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Discovery of photospheric argon in very hot central stars of planetary nebulae and white dwarfs*

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ABSTRACT

Context. We report the first discovery of argon in hot evolved stars and white dwarfs. We have identified the Ar VII 1063.55 Å line in some of the hottest known ($T_{\rm eff}$ = 95 000−110 000 K) central stars of planetary nebulae and (pre-) white dwarfs of various spectral type.

Aims. We determine the argon abundance and compare it to theoretical predictions from stellar evolution theory as well as from diffusion calculations.

Methods. We analyze high-resolution spectra taken with the *Far Ultraviolet Spectroscopic Explorer*. We use non-LTE line-blanketed model atmospheres and perform line-formation calculations to compute synthetic argon line profiles.

Results. We find a solar argon abundance in the H-rich central star NGC 1360 and in the H-deficient PG 1159 star PG 1424+535. This confirms stellar evolution modeling that predicts that the argon abundance remains almost unaffected by nucleosynthesis. For the DAO-type central star NGC 7293 and the hot DA white dwarfs PG 0948+534 and RE J1738+669 we find argon abundances that are up to three orders of magnitude smaller than predictions of calculations assuming equilibrium of radiative levitation and gravitational settling. For the hot DO white dwarf PG 1034+001 the theoretical overprediction amounts to one dex.

Conclusions. Our results confirm predictions from stellar nucleosynthesis calculations for the argon abundance in AGB stars. The argon abundance found in hot white dwarfs, however, is another drastic example that the current state of equilibrium theory for trace elements fails to explain the observations quantitatively.

Key words. stars: abundances – stars: atmospheres – stars: evolution – stars: AGB and post-AGB – white dwarfs

1. Introduction

The determination of elemental abundances in the extremely hot hydrogen-deficient post-AGB stars of spectral type PG 1159 is of particular interest, because it is believed that these stars exhibit intershell matter as a consequence of a late helium-shell flash. This allows one to directly study the outcome of AGB star nucleosynthesis taking place in the region between the H- and He-burning shells. While some elements are in line with expectations from stellar evolution calculations, other elements clearly point at shortcomings in the theory. For example, the extreme iron and sulfur depletion found in several PG 1159 stars is still not understood. On the other hand, the observed extreme overabundances of fluorine confirms that AGB stellar modeling of complicated nucleosynthesis processes is basically correct in other respects.

The detection of metals in PG 1159 stars (and stars of other spectral types in the same region of the HRD) is problematic because of their extremely high effective temperatures ($T_{\rm eff}$ = 75 000−200 000 K, Werner & Herwig 2006). All species are highly ionised so that spectral lines of elements heavier than C, N, and O are, typically, from ionization stages V−VIII. The vast majority of these transitions is at wavelengths below the hydrogen Lyman edge and, hence, essentially inaccessible. However, a few exceptions are known and particularly the *Far Ultraviolet Spectroscopic Explorer* (FUSE) is playing a principal role in the discovery of such highly ionised species. Two examples are the Ne VII 973.3 Å and F VI 1139.5 Å lines which were never identified before in any stellar atmosphere (Werner et al. 2004, 2005).

The argon abundance determination in stellar atmospheres is a challenge. Similarly to neon, the solar abundance of this element cannot be determined directly because of the lack of suitable spectral lines. The currently adopted solar argon abundance (Table 1) has been estimated from solar coronal emission lines and solar energetic particles (Asplund et al. 2005). To our best knowledge, the only stellar photospheric argon abundance determination was performed for B stars which exhibit weak Ar II lines in the optical band (the derived mean Ar abundance is 0.3 dex oversolar; Keenan et al. 1990; Holmgren et al. 1990).

