PG 1159 Stars

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Abstract. This paper reviews the latest progress in the field of PG 1159 star research since the most recent review given at the European White Dwarf workshop in Kiel 1994 (Dreizler et al. 1995a). Many new results for PG 1159 stars emerge from space based observatories (HST, HUT, ROSAT, EUVE, IUE) but also from refined ground-based spectroscopy and imagery. In combination with the rapid progress with analyses of related H-deficient post-AGB stars (Wolf-Rayet central stars, helium-rich white dwarfs) we obtain a more coherent picture of the post-AGB evolution of hot H-deficient objects. Yet, the basic question about the origin of the hydrogen deficiency remains unanswered.

1. Introduction

The spectroscopic analyses of the PG 1159 stars performed during the recent five years comprise almost all of the 27 known objects. The review mentioned above (Dreizler et al. 1995a) gives detailed information about individual objects. The characteristics of the PG 1159 stars are shortly summarized as follows. They are very hot ($T_{\rm eff}$=65–170 kK) post-AGB stars (with a single possible exception, an EHB descendant) with typical white dwarf masses ($M/M_\odot$=0.50–0.83). No hydrogen has been detected in any of these stars, although in all cases (except for the prototype PG 1159−035) only a crude upper limit was estimated (H/He<1, by number). The atmospheres are composed of carbon, helium, and oxygen, showing a large variety of abundance patterns.

These results are in agreement with asteroseismological analyses of a handful of PG 1159 stars which are non-radial g-mode pulsators. The He-rich surface layer with a mass of the order of 10^{-3} solar masses lies on top of a carbon and oxygen rich stellar core. This corroborates our earlier suggestion that the PG 1159 stars have completely lost their H-rich layer and most of the He-rich envelope. We think that this phenomenon is due to a late He shell flash ("born-again AGB star" scenario) but it is highly unsatisfactory that up to now only one single self-consistent evolutionary computation of a late He-flash exists (Iben & MacDonald 1995), and this results in surface abundances which are not in agreement with the obervations of PG 1159 stars.

The idea that the PG 1159 phase is intermediate between Wolf-Rayet central stars of planetary nebulae ([WC]) and the hot He-rich (i.e. DO) white dwarfs has become very attractive. It is now based on first reliable NLTE model atmosphere analyses of the proposed PG 1159 progenitors and descendants (see reviews by Hamann 1996, and Dreizler & Werner 1996).

Though the evolutionary state of the PG 1159 stars seems to be revealed, there are many past and new observations and analyses which do not fit into this simple picture. The new results which appeared since the last review are summarized here and discussed in the context of our current understanding of these stars.

2. New discoveries and observations

2.1. Detection of a planetary nebula around PG 1520+525

Attempts have been made by many observers to detect faint nebulosities around PG 1159 stars which are not known to be associated with a PN, either by long slit spectroscopy or by direct imaging. All of them failed, just like the recent effort by Tweedy & Kwitter (1994, and references therein) who unsuccessfully searched for PNe around five objects, PG 1159−035 being among them. But there is one interesting exception. Jacoby & Van de Steene (1995) announced the detection of an ancient, spherical PN around PG 1520+525, which is the non-pulsating spectroscopic twin of the pulsating protoype PG 1159−035. They derive a unusually high nebula mass (1.4 $M_\odot$) which certainly favored the detection of the nebula.

After a thorough discussion of the nebular and central star properties the authors conclude that the distance of PG 1520+525 may be slightly shorter than thought before. They propose 0.8 kpc whereas the spectroscopic distance is 1.1 kpc (Werner et al. 1991). It should be noted that the new value is well within the error range of ours, which is fairly large (≈50%), mainly because of the uncertainly known surface gravity (±0.5 dex). The fact that $T_{\rm eff}$ is 150 kK instead of 140 kK (see below) as was assumed in the spectroscopic distance determination plays a minor role. In any case, the large angular diameter measured from the Hα image (11', corresponding to 3.5 pc at d=1.1 kpc) places the nebula among the largest PNe known.

Another conclusion concerns the question why we do not see PNe around other PG 1159 stars. Jacoby & Van de Steene find that the detectability of a nebula depends strongly on small variations in the initial conditions of the PN (ejection velocities, central star mass). Hence there is presently no observational requirement to argue for the existence of a non-PN path to the PG 1159 evolutionary stage.

