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# AGB star intershell abundances inferred from analyses of extremely hot H-deficient post-AGB stars

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**Abstract.** The hydrogen-deficiency in extremely hot post-AGB stars of spectral class PG1159 is probably caused by a (very) late helium-shell flash or a AGB final thermal pulse that consumes the hydrogen envelope, exposing the usually-hidden intershell region. Thus, the photospheric element abundances of these stars allow to draw conclusions about details of nuclear burning and mixing processes in the precursor AGB stars. We compare predicted element abundances to those determined by quantitative spectral analyses performed with advanced non-LTE model atmospheres. A good qualitative and quantitative agreement is found for many species (He, C, N, O, Ne, F, Si) but discrepancies for others (P, S, Fe) point at shortcomings in stellar evolution models for AGB stars.

**Key words.** Stars: AGB and post-AGB – Stars: abundances – Stars: atmospheres — Stars: evolution – Stars: interiors – Nuclear reactions, nucleosynthesis, abundances

## 1. Introduction

The PG1159 stars are a group of 40 extremely hot hydrogen-deficient post-AGB stars[1]. Their effective temperatures ($T_{\rm eff}$) range between 75 000 K and 200 000 K. Many of them are still heating along the constant-luminosity part of their post-AGB evolutionary path in the HRD ($L \approx 10^4\,{\rm L}_\odot$) but most of them are already fading along the hot end of the white dwarf cooling sequence (with $L \gtrsim 10\,{\rm L}_\odot$). Luminosities and masses are inferred from spectroscopically determined $T_{\rm eff}$ and surface gravity ($\log g$) by comparison with theoretical evolutionary tracks. The position of analysed PG1159 stars in the "observational HRD", i.e. the $T_{\rm eff}$–$\log g$ diagram, are displayed in Fig. 1. The high-luminosity stars have low $\log g$ ($\approx 5.5$) while the low-luminosity stars have a high surface gravity ($\approx 7.5$) that is typical for white dwarf (WD) stars. The derived masses of PG1159 stars have a mean of 0.62 ${\rm M}_\odot$, a value that is practically identical to the mean mass of WDs. The PG1159 stars co-exist with hot central stars of planetary nebulae and the hottest

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[1] For a recent review with a detailed bibliography see Werner & Herwig (2006).

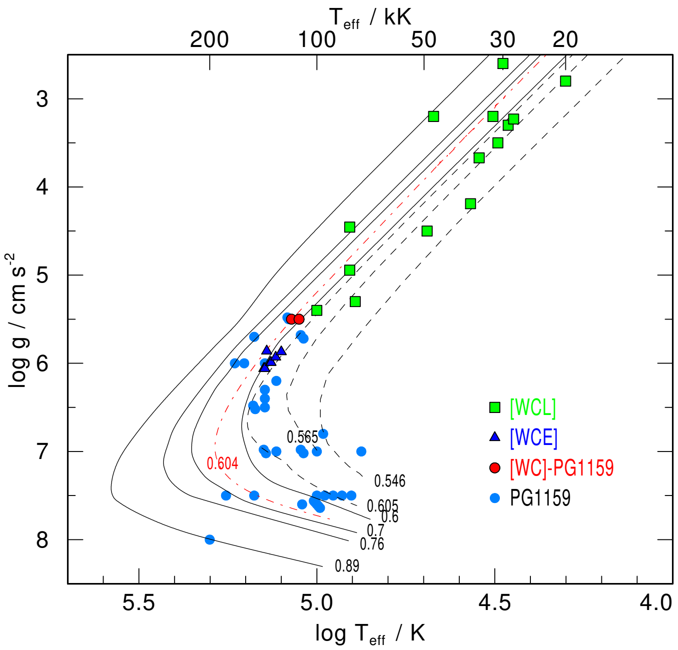


**Fig. 1.** Hot hydrogen-deficient post-AGB stars in the $g$–$T_{\rm eff}$–plane. We identify Wolf-Rayet central stars of early and late type ([WCE], [WCL], from Hamann 1997), PG1159 stars (from Werner & Herwig 2006) as well as two [WC]–PG1159 transition objects (Abell 30 and 78). Evolutionary tracks are from Schönberner (1983) and Blöcker (1995) (dashed lines), Wood & Faulkner (1986) and Herwig (2003) (dot-dashed line) (labels: mass in $M_{\odot}$). The latter 0.604 $M_{\odot}$ track is the final CSPN track following a VLTP evolution and therefore has a H-deficient composition. However, the difference between the tracks is mainly due to the different AGB progenitor evolution.

hydrogen-rich (DA) white dwarfs in the same region of the HRD. About every other PG1159 star is surrounded by an old, extended planetary nebula.

