New powerful diagnostics for hot evolved stars: constraining the hottest temperatures, the faintest winds, and the neon abundance

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ABSTRACT

We have identified a strong P Cygni feature (λ 973) in the far-UV spectra of some very hot ($T_{\rm eff} \gtrsim 85,000$ K) central stars of planetary nebulae (CSPN) and PG 1159 stars as originating from NeVII. Using stellar atmosphere models, we reproduce this feature as it is observed in the spectra of hydrogen-deficient CSPN, as well as in PG 1159 stars. The discovery of highly ionized neon in CSPN spectra is important because an overabundance of this element is indicative of processed material that has been dredged up to the surface from the interior region as predicted in the "born-again" scenario, an explanation of H-deficient post-Asymptotic Giant-Branch (AGB) objects. We show the potential of this strong feature as well as weaker neon features as diagnostics in stellar atmospheres analyses for extremely hot post-AGB objects, where other diagnostics are scarce. This diagnostic is potentially useful also in the analysis of massive stars with winds such as WO stars.

Key words: UV spectroscopy, post-ABG stars, planetary nebulae, PG1159 stars, winds, neon abundance, stellar evolution

1. Introduction

Low and intermediate mass stars reach their highest effective temperatures at the end of the constant-luminosity post-AGB / central-star of planetary nebulae (CSPN) phase, then move onto the white dwarf (WD) cooling sequence. During this phase, their winds (which typically have mass-loss rates of $\dot{M} \simeq 10^{-8}$ $M_\odot$ yr^{-1}and $V_\infty \simeq$ 2000 km s^{-1}) are fading, and because of the extreme temperatures ($T_{\rm eff} \gtrsim 80$ kK) strong spectral features are scarce. About 10-20% of CSPN are hydrogen-deficient, and the origin of these H-deficient CSPN is the matter of some debate. In the "born-again" scenario (6; 3 and references therein), material enriched in C, O, and Ne from previous CNO burning in the intershell region is brought to the surface when the star experiences a late helium-shell flash, causing it to enter a second (or "born-again") asymptotic giant-branch (AGB) phase. Classes of H-deficient objects in this region are the PG 1159 stars (extremely hot WD type objects which have evolved from H-deficient CSPN) and a rare class of "[WR]-PG 1159" objects, which are stars transitioning to the PG 1159 phase from the [Wolf-Rayet] CSPN phase. The far-UV spectra of several PG 1159 stars (8) and a couple [WR]-PG 1159 stars (7; 1) display a strong P-Cygni line at ∼975 Å. This line was originally identified as C III λ 977, but past modeling efforts to reproduce this line with carbon included in the stellar atmospheres codes had failed (7; 1). Using an updated atomic data set for neon, we (2) showed this feature actually originates from Ne VII λ973.33 ($2p^1P^o - 2p^2\,{}^1D$). This is important, not only because it adds to a sparse list of wind diagnostics for an important evolutionary phase, but because it offers a possibility to measure the neon abundance (X_{Ne}) in H-deficient objects, where an enhancement of up to 20 times the solar value is predicted by the born-again scenario. We have thus explored this diagnostic for different stellar parameters ($T_{\rm eff}$, $\dot{M}$, and X_{Ne}).

We have modeled so far the far-UV and UV spectra of two PG 1159 stars, NGC 246 and K1-16, and two "transition" [WR]-PG 1159 stars, Abell 78 and NGC 2371, using archival FUSE and IUE spectra. We modified the CMFGEN (4; 5) code, that calculates non-LTE stellar atmospheres solving the radiative transfer equation in extended, expanding spherical geometry, and included H, He, C, N, O, Ne, Si, P, S, and Fe in the calculations (Herald, Bianchi & Hillier 2005). The parameters of the stellar models presented here are given in Table 1. The far-UV is home to numerous H_2 transitions, from the Lyman and Werner series, which create a series of absorption "bands" typically seen in FUSE spectra. We have modeled the H_2 along the sight lines of our sample stars and applied its absorption effects to the stellar model spectra.

Star	$T_{\rm eff}$ (kK)	V_∞ (km s^{-1})	R_* ($R_\odot$)	$\log L$ ($L_{\rm sun}$)	$\log \dot{M}$ (M$_\odot$ yr^{-1})	Ref.
NGC 2371	**135**	**3700**	**0.09**	**3.45**	**-7.11**	(2)
Abell 78	**113**	**3200**	**0.19**	**3.73**	**-7.33**	(2)
K 1-16	**135**	**3700**	**0.11**	**3.6**	**-8.3**	(2)
NGC 246	**165**	**3450**	**0.09**	**3.7**	**-7.45**	this work

Fig. 1 displays the FUSE spectra for four stars, along with our computed models from (2) and this work (for NGC 246), which have a neon abundance 10 times the solar value (discussed in section 2). Displayed are the models with and without the absorption effects of H_2 applied, as well as models for NGC 2371 and Abell 78 from (1), which did not include neon in the stellar atmospheres. As can be seen, the strong P-Cygni feature at λ973 is reproduced by our newer models.