2.2. RX J 0122−7521: The 2nd PG 1159 star detected by ROSAT

Number 27 in the sample of known PG 1159 stars is a detection originally recorded in the ROSAT all sky survey performed during 1990/1991. Although known as an X-ray source with the designation RX J 0122−7521 since that time, it took a while until the optical counterpart was identified as a PG 1159 star (Cowley et al. 1995). It is the second discovery of a PG 1159 star by ROSAT, the first one being RX J 2117+3412 (Motch et al. 1993) which is discussed in more detail below. The only other PG 1159 star discovered by its X-ray emission (with HEAO 1) is H 1504+65, to which we will turn our attention below, too.

RX J 0122−7521 is a remarkable individuum within the PG 1159 zoo. A rough estimate from the optical spectra points at atmospheric parameters rather similar to PG 1159−035 ($T_{\rm eff}$=140 kK, $\log g$ =7) which means a lower temperature and luminosity when compared to RX J 2117+3412 ($T_{\rm eff}$=170 kK, $\log g$ =6). Together with the fact that it is visually fainter by more than two magnitudes it is surprising that the X-ray luminosity is a factor of 2.4 higher. Clearly, a sophisticated analysis is desirable to explain this high X-ray to visual luminosity ratio. This new PG 1159 star is also remarkable because it shows prominent signatures for the presence of nitrogen, which points at complicated mixing processes taking place during the late He flash. For a detailed discussion of this problem see Werner & Heber (1991). The nitrogen phenomenon is indeed very rare among the PG 1159 stars. The only N-rich PG 1159 star known before is PG 1144+001 whose spectrum is very similar to that of the new object. The presence of nitrogen in RX J 0122−7521 might be a clue to the high X-ray luminosity. In the case of PG 1144+001 we have shown that the N-enrichment goes along with a strong oxygen depletion compared to other PG 1159 stars (mass fraction O=1% instead of typically 15%). If O is reduced in the case of RX J 0122−7521, too, then the strongest X-ray absorbing feature, the O VI (2p) continuum edge near 100Å (see below), drastically weakens and gives rise to an enhanced X-ray emissivity.

The presence of nitrogen seems to be more common among the Wolf-Rayet central stars. Some of the analysed late type WRs ([WC8]–[WC12]) do show nitrogen lines, but not all (Leuenhagen et al. 1996). It seems to be correlated with the presence of residual hydrogen, but there is also a counter-example. Among the more evolved early-type WRs there are a few objects with prominent nitrogen lines (Sanduleak 3 and NGC 6751) and finally the [WC]-PG 1159 transition objects Abell 30 and Abell 78 exhibit N emissions.

The optical spectra of RX J 0122−7521 show some evidence for variations in the emission-line strengths, which would be highly interesting, but on the other hand GW Vir pulsations on time scales above 5 minutes were not found on hand of limited photometry. Further observations are required to confirm this and a search for nebulosity is also highly desirable.

2.3. HST observations of RX J 2117+3412 and KPD 0005+5106

RX J 2117+3412 is the first PG 1159 star which was observed with the Hubble Space Telescope in high spectral resolution ($\Delta\lambda = 0.1$Å) using the GHRS instrument (Werner et al. 1995a). The high quality data revealed problems with the theoretical modeling of carbon and oxygen line profiles which still suffers from the lack of reliable broadening data for C IV and O VI lines. In the case of the

O VI ion we even encountered the problem of inaccurate level energies which prevents the identification of a few highly excited line transitions. Despite of these problems, a very weak O V 1371Å line suggests that the effective temperature is higher than previously thought. With $T_{\rm eff}$=170 kK, RX J 2117+3412 is the hottest known PG 1159 star together with H 1504+65. Since the star is a nonradial g-mode pulsator this means that the blue edge of the GW Vir instability strip extends to very high temperatures at high luminosities (see below).

RX J 2117+3412 is the central star of a very old PN and shows an emission line at 6068Å which is due to recombination cascades in the O VIII ion. We have suggested that this process takes place in shock fronts along the stellar wind, because photospheric temperatures are not high enough to ionise O VIII. The observed O VIII line at 2977Å shows no velocity shift against the stellar rest frame and the profile is narrow and only slightly asymmetric. So if it originates from the wind then this must happen in the acceleration region of the expanding shell, close to the stellar surface. In contrast, the C IV resonance line, recorded in an IUE spectrum shows a distinct triangular shape pointing at high wind velocities as can be expected for such hot central stars.