What is the characteristic feature that discerns PG1159 stars from "usual" hot central stars and hot WDs? Spectroscopically, it is the lack of hydrogen Balmer lines, pointing at a H-deficient surface chemistry. The proof of H-deficiency, however, is not easy: The stars are very hot, H is strongly ionized and the lack of Balmer lines could simply be an ionisation effect. In addition, every Balmer line is blended by a Pickering line of ionized helium. Hence, only detailed modeling of the spectra can give reliable results on the photospheric composition. The high effective temperatures require non-LTE modeling of the atmospheres. Such models for H-deficient compositions have only become available in the early 1990s after new numerical techniques have been developed and computers became capable enough.

The first quantitative spectral analyses of optical spectra from PG1159 stars indeed confirmed their H-deficient nature (Werner et al. 1991). It could be shown that the main atmospheric constituents are C, He, and O. The typical abundance pattern is C=0.50, He=0.35, O=0.15 (mass fractions). It was speculated that these stars exhibit intershell matter on their surface, however, the C and O abundances were much higher than predicted from stellar evolution models. It was further speculated that the H-deficiency is caused by a late He-shell flash, suffered by the star during post-AGB evolution, laying bare the intershell layers. The re-ignition of He-shell burning brings the star back onto the AGB, giving rise to the designation "born-again" AGB star (Iben et al. 1983). If this scenario is true, then the intershell abundances in the models has to be brought into agreement with observations. By introducing a more effective overshoot prescription for the He-shell flash convection during thermal pulses on the AGB, dredge-up of carbon and oxygen into the intershell can achieve this agreement (Herwig et al. 1999). Another strong support for the born-again scenario was the detection of neon lines in optical spectra of some PG1159 stars (Werner & Rauch 1994). The abundance analysis revealed Ne=0.02, which is in good agreement with the Ne intershell abundance in the improved stellar models.

If we do accept the hypothesis that PG1159 stars display former intershell matter on their surface, then we can in turn use these stars as a tool to investigate intershell abundances of other elements. Therefore these stars offer the unique possibility to directly see the outcome of nuclear reactions and mixing processes in the intershell of AGB stars. Usually the intershell is kept hidden below a thick H-rich stellar mantle and the only chance to obtain information about intershell processes is the occurrence of the third dredge-up. This indirect view onto intershell abundances makes the interpretation of the nuclear and mixing processes very difficult, because the abundances of the dredged-up elements may have been changed by additional burning and mixing processes in the H-envelope (e.g., hot-bottom burning). In addition, stars with an initial mass below 1.5 $M_{\odot}$ do not experience a third dredge-up at all.

For completeness we note that the central stars of planetary nebulae of spectral type [WC] are believed to be immediate progenitors of PG1159 stars, representing the evolutionary phase between the early post-AGB and PG1159 stages. This is based on spectral analyses of [WC] stars which yield very similar abundance results (Hamann 1997). We do not discuss the [WC] stars here because the analyses of trace elements are much more difficult or even impossible due to strong line broadening in their rapidly expanding atmospheres.

## 2. Three different late He-shell flash scenarios

The course of events after the final He-shell flash is qualitatively different depending on the moment when the flash starts. We speak about a very late thermal pulse (VLTP) when it occurs in a WD, i.e. the star has turned around the "knee" in the HRD and H-shell burning has already stopped (Fig. 2). The star expands and develops a H-envelope convection zone that eventually reaches deep enough that H-burning sets in (a so-called hydrogen-ingestion flash). Hence H is destroyed and whatever H abundance remains, it will probably be shed off from the star during the "born-again" AGB phase. A late thermal pulse (LTP) denotes the occurrence of the final flash in a post-AGB star that is still burning hydrogen, i.e., it is on the horizontal part of the post-AGB track, before the "knee". In contrast to the VLTP case, the bottom of the developing H-envelope convection zone does not reach deep enough layers to burn H. The H-envelope (having a mass of about $10^{-4}$ $M_{\odot}$) is mixed with a few times $10^{-3}$ $M_{\odot}$ intershell material, leading to a dilution of H down to about H=0.02, which is below the spectroscopic detection limit. If the final flash occurs immediately before the star departs from the AGB, then we talk about an AFTP (AGB final thermal pulse). In contrast to an ordinary AGB thermal pulse the H-envelope mass is particularly small. Like in the LTP case, H is just diluted with intershell material and not burned. The remaining H abundance is relatively high, well above the detection limit ($H \gtrsim 0.1$).

There are three objects, from which we believe to have witnessed a (very) late thermal pulse during the last $\approx 100$ years. FG Sge suffered a late flash in 1894 (Gonzalez et al. 1998). The star became rich in C and rare earth elements. It most probably was hit by an LTP, not a VLTP, because it turned H-deficient only recently (if at all, this is still under debate). As of today, FG Sge is located on or close to the AGB.