Taresch et al. (1997) were the first who considered argon in model atmosphere analyses for even hotter stars. From their models tailored to the analysis of UV and FUV spectra of the O3 If supergiant HD 93129A ($T_{\rm eff}$ = 52 000 K, log g = 3.95) they pointed out that the Ar VI/Ar VII ionisation balance could be used as an additional independent temperature indicator. However, the blend of potential Ar lines exhibited by their models with strong interstellar H_2 prevented the successful use of this tool in their case. To our knowledge, this investigation of highly ionised argon was never addressed again in subsequent spectroscopic

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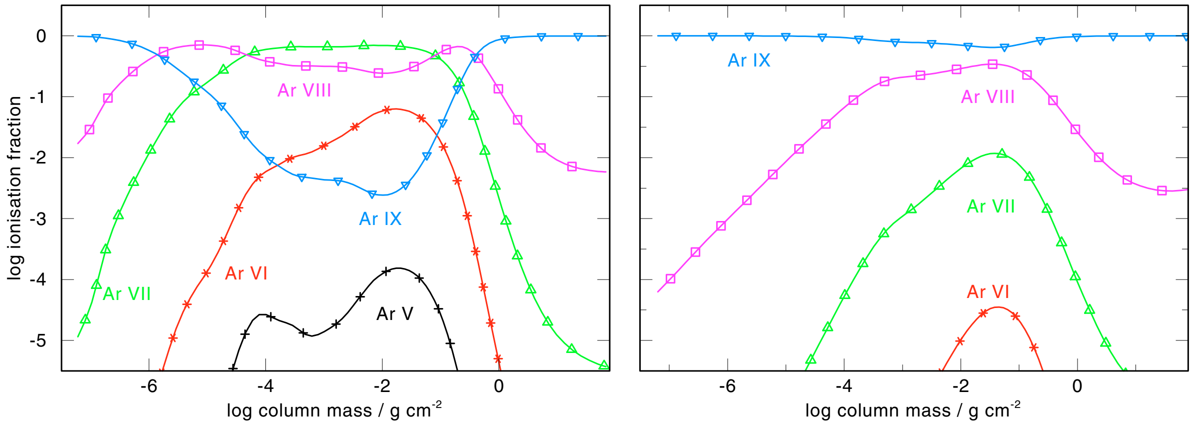

Fig. 1. Ionization fraction of argon as a function of atmospheric depth. *Left*: model with $T_{\rm eff} = 110\,000$ K, log $g = 7.0$ (for PG 1424+535). *Right*: model with $T_{\rm eff} = 140\,000$ K, log $g = 7.0$ (for PG 1159-035). Ar VII is dominant in the line-forming regions of the cooler model but is strongly depopulated in the hotter model, explaining the dependency of the Ar VII 1063.55 Å line strength from $T_{\rm eff}$.

