Low-mass, helium-enriched PG1159 stars: a possible evolutionary origin and the implications for their pulsational stability properties

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1. Introduction

PG1159 stars constitute the evolutionary link between the asymptotic giant branch (AGB) stars and most of the hydrogen–deficient white dwarf (WD) stars. Currently, 37 stars are members of the PG1159 family, which span a wide domain in the log $T_{\text{eff}}$–log $g$ diagram ($g$ in cgs units): $5.5 \lesssim \log g \lesssim 8$ and $75000 \lesssim T_{\text{eff}} \lesssim 200000$ K; see Werner & Herwig (2006) for a review. These hot stars are thought to be formed via a born–again episode resulting either from a very late thermal pulse (VLTP) experienced by a hot WD during its early cooling phase — see Schönbömer (1979) and Iben et al. (1983) for earlier references — or a late thermal pulse (LTP) that occurs during the post-AGB evolution when hydrogen burning is still active; see Blöcker (2001) for references. During the VLTP, the helium flash driven convection zone reaches the hydrogen-rich envelope of the star, with the consequence that most of the hydrogen content is burnt. The star is then forced to evolve rapidly back to the AGB and finally into the domain of the PG1159 stars at high $T_{\text{eff}}$ values. LTP also leads to a hydrogen–deficient composition but as a result of a dilution episode.

Interest in PG1159 stars is additionally motivated by the fact that eleven of them exhibit multiperiodic luminosity variations induced by nonradial $g$–mode pulsations. Pulsating PG1159 — commonly referred to as GW Virginis variables — show low degree ($\ell \leq 2$), high radial order ($k \gtrsim 18$) $g$–modes with periods in the range from about 300 to 3000 s. About half of them are still surrounded by a planetary nebula. Since the pioneering works of Starrfield et al. (1983, 1984) — see also Starrfield et al. (1985) and Stanghellini et al. (1991) — the pulsation driving mechanism and in particular the chemical composition of the driving zone in PG1159 stars have been the subject of hot debate. The works of Saio (1996) and Gautschy (1997), and more recently Quirion et al. (2004), Gautschy et al. (2005), and Córnsico et al. (2006) have convincingly demonstrated that $g$-mode pulsations in the range of periods of GW Virginis stars can be easily driven in PG1159 models with a uniform envelope composition — compatible with observed photospheric abundances — through the $\kappa$-mechanism associated with the cyclical partial ionization of the K–shell.

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The dispersion in the atmospheric composition of PG1159 stars bears relevance in the question of the excitation of pulsation modes in models of these stars, and particularly the coexistence of variable and non-variable stars in the domain of the GW Virginis, a longstanding issue recently addressed by Quirion et al. (2004). The helium–enriched and nitrogen–deficient nonpulsating PG1159 star MCT 0130–1937 is particularly outstanding. In fact, this object — characterized by a surface composition of about 0.74 He, 0.22 C, and 0.03 O (Werner & Herwig 2006) and a helium abundance range of about 0.30–0.85, and carbon and oxygen abundances span the ranges 0.15–0.60 and 0.02–0.20, respectively. In particular, the helium abundance covers mostly the range 0.3–0.5; only a minority of PG1159 stars show a helium–enriched abundance in the range 0.6–0.85.

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2. Evolutionary scenario

The evolutionary scenario proposed by Miller Bertolami & Althaus (2006) involves the computation of the advanced stages of the evolution of a low–mass star that, as a result of mass–loss events, avoids the thermally pulsing AGB phase and it experiences its first thermal pulse as a LTP after leaving the AGB. Indeed, helium abundances as high as those observed in the helium–enriched PG1159 stars are typical of the intershell helium abundances that develops during the first thermal pulse (∼0.74). Because the small envelope mass characterizing low–mass stars, this scenario appears to be quite likely in these stars.

The Hertzsprung–Russell diagram corresponding to the evolutionary scenario is shown in Fig. 1. Artificial mass–loss rates force the initially 1-M⊙ model star to undergo its first thermal pulse as a LTP at about 10000 K, after leaving the AGB. After the short–lived born–again episode and before the PG1159 domain, the remnant experiences two additional excursions to lower temperatures — the two double loop paths in Fig. 1 — by virtue of helium sub–flashes. The total time spent by the remnant in the red during these loop episodes amounts to about 3000 yr. During this time, mass–loss episodes are expected to erode the outer envelope considerably. For instance, mass–loss rates as high as 10−5 M⊙/yr and even larger have been observed in Sakurai’s object (Hajduk et al. 2005).