Together with the observation of RX J 2117+3412 we proposed HST UV high resolution spectroscopy for KPD 0005+5106. It is the hottest known DO white dwarf ($T_{\rm eff}$=120 kK) and it is the first and only white dwarf from which coronal X-ray emission has been observed (Fleming et al. 1993, Werner et al. 1994). The occurrence of optical O VIII lines as in RX J 2117+3412 was regarded as a link between DO and PG 1159 stars and worthwhile to be studied in more detail. KPD 0005+5106 also exhibits the 2977Å emission line of O VIII and it looks very similar to that in the PG 1159 central star so that a similar conclusion as to its origin is likely. Hence this is probably the most convincing proof that mass-loss is still going on from hot white dwarfs. As a by-product of this study, precise metal abundances for KPD 0005+5106 were derived which are severely at odds with diffusion/radiative forces theory. One possible explanation is the neglect of wind effects on equilibrium abundances in the theory.

We note in passing that we have taken high-resolution IUE spectra of RX J 2117+3412, which are under analysis. They show a vast amount of C IV and O VI lines. The quality of the spectra cannot compete with the HST data, but they have the advantage that they cover a much broader wavelength range. A useful list of line identifications in the IUE spectra of this star, as well as in the IUE data of the (brightest) PG 1159 star, NGC 246, has been published by Feibelman (1995) and Feibelman & Johansson (1995). In nine co-added spectra of NGC 246 more than 100 lines were identified, most of them are due to C IV and O VI.

The above mentioned link between the PG 1159 and DO stars has recently been strengthened by the detection of a number of DOs which show absorption (!) lines from ultrahigh ionisation stages of the CNO elements, e.g. O VIII (Werner et al. 1995b, Dreizler et al. 1995b). We have interpreted this phenomenon as due to a very hot wind around these white dwarfs. First HST/GHRS spectra were received at the time of writing and are now analysed.

2.4. HUT and EUVE observations

During the Astro-2 space shuttle mission in March 1995, the Hopkins Ultraviolet Telescope (HUT) has for the first time delivered spectra from PG 1159 stars in a UV wavelength region which is accessible neither by IUE nor by HST, namely between the Lyman edge and $\approx$ 1150Å. Data analysis and spectral modeling are not yet completed, but first interesting results have already been reported (Kruk & Werner 1996).

Generally, the synthetic spectra computed from models with parameters as determined in previous analyses are in a good overall agreement with the observed spectra. A central question concerned an independent proof of the helium-deficiency of the unique PG 1159 star H 1504+65, which will be discussed later. A very surprising observation was the detection of H_2 molecular features in the spectrum of KPD 0005+5106, whose important role as a link between DOs and PG 1159 stars has been described above. Whether the strong Lyman and Werner bands are caused by interstellar H_2 clouds in the ISM or by the remnants of a PN surrounding the DO requires further analysis. Another preliminary result is the hint that the O abundance in the non-pulsating PG 1424+535 is lower than in the pulsating twin PG 1707+427 which could explain the stability against pulsations of the former star (see below).

H 1504+65 – still the most curious PG 1159 star

H 1504+65 has obtained highest attention among the PG 1159 stars since its optical identification as a very blue stellar object. The immediate suspicion, expressed by Nousek et al. (1986), that H 1504+65 is not only hydrogen-deficient but also virtually helium free, has been corroborated later by a model atmosphere analysis (Werner 1991). In analogy to the difficulty to detect hydrogen in a hot helium-dominated atmosphere, it turns out to be a problem to detect traces of helium in a hot carbon/oxygen dominated atmosphere. The reason is that every He II line transition between levels with principal quantum numbers n→m is contaminated by transitions in (the hydrogen like ions) C IV and O VI between levels with quantum numbers 2·n→2·m and 3·n→3·m, respectively. In the case of the 4686Å depression (He II n=3→4) in H 1504+65, the observed broad and shallow line profile can be entirely modelled with C IV (n=6→8) and O VI (n=9→12) lines. The only feature which would reveal the presence of helium in this line blend is a narrow NLTE emission core of He II 4686Å, which is detectable in all PG 1159 stars with $T_{\rm eff}$>120 kK – except for H 1504+65. The physical mechanism for its formation is similar to the formation of the Hα emission in PG 1159 models with traces of hydrogen, since He II 4686Å is also an α-transition. According to our model calculations we found that the absence of this emission spike requires He<1% by mass. However, it has been shown in the context of the Balmer line problem (Werner 1996b,c) that the strength of the central emission reversal of Hα strongly depends on details in metal opacity calculations. Hence relying exclusively on the lacking He II emission reversal when claiming the He-deficiency in H 1504+65 is not completely convincing.