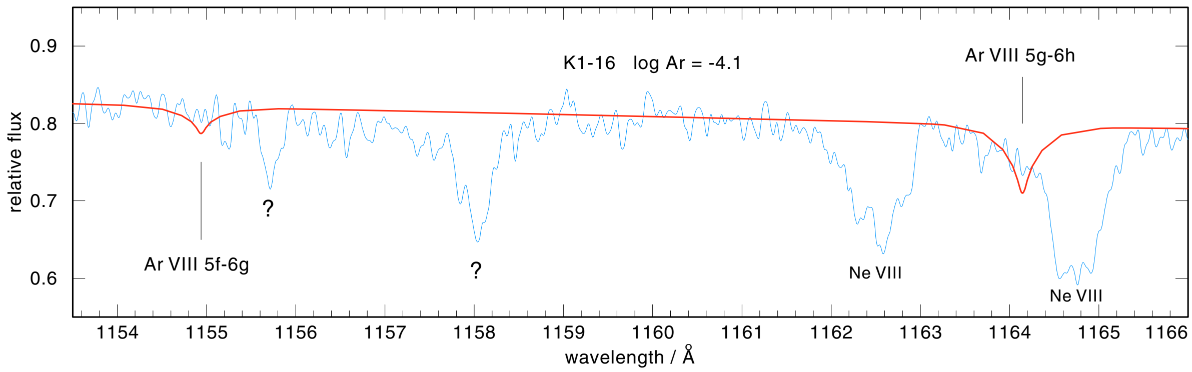

Fig. 2. The strongest Ar VIII lines are exhibited by models with $T_{\rm eff} \gtrsim 140\,000$ K. They are located in a region where two unidentified and two Ne VIII photospheric lines are detected in the spectrum of K 1-16. Unfortunately, the position of the Ar VIII lines is uncertain by ±1.2 Å, preventing a unique identification. The parameters for the displayed model are those given for K 1-16 in Table 1 except for the Ar abundance. It is was set to log Ar = −4.1 (mass fraction).

work. It was this investigation that inspired us to look for argon in hot post-AGB stars.

In this paper we report the discovery of an absorption line of highly ionised argon, namely Ar VII 1063.55 Å, in a number of hot post-AGB stars and white dwarfs with $T_{\rm eff} \approx 100\,000$ K. We describe in some detail the argon model atom and the line identification in Sect. 2. We present the abundance analysis in Sect. 3 and conclude in Sect. 4.

2. Argon abundance analysis

FUSE observations and data reduction for most of our program stars were described in our previous work as indicated in the Introduction. Because of the higher gravity of our program stars (2–4 dex) compared to the supergiant HD 93129A one can expect that the Ar VI/Ar VII lines are strongest at effective temperatures significantly higher than 50 000 K. This is because the ionization balance is shifted to lower ionisation stages with increasing gravity (and hence increasing gas pressure) which is compensated by increasing temperature. Our models show that the Ar VII line is strongest at $T_{\rm eff} \approx 100\,000$ K. In Fig. 1 we display the depth dependency of the Ar ionization fractions in the atmospheric models of two PG 1159 stars with different effective temperatures (110 000 and 140 000 K). The ionization balance in the hotter model is shifted away significantly to ionization stages higher than Ar VII.

We have identified the Ar VII 1063.55 Å line and performed an Ar abundance determination in six stars (see Sect. 3). The following objects do not show this line: PG 1159-035, K 1-16, PG 1144+005, and PG 1520+525. This allows us to derive a meaningful upper abundance limit for these PG 1159 stars.

In the spectra of the PG 1159 stars NGC 246 and H1504+65 there is no H_2 blend at the Ar VII 1063.55 Å line position, however, $T_{\rm eff}$ and log g are such that the argon line has disappeared. The following objects have a too strong H_2 line blend: The PG 1159 stars PG 1707+427, RX J2117+3412, HS 2324+397, NGC 7094, Abell 43, Longmore 4, the hot DO white dwarf KPD 0005+5106, the hot DA white dwarf PG 0038+199, the hydrogen-rich central stars NGC 6853, LSS 1362, NGC 1535, and the hot helium-rich stars (i.e., spectral type O(He)) K 1-27, HS 2209+8229, HS 1522+6615, and LoTr 4.

We have designed an argon model atom for NLTE line-formation calculations. These are performed using and keeping fixed the physical structure (temperature, densities) of line-blanketed NLTE model atmospheres which are described in detail in Werner et al. (2004). In short, they are plane-parallel and in hydrostatic and radiative equilibrium. Model parameters and references to the previous analyses are given in Table 1. The models are composed of H, He, C, O, and Ne. For the H-rich central star NGC 1360 we calculated models with a solar composition. We do not adopt the oversolar helium abundance suggested by Traulsen et al. (2005) because we regard this

Table 1. List of objects and measured argon abundances. For the two DA white dwarfs $T_{\rm eff}$ and $\log g$ are rather uncertain. We list the Ar abundances that we derive for the different sets of published $T_{\rm eff}/\log g$ values. In the last column we note the technique used to derive these sets (LTE or NLTE models, and fits to hydrogen Balmer or Lyman lines).

