after) the evolutionary knee. Numbers indicate the radial order of the modes.

(A color version of this figure is available in the online journal.)

on the exact O/C/He abundances at the driving regions (see Quirion et al. 2007).

3.3. The Case of the PNNV Star VV 47

An immediate prediction of the present study is that PG1159-type stars populating the overlapping region of κ- and ϵ-destabilized modes in the $\log T_{\rm eff}$–$\log g$ diagram (the shaded region in Figure 3) should exhibit both short- and intermediate/long-period luminosity variations simultaneously. Table 2 lists the known PG1159 candidate stars. A glance of this table leads us to a somewhat disappointing conclusion: most of the stars located in the region of interest are not variables at all or have not been scrutinized for variability. Other stars, at most, exhibit intermediate/long-period luminosity variations which are typical of the high/intermediate-order g-modes driven by the κ-mechanism, but not the expected short periods typical of ϵ-destabilized modes. In particular, this is the case for the prototype DOV star, PG1159−035.

There is one object, the PNNV star VV 47, which is suspected to pulsate in short- and long-period modes (González Pérez et al. 2006). This star ($T_{\rm eff} = 130{,}000 \pm 5000$ K, $\log g = 7 \pm 0.5$, C/He = 1.5, and O/He = 0.4; Werner & Herwig 2006) was first observed as potentially variable by Liebert et al. (1988). Later, it was monitored by Ciardullo & Bond (1996), but no clear variability was found. Finally, González Pérez et al. (2006) were able to confirm the—until then, elusive—intrinsic variability of VV 47 for the first time. They found evidence that the pulsation spectrum of this star is extremely complex. The most outstanding feature of VV 47 is the presence of high-frequency peaks (at periods ∼130–300 s) in the power spectrum, which could be serious candidates for low-k radial order g-modes triggered by the ϵ-mechanism.

We decided to test the attractive possibility that the short periods observed in VV 47 could be due to the ϵ-mechanism.

Table 2
Known PG1159 Stars Populating the Overlapping Instability Region of ϵ- and κ-destabilized Modes

#	Star	PN	Variable	Period Range (s)
1	PG1159−035	No	Yes	430–840
2	NGC 650−1	Yes	No	. . .
3	VV 47	Yes	Yes (?)	∼ 260
				∼ 2170–4300
4	PG 1144+005	No	No	. . .
5	Jn 1	Yes	Yes (?)	454–1860
6	Abell 21	Yes	No	. . .
7	K 1−16	Yes	Yes	1500–1700
8	Longmore 3	Yes	No	. . .
9	HS 2324+3944	No	Yes	2005–2570
10	HS 1517+7403	No	No	. . .
11	PG 1424+535	No	No	. . .
12	IW 1	Yes	No	. . .
13	Sh 2−68	Yes	?	. . .
14	HS 0704+6153	No	?	. . .

We first estimated the stellar mass of VV 47. From the location of VV 47 in the $\log T_{\rm eff}$–$\log g$ plane (see Figure 1), it is apparent that the spectroscopic mass of VV 47 is of $\approx 0.525\,M_\odot$. In addition, a preliminary adiabatic asteroseismological analysis on this star indicates that the seismological mass of VV 47—obtained from the period spacing data ($\Delta\Pi \approx 24$ s)—is of ≈ 0.52–$0.53\,M_\odot$, in excellent agreement with the spectroscopic derivation. So, we shall focus on the case of the evolutionary sequence of $M_* = 0.530\,M_\odot$. This sequence is characterized by a thick He-rich envelope ($M_{\rm env} \sim 0.045\,M_\odot$).