The new spectral window opened up by HUT enables an independent check for the helium-deficiency. Preliminary calculations show that the He II Balmer lines located in the FUV region (e.g. n=2→5, n=2→7) are less affected by overlapping C IV and O VI lines because pressure ionisation of the upper levels of the latter ions favors the He II line strengths. Thus from the absence of significant line features at the positions of He II n=2→5,7 one can derive an independent upper limit for the He abundance, however, detailed calculations still need to be done.

An impressive EUV spectrum of H 1504+65 has been obtained with the Extreme Ultraviolet Explorer (EUVE) satellite (Barstow et al. 1995). It covers the range 80-140Å and is dominated by O VI absorption features which are qualitatively in agreement with model predictions. But still, the quantitative interpretation is not successful, because absolute model fluxes are an order of magnitude too high. This points at metal opacities which are not yet included in the models, but no further progress has been made up to now. Similar problems were encountered in the analysis of ROSAT EUV and X-ray data of two other PG 1159 stars, namely NGC 246 and K 1-16 (Hoare et al. 1995).

Other data sources still await exploitation. A ROSAT PSPC X-ray measurement with excellent signal/noise ratio has been obtained. In addition, a UV spectrum of medium resolution taken with the HST Faint Object Spectrograph has been published by the white dwarf consortium (Shipman et al. 1995), which is in overall agreement with synthetic spectra from our model with the standard parameters for H 1504+65 ($T_{\rm eff}$=170 kK, $\log g$=8, C/O=1).

In summary, the latest observations confirm our idea about the nature of H 1504+65. It appears to be the hot, naked C/O core of a former AGB star which has lost its H and He envelopes. The cause for this unique peculiarity is probably connected to the fact that the mass of H 1504+65 is the highest one of all PG 1159 stars (0.83 $M_\odot$).

The spectroscopic twins PG 1159−035 / PG 1520+525 and PG 1707+427 / PG 1424+535 revisited

The blue edge of the GW Vir instability strip (see below) is most precisely confined by the pulsator/non-pulsator pair PG 1159−035 and PG 1520+525, which from optical spectroscopy had essentially identical parameters. PG 1159−035 was observed with HST/FOS in the UV and we could confirm our earlier result for $T_{\rm eff}$ (140 kK) but now with a high precision of ±5 kK (Werner & Heber 1993) in contrast to the optical analysis where we faced an uncertainty of ±15 kK (Werner et al. 1991). The non-pulsating twin brother PG 1520+525 was also scheduled for a HST observation but later-on dropped from the target list because of the intervening HST servicing mission. Fortunately we also had successfully applied for observations with the EUVE satellite which opened up a new spectral window. Most PG 1159 stars are not accessible in the EUV and soft X-ray region because they are distant and strongly attenuated by interstellar absorption (Werner 1996d). But PG 1520+525 is hot enough to have considerable flux around 100Å where the ISM absorption is less severe than at longer wavelengths. Yet, an integration time of almost 2 days was necessary to obtain a useful spectrum. Our analysis showed that the observation can only be reproduced by models exceeding $T_{\rm eff}$=140 kK. Our best fit is obtained at $T_{\rm eff}$=150 kK. This value is within the error limit of our optical analysis but it is clearly higher than that of the pulsating prototype. We thus concluded that the blue edge of the GW Vir instability strip runs right between both stars, say near 145 kK (Werner et al. 1995c,d). Note in passing that our efforts to obtain an EUVE spectrum of PG 1159−035 failed. The obtained count rates were much too low. Another pulsator/non-pulsator pair located near $T_{\rm eff}$=100 kK (PG 1707+427 and PG 1424+535) is suited to determine the red edge of the instability strip. HST observations of this twin pair were performed for us very recently and will be analysed soon. Both stars were also observed by HUT during the above mentioned mission and the spectra are being analysed (Kruk & Werner 1996).

2.5. Upper limits on the hydrogen abundance from new optical high-resolution spectra

The determination of an upper limit for the hydrogen abundance in PG 1159 stars from spectroscopic observations poses a difficult problem, because of the high temperatures and high degree of ionisation of hydrogen and the fact that every hydrogen line is blended with a He II line. First quantitative analyses have shown that the equivalent widths of the optical He II lines which blend the Balmer lines are not affected by hydrogen unless the H/He number ratio exceeds unity. This is clearly an uncomfortably high limit and our suggestion that hydrogen must be completely absent is only based on indirect evidence. If envelope stripping has layed bare the 3α burning products then all the H-rich layer was expelled before.