V605 Aql has experienced a VLTP in 1917 (Clayton & De Marco 1997). Since then, it has quickly evolved back towards the AGB, began

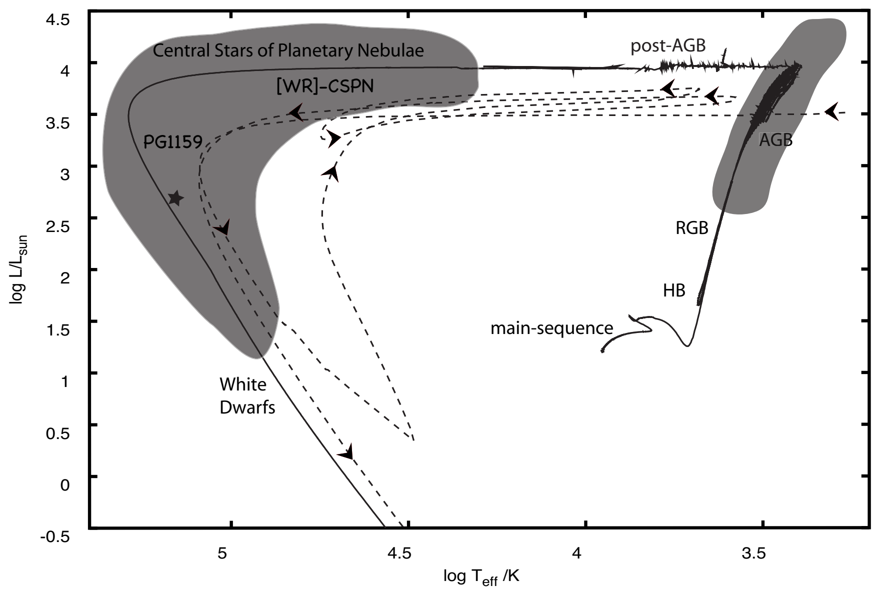


**Fig. 2.** Complete stellar evolution track with an initial mass of $2\,M_\odot$ from the main sequence through the RGB phase, the HB to the AGB phase, and finally through the post-AGB phase that includes the central stars of planetary nebulae to the final WD stage. The solid line represents the evolution of a H-normal post-AGB star. The dashed line shows a born-again evolution of the same mass, triggered by a very late thermal pulse, however, shifted by approximately $\Delta \log T_{\rm eff} = -0.2$ and $\Delta \log L/\,L_\odot = -0.5$ for clarity. The star shows the position of PG1159-035.

to reheat and is now in its second post-AGB phase. It has now an effective temperature of the order 100 000 K and is H-deficient.

Sakurai's famous object (V4334 Sgr) also experienced a VLTP, starting around 1993 (Duerbeck & Benetti 1996). It quickly evolved back to the AGB and became H-deficient. Recent observations indicate that the reheating of the star already began, i.e., its second departure from the AGB might just have begun.

The spectroscopic study of FG Sge and Sakurai's object is particularly interesting, because we can observe how the surface abundances change with time. The stars are still cool, so that isotopic ratios can be studied from molecule lines (Pavlenko et al. 2004) and abundances of many metals can be determined. The situation is less favorable with the hot PG1159 stars: All elements are highly ionised and for many of them no atomic data are available for quantitative analyses. On the other hand, in the cool born-again stars the He-intershell material is once again partially concealed.

## 3. Comparison of observed and predicted element abundances

Abundance analyses of PG1159 stars are performed by detailed fits to spectral line profiles. Because of the high $T_{\rm eff}$ all species are highly ionized and, hence, most metals are only accessible by UV spectroscopy. Optical spectra always exhibit lines from He II and C IV. Only the hottest PG1159 stars display additional lines of N, O, and Ne (N V, O VI, Ne VII). For all other species we have utilized high-resolution UV spectra that were taken with the Hubble Space Telescope (HST) and the Far Ultraviolet Spectroscopic Explorer (FUSE). FUSE allows observations in the Lyman-UV range (≈ 900–1200 Å) that is not accessible with HST, and this turned out to be essential for many results reported here.

*Hydrogen* – Four PG1159 stars show residual H with an abundance of 0.17. These objects are the outcome of an AFTP. All other PG1159 stars have H $\lesssim$ 0.1 and, hence, should be LTP or VLTP objects.

*Helium, carbon, oxygen* – These are the main constituents of PG1159 atmospheres. A large variety of relative He/C/O abundances is observed. The approximate abundance ranges are: He=0.30–0.85, C=0.15–0.60, O=0.02–0.20. The spread of abundances might be explained by different numbers of thermal pulses during the AGB phase.