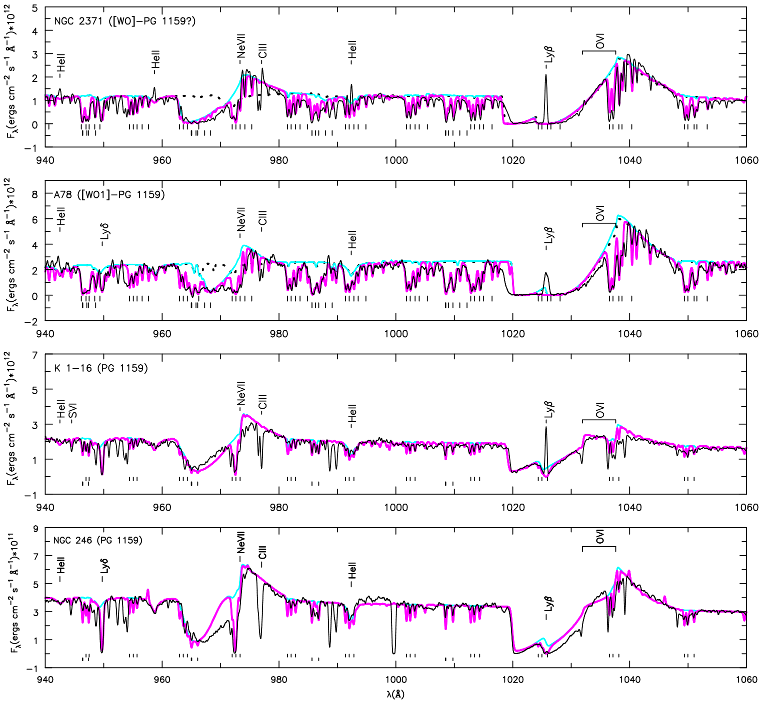

Figure 1: The FUSE observations (black) along with our stellar models (with $X_{Ne} = 10X_{\odot}$) for K1-16, NGC 2371 and Abell 78 from (2) and for NGC 246 (this work), both with (pink/grey-thick) and without (aqua/grey-light) the effects of the hydrogen absorption models applied (H_2 transitions are marked with ticks). The models indicate Ne VII to be responsible for the P-Cygni feature seen at ~ 975 Å. We also show models of NGC 2371 and Abell 78 from (1) (black dotted), which did not include neon in the model atmospheres.

2. Ne VII as a Diagnostic of Stellar Parameters

We computed several exploratory models to evaluate the potential of the Ne VII line as a diagnostic of various stellar parameters, particularly to the neon abundance, as this quantity has important evolutionary implications. Figs. 2 & 3 illustrate the behavior of the Ne VII line in different temperature and mass-loss regimes, as well as its sensitivity to the neon abundance. As can be seen, when saturated, the line is not very sensitive to the neon abundance (as expected). However, when unsaturated, it can be very sensitive to the neon abundance, therefore - in principle - can be used to determine this quantity in very hot stars with low mass-loss rates, such as PG 1159 stars. Since PG 1159 stars represent an advanced evolutionary stage when the star is hottest and the wind is fading, our model grids indicate that Ne VII $\lambda973$ may be the last wind feature to disappear if the atmosphere is enriched in neon.

Fig. 4 shows the Ne VII profiles of NGC 246 and K1-16, along with models with neon abundances at solar and super-solar values. The models indicate a super-solar neon abundance for these objects, as predicted in the born-again scenario.

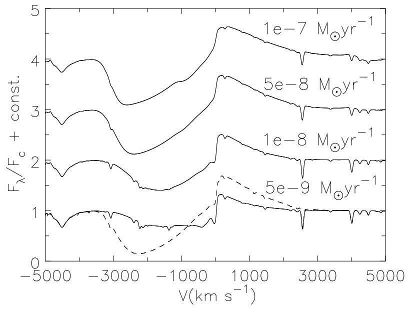

Figure 2: The effects of varying $\dot{M}$ and X_{Ne} of our K 1-16 model on Ne VII $\lambda973$. The solid and dashed lines represent models with neon abundances of $1X_{\odot}$ (solar) and $10X_{\odot}$, respectively. The feature is very sensitive to $\dot{M}$ when not saturated (*e.g.*,the $\dot{M} = 5 \times 10^{-9}$ $M_{\odot}$ yr^{-1} model).