But several facts call for caution that this simple idea might not be true. First of all, evolution through the DB-gap (non-existence of He-rich WDs in within the $T_{\rm eff}$ range 28–45 kK) will eventually turn all PG 1159 stars into objects with a H-dominated atmosphere. One explanation is accretion of interstellar matter, another one the float-up of hydrogen which was kept mixed within the He-rich stellar envelope during preceding evolutionary stages. If the latter provides the right answer then we have to face the possibility that considerable amounts of H are present in PG 1159 stellar atmospheres. Two other observations are important in this context. One is the detection (Napiwotzki & Schönberner 1991) and analysis (Werner 1992, Dreizler et al. 1996) of the hybrid stars (having PG 1159 spectra plus distinct hydrogen Balmer lines) yielding typical number ratios of H/He=2, and the other one is the detection of trace hydrogen in some [WC] central stars which probably represent progenitor stars (Leuenhagen et al. 1996; Hamann 1996). And finally we have discussed whether the location of non-pulsating PG 1159 stars within the GW Vir instability strip is a consequence of trace hydrogen which prevents pulsation driving.

Taken together, these considerations strengthen the hypothesis that many, if not all, PG 1159 stars have retained some hydrogen in their envelopes. Support also comes from recent theoretical calculations of a final helium shell flash accounting for the first time for time-dependent mixing (Iben & MacDonald 1995). These predict high C and He surface abundances together with trace H which might kept hidden in the spectra. Hence we looked for an alternative method to detect hydrogen down to a stricter limit than before.

Synthetic NLTE line profiles predict a narrow Hα emission feature when the hydrogen abundance fraction exceeds about 1% by mass. But high resolution high-S/N spectra are required to detect this weak feature and to separate it from the nearby (2.7Å blueward) He II line core. In Febr. 1995 we have obtained suitable spectra of two DO white dwarfs and PG 1159−035. Since PG 1159−035 is relatively faint a total integration time of 6 hours was necessary at the 3.6m telescope of ESO (Chile). The spectrum shows a distinct emission feature from He II 6560Å line but no hint for such a feature at the position of Hα. We concluded a new upper limit for hydrogen, namely 2% by mass which is equivalent to a H/He=0.2 number abundance ratio (Werner 1996a). This limit is five times lower than our previous one. It is an important constraint for new theoretical evoutionary calculations of late He flash post-AGB stars (see our final section).

3. Pulsation properties of PG 1159 stars

Eight variable PG 1159 stars are known and they are multimode non-radial g-mode pulsators. They define the GW Vir instability strip in the HR diagram. The variability is measured photometrically (amplitudes of the order 1%) but in extension some authors claim to have observed subtle changes of line profiles (e.g. in the case of RX J 0122−7521, see above, and in the case of K 1-16, see Feibelman et al. 1995). This certainly needs further confirmation.

Independent from spectroscopic results, stellar parameters can be determined by means of asteroseismology, and the interior structure of the star can be studied.

3.1. The GW Vir instability strip in the HRD

The location of the instability strip can be confined by our spectroscopic analyses which yield $T_{\rm eff}$ and $\log g$. The strip position in the $\log g$–$T_{\rm eff}$ diagram based on our latest results is discussed elsewhere (Werner 1995, Werner et al. 1995c,1996). If we determine the stellar masses by comparison with evolutionary tracks, we also obtain the luminosities and can locate the PG 1159 stars in the HR diagram. It is obvious that the edges of the instability strip are dependent on surface gravity and hence luminosity and we have to bear in mind that the strip boundaries are certainly depending on the chemical composition of the stellar envelope, too (see below). Table 1 lists all analysed PG 1159 stars and gives their spectroscopically determined $T_{\rm eff}$ and $\log g$ together with deduced quantities mass and luminosity. Fig. 1 shows a HR diagram with PG 1159 stars.

The GW Vir strip at low luminosities ($\log {\rm L/L_\odot} < 3$) is defined by four pulsators. It appears to be very narrow and runs along an evolutionary cooling track indicating pulsator masses between 0.53 and 0.57 $\rm M_\odot$. Going to higher luminosities, the strip seems to widen and crosses the horizontal parts of the post-AGB tracks and involves the most massive and luminous PG 1159 central star (NGC 246). The confinement of strip boundaries on hand of pulsator/non-pulsator pairs was described above. It can be seen that numerous non-pulsators are located in the strip. Considering the possible error of our analyses it is conceivable that all of the stable stars are in fact located outside a well defined strip, but we regard this as unlikely. Instead it is possible that the driving mechanism in these stars is not working due to a relative oxygen deficiency in the driving regions, or by the presence of hitherto undetected hydrogen (see discussion below).