We would like to see how well the theoretical ranges of periods of unstable modes corresponding to this sequence fit the observed period spectrum of VV 47. Figure 5 displays the regions of the κ-mechanism instability domain (light and dark gray) for the $0.530\,M_\odot$ sequence. The figure also shows the presence of a well defined instability domain ($77\,{\rm s} \lesssim \Pi \lesssim 180\,{\rm s}$) that corresponds to ϵ-destabilized g-modes with $k = 2, \ldots, 6$ (large and small dots). Also depicted in the plot are the periods reported by González Pérez et al. (2006) for VV 47 with their corresponding uncertainties in $T_{\rm eff}$. We have emphasized with black small circles the periods associated with modes having the best chances to be real, according to González Pérez et al. (2006). It is apparent that, whereas most of the long periods observed in VV 47 are qualitatively explained by the κ-mechanism when the model star is before the evolutionary knee, the short-period branch (below ∼300 s) of the pulsation spectrum of the star is not accounted for at all by the theoretical domains corresponding to this destabilizing agent. We can see instead that the short periods of VV 47—in particular $\Pi \lesssim 200$ s—are sufficiently accounted for by the ϵ-destabilized g-modes. Note, however, that if only periods detected with sufficiently high significance (black filled circles) are used to compare with our theoretical predictions, then the period at 261.4 s cannot be explained by a low-order g-mode excited by the ϵ-mechanism. In fact, this period is considerably longer than the longest period (≈180 s) of the g-modes which can be excited by the ϵ-mechanism as our analysis predicts.

Clearly, more observational work is needed to put the reality of the short periods in VV 47 on a solid basis. Were the existence of these short periods confirmed by future observations, then they could be attributed to the ϵ-mechanism, and this could be indicating that VV 47 should have a *thick* He-rich envelope to support an active He-burning shell.

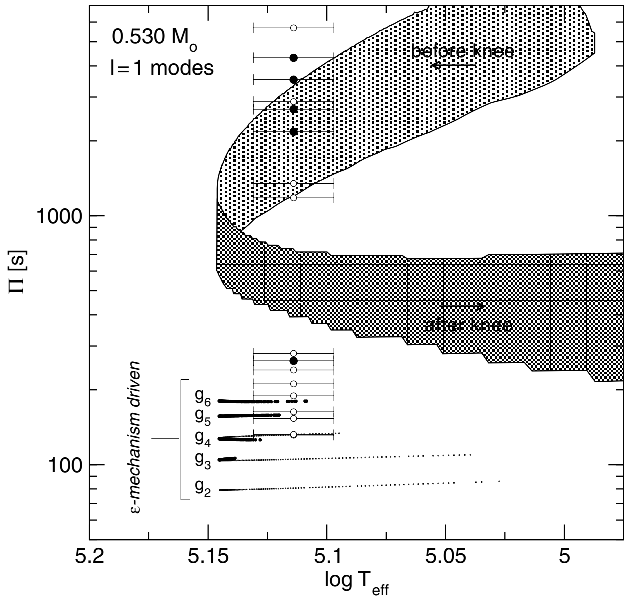

Figure 5. $\ell = 1$ regions of the κ-mechanism instability domain, shown with light (dark) gray for stages before (after) the evolutionary knee, corresponding to the 0.530 $M_{\odot}$ sequence. Arrows indicate the time sense of evolution. Also shown is the evolution of the periods corresponding to the ϵ-destabilized modes $g_2, \ldots, g_6$, with large (small) dots for stages before (after) the evolutionary knee. Finally, the periods reported by González Pérez et al. (2006) for VV 47 with their corresponding uncertainties in $T_{\rm eff}$ are displayed with small circles. Periods detected with sufficiently high significance are emphasized with black filled circles.

3.4. *The Case of the DOV Star PG1159−035*

Another consequence of our investigation concerns the pulsating star PG1159−035, the prototype of the class and the best-studied DOV. Indeed, note from Figure 3 that a trend of our results is that this variable star should exhibit short-period ϵ-destabilized modes if the thick He-rich envelopes derived from our evolutionary calculations were representative of the star. These modes are not observed by Costa et al. (2007). This result suggests that the He-burning shell may not be active in PG1159−035. This would indicate that this star has a thinner He-rich envelope than what is traditionally derived from standard evolutionary calculations, in line with the recent finding by Althaus et al. (2008) that a thinner He-rich envelope (at least a factor of 2 below of the value predicted by the standard evolution theory) for PG1159−035 should be invoked to alleviate the longstanding discrepancy between the observed (Costa & Kepler 2008) and the theoretical (Córsico et al. 2008) rates of period change in that star.

If the short periods observed in VV 47 were confirmed, then we should face the problem of the coexistence of two PG1159 stars located very close to each other in the $\log T_{\rm eff}$–$\log g$ diagram (see Figure 3) but with substantially different thickness of the He-rich envelopes. This would suggest that these stars could have had a different evolutionary history, a suggestion reinforced by the fact that VV 47 still retains a planetary nebula while PG1159−035 does not.