In the interests of helping to understand the evolutionary connections to be studied later, we show in Fig. 2 the chemical stratification by the end of the born–again (about 300 yr after the occurrence of the LTP). This figure illustrates the inner 1H, 4He, 12C, 14N, and 16O distribution in terms of the outer mass fraction q, where q = 1 − m∗/M∗.

1 Throughout this paper, we shall use abundances by mass fraction.

2 The spread in surface composition of most PG1159 stars can be explained by differences in stellar mass and the number of thermal pulses experienced by progenitors during the AGB.

3 During subsequent thermal pulses, the helium abundance in the intershell layer gradually decreases if convective extramixing like overshooting is considered; see Herwig (2000).
Note the presence of the intershell layer below the thin helium buffer, that results from the short-lived mixing episode during the helium flash at the LTP. This intershell layer of $0.04 \, M_\odot$ is substantially enriched in helium and deficient in nitrogen: $[^4\text{He}, ^{12}\text{C}, ^{16}\text{O}] = [0.73, 0.21, 0.03]$. Despite the small envelope ($3.7 \times 10^{-3} \, M_\odot$) overlying the intershell region, no strong dredge-up occurs. This is expected because of the low intensity of the first thermal pulse in low–mass stars. By assuming mass–loss rates within observational expectations, Miller Bertolami & Althaus (2006) found that the hydrogen–rich outer envelope is eroded and surface abundances start to change gradually by $\log T_{\text{eff}} \sim 4.6$, well before the sequence reaches the domain of the PG1159 stars. From this point until the intershell chemistry is uncovered, the nitrogen surface abundance remains $0.012$ with no trace of carbon. 30000 yr later — at $T_{\text{eff}} \sim 108000$ K — the last vestiges of hydrogen–rich material left in the star are removed and the surface exhibits the buffer abundances: $[^4\text{He}, ^{12}\text{C}, ^{14}\text{N}, ^{16}\text{O}] = [0.98, 0, 0.012, 0]$. These will be the surface abundances until the helium buffer is eroded by further mass loss during the subsequent 50000 yr of evolution, see Fig. 1. During this time, the surface abundance will be typical of those exhibited by O(He) stars. Finally, when the helium buffer is removed the models display the intershell abundances — $[^4\text{He}, ^{12}\text{C}, ^{14}\text{N}, ^{16}\text{O}] = [0.74, 0.20, 0, 0.029]$ — characteristic of the helium–enriched PG1159 stars.

The location of these abundance changes in the log $T_{\text{eff}}$–log $g$ diagram is shown in Fig. 2. We also depict the location of two helium–rich O(He) stars: K1–27 and HS 2209+8229. In particular K1–27, for which detailed abundances have been derived, displays an almost pure helium composition (0.98) with traces of $^{14}\text{N}$ (0.017) — however small hydrogen and carbon contents cannot be excluded, see Rauch et al. (1998) — which are similar to the surface abundances predicted by the evolutionary scenario by the time the small helium buffer is uncovered: 0.98 $^4\text{He}$ and 0.012 $^{14}\text{N}$. In addition, we include in the figure the three helium–enriched and nitrogen–deficient PG1159 stars from the sample of non-pulsating stars of Dreizler & Heber (1998): HS 0704+6153, HS 1517+7403, and MCT 0130–1937 with
We are performing new simulations that show that tracks for H and He burning post–AGB stars are remarkably different for low–mass remnants ($M < 0.55 M_\odot$).

Needless to say, the exact location in the log $T_{\text{eff}}$–log $g$ diagram where the star will show O(He)- or helium–enriched surface abundances depends on the actual course of mass–loss events. To assess this, we have re–computed the post VLT evolution of the sequence but for the case in which mass–loss rates are one order of magnitude lower than assumed in Miller Bertolami & Althaus (2006). In particular, we assume a mass–loss rate during the giant phase of about 10$^{-7}$ $M_\odot$/yr. As a result, the surface layers of the models stay hydrogen– and helium–rich throughout the evolution. This places a lower limit — below observational expectations — to the mass–loss rates for which the evolutionary scenario may explain the existence of helium–enriched PG1159 stars like MCT 0130–1937.

Finally, we note that the low–mass helium–enriched PG1159 stars could be the result of a VLTP instead a LTP. To assess this we forced our post–AGB sequence to undergo a VLTP episode. In Fig. 1 we include the resulting track. The full track is shown in the inset. Note that for the PG1159 regime, both tracks are almost indistinguishable. As in the case for the LTP, the surface chemistry of the emerging star will be essentially that of the intershell layers. As in the case for the LTP, the surface layers of the models stay hydrogen– and helium–rich throughout the evolution. This makes the plausibility of the evolutionary scenario for the origin of this star even more attractive.