Table 1. A list of the 23 spectroscopically analysed PG 1159 stars. Surface gravities are given in cgs units. A colon denotes preliminary results. Masses and luminosities are derived from comparison with theoretical evolutionary tracks for helium burning post-AGB stars (Wood & Faulkner 1986, mass loss type B). The mean mass amounts to 0.59 $M_\odot$.

star	$T_{\rm eff}$/kK	$\log g$	$M/M_\odot$	$\log L/L_\odot$
H 1504+65	170	8.0	0.83	2.2
RX J 2117+3412	170	6.0	0.70	4.2
PG 1144+001	150	6.5	0.57	3.3
Jn 1	150:	6.5	0.57	3.3
NGC 246	150:	5.7	0.76	4.2
PG 1520+525	150	7.0	0.58	2.9
PG 1159−035	140	7.0	0.57	2.7
NGC 650	140:	7.0	0.57	2.7
Abell 21=Ym29	140:	6.5	0.55	3.2
Longmore 3	140:	6.3	0.56	3.4
K 1-16	140:	6.1	0.59	3.6
PG 1151-029	140:	6.0	0.60	3.7
VV 47	130:	7.0	0.54	2.6
Longmore 4	120	5.5	0.65	4.0
HS 0444+0453	100:	7.5	0.59	1.7
PG 1707+427	100	7.0	0.53	2.1
PG 1424+535	100	7.0	0.53	2.1
IW 1	100:	7.0	0.53	2.1
MCT 0130-1937	95	7.5	0.58	1.6
HS 1517+7403	95	7.5	0.58	1.6
PG 2131+066	80	7.5	0.54	1.2
PG 0122+200	75	7.5	0.52	1.1
HS 0704+6153	65	7.0	0.50	1.3

3.2. Driving mechanism

The κ mechanism near the opacity peak due to carbon and oxygen at temperatures around 10^6 K is driving the pulsations in PG 1159 stars (Starrfield et al. 1984). Stanghellini et al. (1991) determined the theoretical location of the instability strip in the HRD as a function of envelope composition. It turned out, that compositions which are in agreement with observed atmospheric abundances result in a blue edge which is too red. The observed location could only be reproduced by models with a pure C/O=1 composition, i.e. reduced helium abundance.

Two new studies were presented recently, which now include the new OPAL opacities. The results of Bradley & Dziembowski (1996) show trends similar to the results of Stanghellini et al. (1991). In particular, the oxygen abundance in the driving region – located near $10^{-9}\,M_\star$ – has to be distinctly higher (about a factor of 3) than the observed photospheric value. This leads them to the