4. SUMMARY AND CONCLUSIONS

In this paper, we have presented a fully nonadiabatic stability analysis on state-of-the-art PG1159 models generated taking into account the complete evolution of progenitor stars, through the thermally pulsing AGB phase and born-again episode. We have explored the possibility that nonradial g-mode pulsations could be destabilized by an He-burning shell through the ϵ-mechanism. Our study covers a broad range of stellar masses and effective temperatures. We confirm and extend the pioneering work of Kawaler et al. (1986), Saio (1996), and Gautschy (1997) on this topic. The main results are the following.

1. We found strong theoretical evidence for the existence of a separate, well defined PG1159 instability strip in the $\log T_{\rm eff}$–$\log g$ diagram characterized by short-period g-modes excited by the ϵ-mechanism due to the presence of active He-burning shells. Notably, this instability strip partially overlaps the already known GW Vir instability strip due to the κ-mechanism acting on the partial ionization of C and/or O in the envelope of the PG1159 stars. We emphasize that while in previous works only some short-period g-modes were found to be destabilized by the ϵ-mechanism, in the present study we found a *complete* instability strip of ϵ-destabilized modes.
2. At variance with the classical κ-mechanism responsible for the intermediate/long-period GW Vir pulsations, the ϵ-mechanism should be efficient even in PG1159 stars with low C and O content in their envelopes.
3. The ϵ-driven g-modes that are destabilized at epochs before the evolutionary knee are characterized by short e-folding times (between $\approx$180 yr for $M_* = 0.741\,M_{\odot}$ and $\approx$3000 yr for $M_* = 0.515\,M_{\odot}$), and so they probably have time enough to reach observable amplitudes before the star leaves the instability strip. Note, however, that nonlinear effects, or the presence of a variety of phenomena such as stellar winds or diffusion, could affect the growth of pulsations.
4. We have closely examined the case of VV 47, the only PG1159 star for which observational evidence of the presence of short-period g-modes exists (González Pérez et al. 2006). For this star, we have derived for the first time a seismological mass of $\approx$0.52–0.53 $M_{\odot}$, in excellent agreement with the spectroscopic mass ($\approx$0.525 $M_{\odot}$). If we accept that all of the periods reported by González Pérez et al. (2006) are real, our stability analysis provides very strong support to the idea that the physical origin of the short periodicities could be the ϵ-mechanism powered by an active He-burning shell, whereas the long-period branch of the period spectrum of this star should be due to the κ-mechanism acting on the region of partial ionization of C and O. However, if only periods detected with sufficiently high significance are taken into account, then the period at 261.4 s cannot be explained by a low-order g-mode excited by the ϵ-mechanism.
5. We speculate that the absence of short periods ($\lesssim$300 s) in the pulsation spectrum of PG1159−035 could be indicating that the He-burning shell may not be active in this star. This would indicate that PG1159−035 has a thinner He-rich envelope than what is traditionally derived from standard evolutionary computations.

In light of our results, if the reality of the short periods of VV 47 were confirmed by follow-up observations, this star could be the first known pulsating PG1159 star undergoing nonradial g-modes destabilized by the ϵ-mechanism. Even more, VV 47 could be the first known pulsating star in which both the κ-mechanism and the ϵ-mechanism of mode driving are *simultaneously* operating. Further time-series photometry of VV 47 will be needed to firmly establish the reality of the short-period pulsations detected in this star.

On the other hand, the apparent absence of short-period pulsations in the remainder variable stars—such as K 1−16, HS 2324+3944, and Jn 1—could be an indication that, like PG1159−035, they are characterized by thin He-rich envelopes, as a result of which they should lack of stable He-shell burning. Another possibility is that short-period pulsations could be indeed present in these stars, but with very low amplitudes, below the actual detection limits.

Also, it is quite intriguing the absence of both short- and intermediate/long-period pulsations in the up to now constant stars (NGC 650−1, PG 1144+005, Abell 21, Longmore 3, HS 1517+7403, PG 1424+535, IW 1) that populate the overlapping region of the ϵ- and κ-destabilized modes. In any case, extensive searches for low-amplitude intrinsic variability in these stars and also in the stars Sh 2−68 and HS 0704+6153, which have not been observed for variability yet, should be worth doing in order to test the existence of the new theoretical instability strip uncovered in this work.

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