object	spectral type	$T_{\rm eff}$ [K]	$\log g$ (cgs)	logarithmic argon abundance: mass fraction Ar	number ratio Ar/H	number ratio Ar/He	reference for $T_{\rm eff}$, $\log g$
NGC 1360	O(H) CSPN	97 000	5.3	−4.1	−5.6		Traulsen et al. (2005)
NGC 7293	DAO CSPN	105 000	7.0	−6.0	−7.5		Napiwotzki (1999)
PG 0948+534	DA	110 000	7.6	−4.1	−5.7		Barstow et al. (2003a) (NLTE Balmer)
		126 000	7.3	−3.5	−5.1		Liebert & Bergeron (1995) (LTE Balmer)
RE J1738+669	DA (CSPN?)	76 000	7.9	−4.5	−6.1		Barstow et al. (2003b) (NLTE Lyman)
		67 000	7.8	−3.7	−5.3		Barstow et al. (2003a) (NLTE Balmer)
		95 000	7.9	−5.5	−7.1		Finley et al. (1997) (LTE Balmer)
PG 1034+001	DO (CSPN?)	100 000	7.5	−2.8		−3.8	Werner et al. (1995)
PG 1424+535	PG 1159	110 000	7.0	−4.5			Dreizler & Heber (1998)
PG 1159-035	PG 1159	140 000	7.0	≤−5.0			Werner et al. (1991)
K 1-16	PG 1159 CSPN	140 000	6.4	≤−5.1			Kruk & Werner (1998)
PG 1144+005	PG 1159	150 000	6.5	≤−4.1			Werner & Heber (1991)
PG 1520+525	PG 1159 CSPN	150 000	7.5	≤−4.1			Dreizler & Heber (1998)
The Sun				−4.6	−5.8	−4.8	Asplund et al. (2005)

result as uncertain. For the DAO central star NGC 7293 the elemental abundances are solar, too, except for helium which is reduced to He/H = 0.03 by number. For the DAs we computed H-dominated models setting He and metal abundances to 1% solar. For the DO PG 1034+001 we fixed the C and O abundances to the values derived by Werner et al. (1995) and set the unknown Ne abundance to log(Ne/He) = −8 (by number). For each star we performed calculations with different argon content in order to estimate the observed abundance and the error of the analysis.

The model atom considers ionization stages Ar V–IX, represented by 1, 15, 20, 41, and 1 NLTE levels, respectively, plus a number of LTE levels. In the ions Ar VI–VIII we include 21, 36, and 199 line transitions, respectively. Due to convergence problems which have their origin in a particular Ar VI EUV line and are not understood, the models for objects with $T_{\rm eff} \leq 110\,000$ K (except for PG 1034+001) do not include Ar VI lines. This is not expected to have an influence on the calculated Ar VII-VIII line profiles. Atomic data were taken from the NIST[1] and Opacity (Seaton et al. 1994) and IRON (Hummer et al. 1993) Projects databases (TIPTOPbase[2]). For all lines we assumed quadratic Stark broadening for the profile calculation, except for Ar VIII lines for which linear Stark broadening is appropriate. Let us comment in some detail on the spectral lines relevant for the present work.