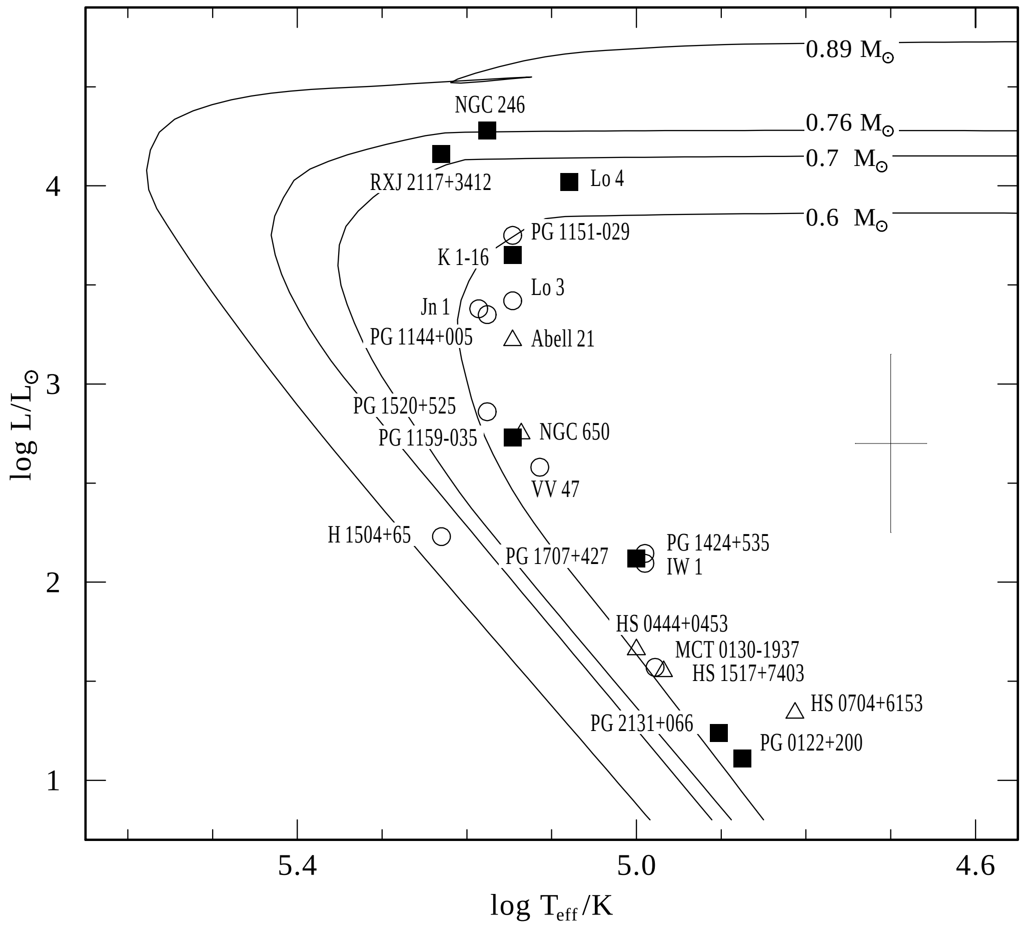

Figure 1. Hertzsprung-Russell diagram with the locations of all analysed PG 1159 stars. Squares: pulsators, circles: non-pulsators, triangles: no photometric data available. Also shown are theoretical post-AGB stellar evolutionary tracks from Wood & Faulkner (1986, helium burners, mass loss type B). A typical error bar is depicted, too.

conclusion that all pulsating PG 1159 stars have to have a stratified envelope composition.

In contrast to this result, Saio (1996) finds that the location of the instability strip can be reproduced by models with an envelope composition which equals the photospheric element abundances. The reason for these discrepant results is unclear and needs to be clarified by a detailed comparison of the stellar models used. Another interesting result from Saio's analysis is the finding that trace amounts of hydrogen (3% by mass) do not affect the stability of g-modes, which is in contrast to earlier suggestions that hydrogen "poisons" the pulsations (Cox 1986). As a consequence the existence of non-pulsating PG 1159 stars in the instability strip cannot be due to trace hydrogen in their envelopes, as we speculated before. However, the spectroscopic detection of H at such a low abundance levels is very difficult and requires high quality spectra (see above).

3.3. Helium layer thickness

Seismological observations allow the determination of the subsurface compositional structure in all types of pulsating white dwarfs. In the case of the prototype PG 1159−035 Kawaler & Bradley (1994) found a composition transition zone at $\approx 3 \cdot 10^{-3}\,\mathrm{M}_\odot$. In this region the helium surface abundance of 33% (by mass) goes down to zero. Thus the surface layer contains about $10^{-3}\,\mathrm{M}_\odot$ of helium. This value can be explained with the post-AGB evolution of a star which has at most $10^{-2}\,\mathrm{M}_\odot$ helium when descending from the AGB (Iben & Tutukov 1984) and then undergoes modest mass loss during evolution to the PG 1159 phase.

Analysis of Whole Earth Telescope (WET) observations of GD 358, the prototype of the DB pulsators, revealed a mass similar to PG 1159−035, but a He-surface layer which is three orders of magnitudes smaller than that of PG 1159−035 (Winget et al. 1994). On first sight there is no evolutionary connection between both stars, unless very finely tuned mass-loss beyond the PG 1159 phase is assumed. Dehner & Kawaler (1995) have now published evolutionary sequences of white dwarf models that include time-dependent diffusive processes. Starting from a model which represents PG 1159−035, diffusion sets in and causes a separation of the elements. At the temperature range inhibited by GD 358 the resulting evolved model essentially has the pulsational properties of GD 358 and a pure He surface layer of $10^{-5.5}\,\mathrm{M}_\odot$, which is close to the value found from the seismological analysis. Hence an evolutionary link between both stars seems probable without invoking mass loss. One drawback of this study is the neglect of radiative forces. The important role of these forces in PG 1159 stellar envelopes has been emphasized by detailed calulations of Unglaub & Bues (1996).