*Nitrogen* – N is a key element that allows to decide if the star is the product of a VLTP or a LTP. Models predict that N is diluted during an LTP so that in the end N=0.1%. This low N abundance is undetectable in the optical and only detectable in extremely good UV spectra. In contrast, a VLTP produces nitrogen (because of H-ingestion and burning) to an amount of 1% to maybe a few percent. N abundances of the order 1% are found in some PG1159 stars, while in others it is definitely much lower.

*Neon* – Ne is produced from $^{14}$N that was produced by CNO burning. In the He-burning region, two $\alpha$-captures transform $^{14}$N to $^{22}$Ne. Stellar evolution models predict Ne=0.02 in the intershell. A small spread is expected as a consequence of different initial stellar masses. Ne=0.02 was found in early optical analyses of a few stars and, later, in a much larger sample observed with FUSE (Werner et al. 2004).

*Fluorine* – F was for the first time discovered by Werner et al. (2005) in hot post-AGB stars; in PG1159 stars as well as hydrogen-normal central stars. A strong absorption line in FUSE spectra located at 1139.5 Å remained unidentified until we found that it stems from F VI. The abundances derived for PG1159 stars show a large spread, ranging from solar to up to 250 times solar. This was surprising at the outset because $^{19}$F, the only stable F isotope, is very fragile and easily destroyed by H and He. A comparison with AGB star models of Lugaro et al. (2004), however, shows that such high F abundances in the intershell can indeed be accumulated by the reaction $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+})^{18}\mathrm{O}(\mathrm{p},\alpha)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$, the amount depends on the stellar mass. We find a good agreement between observation and theory. Our results also suggest, however, that the F overabundances found in AGB stars (Jorissen et al. 1992) can only be understood if the dredge-up of F in the AGB stars is much more efficient than hitherto thought.

*Silicon* – The Si abundance in evolution models remains almost unchanged. This is in agreement with the PG1159 stars for which we could determine the Si abundance.

*Phosphorus* – Systematic predictions from evolutionary model grids are not available; however, the few computed models show P overabundances in the range 4–25 times solar (Lugaro priv. comm.). This is at odds with our spectroscopic measurements for two PG1159 stars, that reveal a solar P abundance.

*Sulfur* – Again, model predictions are uncertain at the moment. Current models show a slight (0.6 solar) underabundance. In strong contrast, we find a large spread of S abundances in PG1159 stars, ranging from solar down to 0.01 solar.

*Lithium* – Unfortunately, PG1159 stars are too hot to exhibit Li lines because Li is completely ionised. If Li were detected then it must have been produced during a VLTP. The discovery of Li in Sakurai's star is a strong additional hint that it underwent a VLTP and not an LTP.

*Iron and Nickel* – Fe VII lines are expected to be the strongest iron features in PG1159 stars. They are located in the UV range. One of the most surprising results is the non-detection of these lines in three examined PG1159 stars (K1-16, NGC 7094, PG1159-035). The derived upper abundance limits (e.g. Werner et al. 2003) indicate that iron is depleted by about 0.7–2 dex, depending on the particular object. Iron depletions were also found for the PG1159-[WC] transition object Abell 78 as well as for several PG1159 progenitors, the [WC] stars. Such high Fe depletions are not in agreement with current AGB models. Destruction of $^{56}$Fe by neutron captures is taking place in the AGB star intershell as a starting point of the s-process; however, the resulting depletion of Fe in the intershell is predicted to be small (about 0.2 dex). It could be that additional Fe depletion can occur during the late thermal pulse. In any case, we would expect a simultaneous enrichment of nickel, but up to now we were unable to detect Ni in PG1159 stars at all. While the solar Fe/Ni ratio is about 20, we would expect a ratio close to the s-process quasi steady-state ratio of about 3. Fittingly, this low ratio has been found in Sakurai's (cool) LTP object.

*Trans-iron elements* – The discovery of s-process elements in PG1159 stars would be highly desirable. However, this is at present impossible due to the lack of atomic data. From the ionization potentials we expect that these elements are highly ionised like iron, i.e., the dominant ionization stages are VI-IX. To our best knowledge, there are no laboratory measurements of so highly ionised s-process elements that would allow us to search for atomic lines in the observed spectra. Such measurements would be crucial to continue the element abundance determination beyond the current state.

## 4. Conclusions

It has been realized that PG1159 stars exhibit intershell matter on their surface, which has probably been laid bare by a late final thermal pulse. This provides the unique opportunity to study directly the result of nucleosynthesis and mixing processes in AGB stars. Spectroscopic abundance determinations of PG1159 photospheres are in agreement with intershell abundances predicted by AGB star models for many elements (He, C, N, O, Ne, F, Si). For other elements, however, disagreement is found (Fe, P, S) that points at possible weaknesses in the evolutionary models.

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