The strategic Ar VII 1063.55 Å line is the singlet transition $3p\,^1P^o$–$3p^2\,^1D$. The same transition in the sulfur isoelectronic configuration gives rise to the S V 1501.76 Å line that is well known in stellar UV spectroscopy. The exact wavelength position of the Ar VII line coincides in the Kelly[3] (1987) and CHIANTI[4] (Young et al. 2003) databases and is in accordance with the energy levels provided by Bashkin & Stoner (1975). The Kentucky database[5] gives $\lambda = 1063.63$ Å which disagrees with the other data sources and with the line position observed in our FUSE spectra. The f-value for this line is reasonably well known. There is only a small difference in the value quoted by Taresch et al. (1997) and the CHIANTI database ($f = 0.113$) and the value given in the Kentucky database ($f = 0.130$). For our calculations we have adopted $f = 0.113$. We have checked with model calculations for the presence of another Ar VII line listed in Taresch et al. (1997) at 982.0 Å. It is the strongest component of an intercombination multiplet ($\lambda\lambda$ 981.97, 999.47, 1066.50 Å) that arises from the same lower level as the 1063.55 Å line but with an upper level in the triplet system. The f-value of the 982.0 Å line, however, is a factor of ≈100 smaller than that of the 1063.55 Å line and as a consequence is undetectable. A number of other Ar VII lines appear in the Taresch et al. (1997) list ($\lambda\lambda$ 1060.1, 1060.4, 1067.4, 1136.7 Å), for which no level energies are publicly available. They are not detected in our program stars probably because they arise from too highly excited levels.

Concerning the Ar VI ion, Taresch et al. (1997) list three lines of the intercombination resonance multiplet $3p^2\,P^o$–$3p^2\,^4P$ ($\lambda\lambda$ 998.4, 1000.2, 1013.3 Å). The f-values of all multiplet components, however, are 6.6×10^{-5} and smaller. The resulting lines are undetectable in our model spectra as well as in the FUSE spectra of our stars. Four other lines listed ($\lambda\lambda$ 1008.8, 1013.3, 1164.5, 1169.4 Å) are very highly excited and not detectable in our program stars.

A look at Fig. 1 suggests that stars with $T_{\rm eff} \gtrsim 140\,000$ K could exhibit lines even from Ar VIII. This is a hydrogen-like ion having line transitions between levels with principal quantum numbers $n = 5 \longrightarrow 6$ in the FUSE spectral range. The two lines with the largest gf-values are 5f ⟶ 6g and 5g ⟶ 6h located at 1154.9 Å and 1164.1 Å, respectively. The latter is stronger and it is indeed clearly seen in the hot star models although it is strongly broadened by linear Stark effect (Fig. 2). Unfortunately the level energies are not known accurately enough so that the line position is uncertain within ±1.2 Å (Kentucky database). Within that uncertainty range of the 5f ⟶ 6g line a hitherto unidentified line at 1155.7 Å can be seen in the spectra of the hottest PG 1159 stars, among them is K 1-16 (Fig. 2), however, the identification with Ar VIII is unclear. The 5g ⟶ 6h line is located in the blue wing of a strong and broad Ne VIII line

[1] http://physics.nist.gov/PhysRefData/ASD/index.html/.
[2] http://vizier.u-strasbg.fr/topbase/.
[3] http://cfa-www.harvard.edu/amdata/ampdata/kelly/kelly.html/.
[4] http://wwwsolar.nrl.navy.mil/chianti.html/.
[5] http://www.pa.uky.edu/~peter/atomic/.