4. Stellar parameters: Pulsational vs. spectroscopic results

Of immediate interest is the mass of the PG 1159 stars. The spectroscopic determination of effective temperature and surface gravity enables a mass determination with the help of theoretical evolutionary tracks. As a caveat, all tracks shown in Fig. 1 are, strictly speaking, not representing PG 1159 stars because all of the stellar models have H-rich envelopes. Current standard evolution theory cannot reproduce the observed exotic surface compositions. Therefore our mass determinations can be affected by a systematic offset and an independent method is highly desirable. Asteroseismology yields stellar masses with striking accuracy, as has been demonstrated in the case of PG 1159−035 (Winget et al. 1991, Kawaler & Bradley 1994). Such independent checks are now possible for four PG 1159 variables, they are summarized in Table 2. Satisfying agreement between spectroscopic and pulsational masses is achieved in those two cases where pulsational analyses are based on WET data (PG 1159−035 and PG 2131+066). The same holds for single-site data from RX J 2117+3412. Discrepant results are obtained for PG 1707+427 but we hope that the analysis of WET data will reduce the pulsational mass to the spectroscopically determined value. Another case concerns single-site data of PG 0122+200 (Vauclair et al. 1995), which indicate a mass significantly higher than the spectroscopic value if a structure similar to PG 1159−035 is assumed. How this will stand up against the results of an upcoming WET observation remains to be seen. We note that the uncertainty in our spectroscopic mass determination aside from the possible systematic error mentioned above is typically of the order 0.05 to 0.1 $M_\odot$.

Table 2. Comparison of spectroscopically determined masses (in $M_\odot$) with results from pulsation analyses

star	M_{spec}	M_{puls}	remarks, reference for pulsation result
PG 1159−035	0.57	0.59	WET data (Kawaler & Bradley 1994)
RXJ2117+3412	0.65	0.62	Vauclair et al. 1993, WET data in analysis
PG 1707+427	0.53	0.70	Fontaine et al. 1991, WET data in analysis
PG 2131+066	0.57	0.61	WET data (Kawaler et al. 1995)

Other results from pulsation analyses are independent determinations of effective temperatures and distances. It is gratifying that for the two PG 1159 pulsators covered by WET runs the temperatures agree very well with our results. For PG 1159−035 Kawaler & Bradley (1994) find $T_{\rm eff}$=136 kK (compared to 140 kK) and for PG 2131+066 Kawaler et al. (1995) find $T_{\rm eff}$ between 81 kK and 88 kK (compared to $T_{\rm eff}$=80 kK). It is worthwhile to note that in the latter case a completely independent pulsational mass determination was not possible, but needed a previous confinement by spectroscopic results. The spectroscopic and pulsational distances to PG 1159−035 are $0.8^{+0.6}_{-0.4}$ and 0.44±0.04 kpc, respectively, which are consistent within the error ranges.

5. Concluding remarks

Asteroseismologic mass determinations are in agreement with spectroscopic results for PG 1159 stars, at least in those cases with most reliable observational pulsation data. This gives us confidence that the spectroscopic masses do not suffer from severe systematic errors which could arise from the discussed problems with theoretical evolutionary tracks, on which the spectroscopic masses are based. The mean mass of the 23 spectroscopically analysed PG 1159 stars (Table 1) amounts to 0.59 $M_\odot$. This value is in striking agreement with the mean masses of the more evolved He-rich white dwarfs: For the DOs we found the very same value (0.59 $M_\odot$, Dreizler & Werner 1996) and Beauchamp et al. (1996) determined 0.57 $M_\odot$ for the DBs. An evolutionary link between the three stellar classes is suggested by these numbers, however, a comparison with the mean mass of DA white dwarfs (again, 0.59 $M_\odot$, Bragaglia et al. 1995; from 149 DAs with $T_{\rm eff}$>12 kK) shows that the H-deficient (pre-) white dwarfs are ordinary white dwarfs in a sense that their existence is not correlated with an unusual stellar mass.

The origin of the PG 1159 phenomenon remains unclear. What is urgently needed are theoretical evolutionary calculations in a manner presented only recently by Iben & MacDonald (1995) in order to confirm or refute the late He-flash (or born-again) scenario. In a complementary manner, spectroscopic and pulsational analyses have now provided us with a rather clear picture of the structure of these stars which must be met by future evolution calculations.

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