We note that the kinematical age of the nebula is not expected to change appreciably as a result of our lower stellar mass for K1–27.
This fact discards the possibility that the progenitors of these stars have experienced a VLTP episode. Note also that because the entire helium–rich buffer is engulfed by the helium flash convection zone during the VLTP, the development of a helium–rich surface composition characteristic of the O(He) stars is certainly not expected in this case. In addition, we want to comment on the fact that from our numerical experiments the occurrence of a VLTP episode in very low-mass stars ($M < 0.53 \, M_\odot$) appears to require a delicate fine tuning in the mass–loss rate. Thus, we are tempted to conclude that in these stars, VLTP episodes might be less likely than the LTP ones.

3. Pulsational stability properties

The evolutionary scenario proposed in Miller Bertolami & Althaus (2006) provides a possible explanation for the existence of helium–enriched PG1159 stars like MCT 0130–1937, linking them with the low–mass O(He) stars. In the frame of recent stability calculations (Quirion et al. 2004), we should expect that — as a result of helium poisoning — the pertinent stellar configurations do not show any sign of variability along the domain of the pulsating PG1159 stars. To assess this, we have performed pulsation stability analysis on our models. It is important to note that we are examining the stability properties of stellar models belonging to a real evolutionary sequence derived from the complete history of the progenitor star, an aspect which renders robustness to our pulsational results.

We performed a pulsation $g$-mode stability analysis by employing the linear, nonradial, nonadiabatic pulsation code described in Córtsico et al. (2006), which has recently been employed to reexamine the theoretical instability domain of pulsating PG1159 stars. This code assumes the “frozen-in convection” approximation in which the perturbation of the convective luminosity is ignored.

We analyze the stability properties of stellar models covering a range of $5.1 \gtrsim \log(T_{\text{eff}}) \gtrsim 4.7$. For each model we have restricted our study to $\ell = 1$ $g$-modes with periods in the range $50 \, \text{s} \lesssim \Pi \lesssim 5000 \, \text{s}$, thus comfortably embracing the full period spectrum observed in pulsating PG1159 stars. Surprisingly enough, we find that, despite the high helium abundance in the driving layers, there exists a region in the $\log(T_{\text{eff}})$–$\log g$ diagram for which our helium–enriched PG1159 sequence exhibits unstable pulsation modes. These modes are driven by the $\kappa$-mechanism associated with the opacity bump due to partial ionization of carbon and oxygen; see Gautschy et al. (2005) and Córtsico et al. (2006). To illustrate this, we present in Fig. 4 two panels which display the $\log(T_{\text{eff}})$–$\log g$ plane (upper panel) and the chemical abundances at the driving region (bottom panel) in terms of the effective temperature. Note the presence of a well-defined, though short, instability domain on the $\log(T_{\text{eff}})$–$\log g$ plane (thick portion of the track).
It is clear that the extension of the instability domain is markedly dependent on the helium abundance in the outer layers. Indeed, it is only by the time mass loss has eroded the helium buffer and exposed the helium– and carbon–rich intershell layer — bottom panel in Fig. 4 — that our models start to exhibit pulsational instability. From the modal diagram in Fig. 4, this instability starts to manifest itself at the longest pulsation periods. Note that unstable mode periods range from about 500 to 1600 s. Note also the strong decrease in the longest expected periods; this is because the high helium content in the driving region. By the time evolution has proceed to $T_{\text{eff}} \sim 100000$ K our models cannot drive unstable modes anymore and they become stable with further evolution (see Fig. 4). This behaviour is in sharp contrast with the situation encountered in low–mass PG1159 models with standard surface helium abundances, which show pulsational instability throughout this region of the log $T_{\text{eff}}$–log $g$ diagram (Córсisco et al. 2006).

It is clear from Fig. 4 that the nonpulsating MCT 0130–1937 star is located well outside the theoretical instability domain. In fact, we do not find any sign of instability in our models by the time evolution has reached the domain of MCT 0130–1937. This result hints at a consistent picture between the evolutionary scenario described in Section 2 that could explain the existence of helium–enriched PG1159 stars and the nonvariable nature of MCT 0130–1937.

4. Discussion and conclusions

We have examined the evolutionary scenario proposed by Miller Bertolami & Althaus (2006) that could explain the existence of low–mass, helium–enriched PG1159 stars. In particular, this scenario remarkably reproduces both the location in the log $T_{\text{eff}}$–log $g$ diagram and the helium–enriched and nitrogen–deficient composition of MCT 0130–1937, and suggests as well a possible evolutionary connection between the low–mass helium–rich O(He) stars (namely K1–27 and HS 2209+8229) and the helium–enriched PG1159 stars.