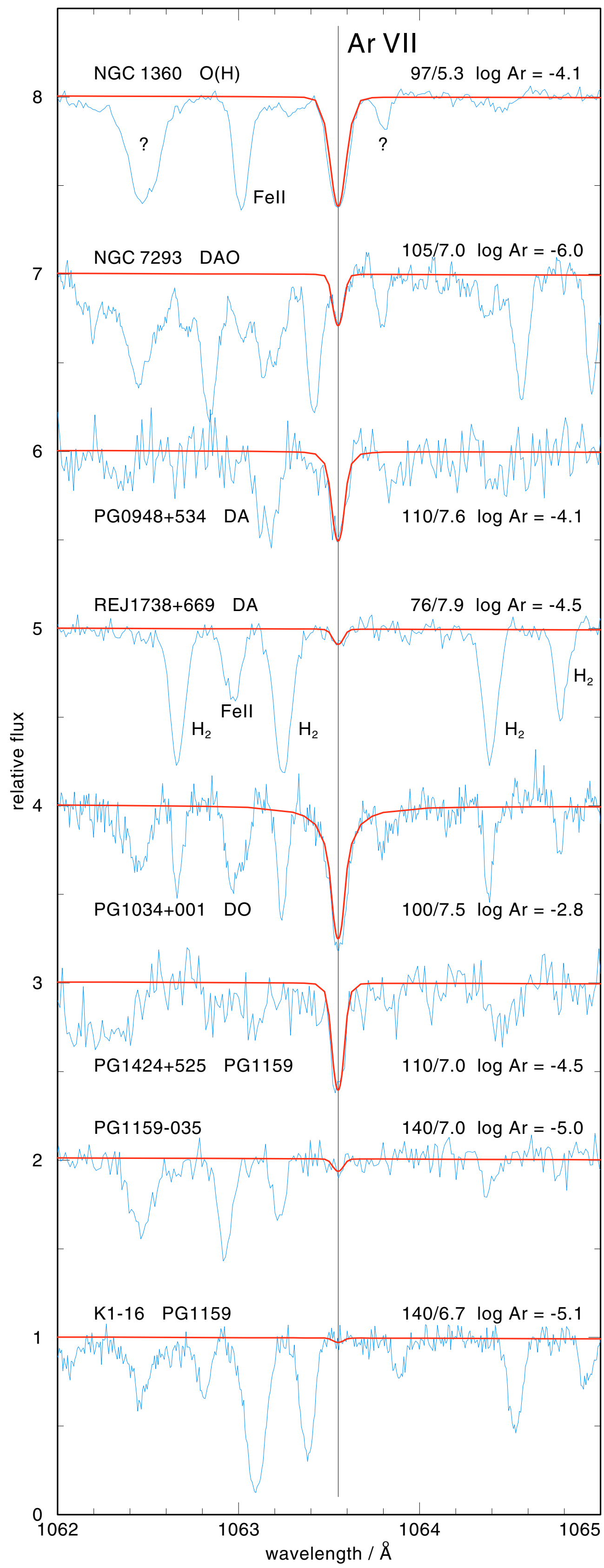

Fig. 3. Identification of the Ar VII 1063.55 Å line. It is not detectable in the hottest objects (PG 1159-035 and K 1-16). Overplotted are synthetic line profiles with log Ar (mass fraction), $T_{\rm eff}$ /kK, and log g as labeled. Unidentified photospheric lines at 1062.45 and 1063.8 Å are seen in several objects (marked by "?" in the top spectrum). All other lines are from interstellar Fe II and H_2; some of them are labeled.

at 1164.7 Å and cannot be identified clearly. The use of these Ar VIII lines as a spectral diagnostic is questionable in any case because for some levels that probably are important for a proper NLTE model atom the energies are completely lacking.

The two Ne VIII lines shown in Fig. 2 are new identifications. Exploratory modeling suggests that they are of photospheric origin. We are preparing detailed NLTE line formation calculations and will present results in future work.

3. Results

We present profile fits to the Ar VII 1063.55 Å line in Fig. 3. The results are given in Table 1. In the following we comment on the individual objects in their order of appearance in Fig. 3 and Table 1.

For the white dwarfs we compare our results to the theoretical argon abundance predictions of Chayer et al. (1995a,b). They are based on the assumption that trace elements in H or He dominated white dwarf atmospheres are kept from gravitational settling by radiative levitation. These authors present detailed predictions for the Ar abundance in DA and DO white dwarfs as a function of effective temperature and surface gravity.

NGC 1360. The central star of this planetary nebula is of spectral type O(H), i.e., its optical spectrum is dominated by the hydrogen Balmer lines. Hoare et al. (1996) derived $T_{\rm eff} = 110\,000$ K and log $g = 5.6$. A more recent analysis using metal lines in UV spectra indicates slightly different values, namely $T_{\rm eff} = 97\,000$ K and log $g = 5.3$ (Traulsen et al. 2005). We find a marginal Ar overabundance, log(Ar/H) = −5.6 (by number), that is within the error limit identical to the solar abundance (−5.8).