In this paper we have assessed the overstability of $g$–modes of the pertinent stellar models as evolution proceeds along the PG1159 domain. We find that — despite the high helium abundance in the driving layers — there exists a region in the log $T_{\text{eff}}$–log $g$ diagram for which our helium–enriched PG1159 sequence exhibits unstable pulsation modes with periods in the range 500 to 1600 s. This is a novel aspect contained in this study. The domain of instability is restricted to a rather narrow region of the log $T_{\text{eff}}$–log $g$ diagram. In particular, MCT 0130–1937 is located outside the theoretical instability domain. In this sense, this finding reinforces the conclusions arrived at in Quirion et al. (2004) about the nonvariability of MCT 0130–1937. This result hints at a consistent picture between the evolutionary scenario proposed by Miller Bertolami & Althaus (2006) for the origin of low–mass, helium–enriched PG1159 stars and the nonvariable nature of MCT 0130–1937. We conclude that MCT 0130–1937 is likely a real non-pulsating star and that the lack of pulsations cannot be attributed to unfavorable geometry.

However, as documented in Fig. 4 the nonpulsating helium–enriched object HS 1517+7403 lies well inside the predicted instability domain of our sequence. The presence of this non-variable star in the unstable region of our sequence could be understood in terms of its higher surface helium abundance (about 0.85, see Werner & Herwig 2006) as compared with that of MCT 0130–1937. In fact, the helium surface abundance of HS 1517+7403 is intermediate between the intershell helium abundance (0.75) of our models and that of the helium buffer (0.98) for which no unstable modes are found at all. For a quantitative inference, we have recomputed the post born–again evolution of our sequence by artificially changing the surface abundance to be compatible with that of HS 1517+7403. Our pulsational analysis shows in this case that, though a very narrow instability domain still persists — see Fig. 4 — HS 1517+7403 is outside the resulting theoretical unstable region. A helium abundance as high as that observed in HS 1517+7403 appears to be required to starve pulsations in this star. In contrast, for a helium abundance of 0.75 we saw that unstable modes are excited. This theoretical finding strongly supports the observational expectation for the unusually high helium abundance in HS 1517+7403.

From an evolutionary point of view, the high helium abundance in HS 1517+7403 is difficult to understand. Indeed, helium abundances larger than about 0.75 are not expected in the intershell layer during the AGB evolution. In addition, the presence of abundant carbon at its surface — about 0.13 by mass, Werner & Herwig (2006) — reflects the occurrence of helium burning in prior evolutionary stages. It is conceivable that the surface composition observed in HS 1517+7403 could be reflecting the chemical abundance distribution existing in the narrow transition layer between the helium buffer and the massive intershell region — see Fig. 4. This layer comprises only about 6.5 $\times 10^{-5} M_\odot$. With our adopted mass–loss rates, this layer is rapidly eroded in a matter of 6500 yr. During this time our sequence barely evolves in the log $T_{\text{eff}}$–log $g$ diagram — see Fig. 3. But for mass–loss rates similar to those characterizing O(He) stars (about $10^{-9} M_\odot/yr$) — a strong reduction in the mass–loss rate is indeed expected with decreasing luminosity — this layer would be eroded slow enough for the remnant to evolve to the domain of HS 1517+7403 with surface abundances similar to those observed in this star. This prompts us to suggest that HS 1517+7403 could be a transition object between the low–mass O(He) stars and the helium–enriched PG1159 stars like MCT 0130–1937.

The evolutionary scenario proposed by Miller Bertolami & Althaus (2006) suggests the possibility that low–mass O(He) stars could be the direct progenitors of the helium–enriched PG1159 stars, and not form a distinct post–AGB evolutionary channel — for instance the result of a stellar merging event. The plausibility of this scenario is sustained not only by spectroscopic evidence but also, as shown in this work, by consistent pulsational stability calculations of helium–enriched PG1159 models. In addition, the substantially smaller ages predicted by this scenario for K1–27 are in line with the expected kinematical age of the nebula. Finally, we have put forward the possibility of an evolutionary connection K1–27 $\rightarrow$ HS 1517+7403 $\rightarrow$ MCT 0130–1937. The existence of these evolutionary links appears more attractive in view of the observational fact that the helium–enriched PG1159 stars are nitrogen–deficient, which rules out the occurrence of a VLTP episode during the progenitor evolution. In case that a VLTP had occurred, then an homogeneous composition — corresponding to the intershell chemistry — throughout the envelope would have been expected immediately after the born
again, with the consequent result that no marked surface abundance change would have resulted from mass–loss episodes during the further evolution. Finally, detailed tabulations of the calculations presented here are available at our website: \url{http://www.fcaglp.unlp.edu.ar/evolgroup/}.

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