NGC 7293. This planetary nebula nucleus is classified as a DAO white dwarf, i.e., it is hydrogen-rich with an admixture of helium. The atmospheric parameters were derived by Napiwotzki (1999) using optical spectra: $T_{\rm eff} = 105\,000$ K, log $g = 7.0$, He/H = 0.03. With log(Ar/H) = −7.5 (by number) we find a strong Ar *underabundance* of a factor of ≈ 50. We can compare this result with the prediction of levitation theory. From Fig. 2 in Chayer et al. (1995b) we read log(Ar/H) = −3.5 for DA white dwarfs, i.e., an extreme *overabundance* (factor ≈200). The fact that the star has some residual helium in the atmosphere is probably unimportant for this prediction (note that for DO white dwarfs the predicted Ar abundance is even higher, by about 1 dex). In essence, the predicted Ar abundance is four orders of magnitude higher than the observed one. Traulsen et al. (2005) have claimed higher $T_{\rm eff}$ and lower log g from UV spectra (120 000 K, 6.5) which both have the tendency to weaken the Ar VII line and, hence, a 0.5 dex higher Ar abundance is derived in this case which is still much below the theoretical prediction.

PG 0948+534. This is one of the hottest known DA white dwarfs. From Balmer line NLTE fits Barstow et al. (2003a) derived $T_{\rm eff} = 110\,000$ K, log $g = 7.6$. Our best fit model has log(Ar/H) = −5.7 (by number). The Chayer et al. (1995b) prediction for these parameters is much higher, log(Ar/H) = −3.9. (A slight extrapolation was needed because their calculations do not consider $T_{\rm eff} > 100\,000$ K.) In their LTE Balmer line analysis Liebert & Bergeron (1995) find $T_{\rm eff}$ even higher and log g lower ($T_{\rm eff} = 126\,000$ K, log $g = 7.3$) which both has the tendency to make the Ar VII line weaker. We have computed a small model set with their log g and $T_{\rm eff} = 130\,000$ K and different

Ar abundances. The best fit is now achieved at log(Ar/H) = −5.1 which makes the difference with the predicted abundance smaller but it is still significant.

RE J1738+669. This is another extremely hot DA white dwarf. The Balmer line LTE analysis by Finley et al. (1997) resulted in $T_{\rm eff} = 95\,000$ K, $\log g = 7.9$. We derive log(Ar/H) = −7.1 (by number). The respective Chayer et al. (1995b) prediction is log(Ar/H) = −4.3 which is again a significant overestimation. The $T_{\rm eff}$/log g values for this DA are, however, rather uncertain. Barstow et al. (2003a,b) have performed a separate analysis of the Balmer and Lyman lines and arrived at significantly lower $T_{\rm eff}$ but with discrepant values: 67 000/7.8 and 76 000/7.9, respectively. For these two parameter sets we derive log(Ar/H) = −5.3 and log(Ar/H) = −6.1 which can be compared to the predicted diffusion abundances for the respective $T_{\rm eff}$/log g sets: −4.8 and −4.5. This means an overestimation of 0.5 and 1.5 dex. Thus, irrespective of the uncertain temperature we find that theory overpredicts the Ar abundance. Only if one accepts the lowest $T_{\rm eff}$ value then the Ar abundance is close to the predicted amount.

PG 1034+001. This DO is among the hottest known helium-rich white dwarfs ($T_{\rm eff} = 100\,000$ K, $\log g = 7.5$). It exhibits the strongest Ar VII line in all stars we examined. We derive log(Ar/He) = −3.8 (by number). From Fig. 16 in Chayer et al. (1995a) we find that the theoretical prediction is about one dex higher: log(Ar/He) = −2.9.

PG 1424+535. This is the only PG 1159 star in which we could identify the Ar VII line. It is rather strong and we derive a mass fraction of log Ar = −4.5. This is close to the solar value (−4.6).

PG 1159-035. The prototype of the PG 1159 class does not show clear evidence for the Ar VII line. We derive an upper limit of log Ar = −4.5 (mass fraction) which is almost equal to the solar abundance value (−4.6).

K 1-16, PG 1144+005, PG 1520+525. These PG 1159 stars have effective temperatures similar to the prototype. Hence the non-detection of argon allows to derive the solar abundance value as an approximate upper limit, too.

From our experience with the profile fitting we estimate the error of our abundance determinations to 0.5 dex.

4. Conclusions

4.1. PG 1159 stars and the H-rich central star NGC 1360

Nucleosynthesis calculations for AGB stars predict that the argon abundance in the intershell region remains almost unchanged. In a particular model calculation for a 2 $M_\odot$ AGB star the most abundant argon isotopes ^{36}Ar and ^{38}Ar are being destroyed and produced by neutron captures, respectively, resulting in a net reduction of the total Ar abundance of 0.2 dex after 30 thermal pulses (Gallino priv. comm.). This is in line with results from argon isotope analyses of meteoritic SiC grains which were formed in the winds from AGB carbon stars (Gallino et al. 1990). All five noble gases detected in such grains have elemental and isotopic abundances which are very similar to results of nucleosynthesis calculations for the intershell of these stars (Lewis et al. 1990).

The solar abundance of argon that we detected in the PG 1159 star PG 1424+535 and in the H-rich central star NGC 1360 further confirm these results. PG 1424+535 displays intershell matter and proves that the Ar abundance remained unchanged during the previous AGB evolution. NGC 1360 could show deviations from the solar Ar abundance if third dredge-up of strongly Ar-depleted/enhanced matter during the previous AGB evolution would have occurred. This is not observed. The solar upper Ar abundance limits determined for the three other PG 1159 stars in our sample rule out an extraordinary argon production.

4.2. DA, DAO, and DO white dwarfs

Chayer et al. (1995a,b) have presented detailed predictions about trace element abundances based on diffusion/levitation equilibrium theory. They found, however, that equilibrium theory is unable to reproduce the observed trace element abundances quantitatively for most species. This failure has become increasingly obvious during the last years when more and more observational results became available.

Vennes et al. (2005) have for the first time discovered trans-iron group elements in hot DAs (germanium and probably tin). The derived abundances are nearly solar (i.e., of the order 10^{-8}–10^{-9} relative to H, by number) and this made these authors ask: "With the detection of such an unlikely candidate [Ge], what of abundant elements such as Ne, Mg, Ar, and Ca? These elements would be detectable in high-dispersion extreme-ultraviolet spectra. Until their abundances have been determined, the abundance pattern in hot DA white dwarfs remains incomplete". Our results on argon are one step towards this goal. They also show that far-ultraviolet data supplied by FUSE offer the only way to this goal as long as high-resolution EUV spectroscopy is unavailable. A significant number of still unidentified photospheric lines in the FUSE spectra of hot white dwarfs (some examples are presented in Figs. 2 and 3) may hold the key to even more hitherto unidentified elements in white dwarfs. The argon abundances derived in the present paper are another example that equilibrium theory is unable to reproduce the observed trace element abundances quantitatively.

To conclude, we recall that not only PG 1159 photospheric metal abundances are affected by s-process nucleosynthesis that took place during the AGB phase. This may also be the case for white dwarfs although diffusion has certainly altered the abundance pattern. This is suggested by the recent discovery of strongly oversolar abundances of trans-iron group elements (up to iodine) in cool ($T_{\rm eff} \approx 50\,000$ K) DO white dwarfs (Chayer et al. 2005). In contrast, the one dex oversolar argon abundance that we found in the hot DO PG 1034+001 cannot be the result of nucleosynthesis but must be the result of selective radiative levitation.

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