2.1. Other Neon diagnostics in the UV range

Although our modeling indicates the Ne VII $\lambda973$ feature may not be useful in diagnosing a super-solar neon abundance in cases where the line is saturated (like NGC 2371), it does show other neon transitions in the far-UV and UV which do not produce significant spectral features for a solar neon abundance, but do for enriched neon abundances. The strongest examples are the $\lambda2213.13$ and $\lambda2229.05$ transitions from the $3d\,^2D - 3p\,^2P^o$ Ne VI triplet which become evident in models of both objects when $X_{Ne} = 10X_{\odot}$ (shown in Fig. 5).

3. Summary

The strong P-Cygni wind feature seen around 975 Å (hitherto unidentified or mistakenly identified as C III $\lambda977$) in the far-UV spectra of very hot ($T_{\rm eff} \gtrsim 85$ kK) CSPN can be reproduced by models which include neon in the stellar atmosphere calculations. When unsaturated, this line is very sensitive to the neon abundance. We have derived a likely super-solar abundance in the case of NGC 146 and K1-16, two PG 1159 stars. This enhanced abundance provides support to the "born-again" scenario, a explanation of H-deficient evolved stars.

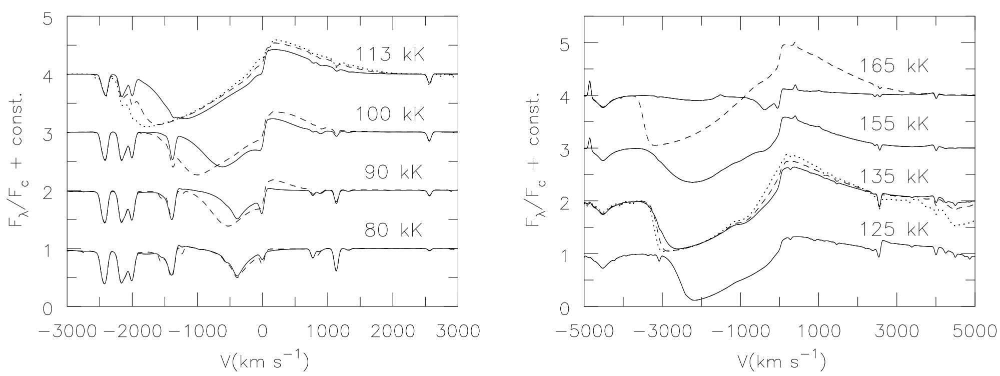

Figure 3: The effects of varying $T_{\rm eff}$ and X_{Ne} of our Abell 78 model (left) and our NGC 2371 model (right) on Ne VII λ973. The solid, dashed, and dotted lines represent models with neon abundances of $1X_\odot$ (solar), $10X_\odot$, and $50X_\odot$, respectively. When saturated (*e.g.,* in the $T_{\rm eff}$ = 135 kK model), the feature is not very sensitive to X_{Ne}. It is sensitive to $T_{\rm eff}$, and becomes pure absorption for $T_{\rm eff} \lesssim 85$ kK and is of significant strength for $100 \lesssim T_{\rm eff} \lesssim 160$ kK. The feature is weak in the solar neon abundance $T_{\rm eff}$ = 165 kK model, but strengthens dramatically when $X_{Ne} = 10X_\odot$, illustrating the abundance sensitivity of the line in some parameter regimes where it is unsaturated.

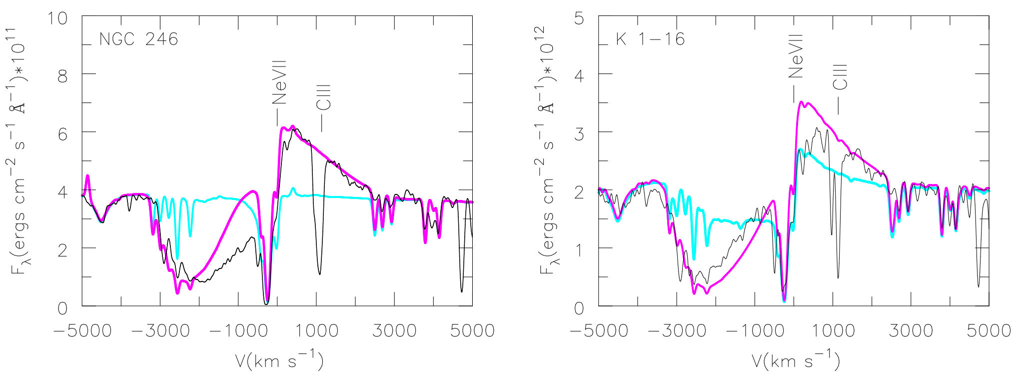

Figure 4: NGC 246 (**LEFT**) and K 1-16 (**RIGHT**): FUSE spectra of the Ne VII λ973 profile (in velocity space) (black) along model spectra with two neon abundances, one with $X_{Ne} = 1X_\odot$ (solar), and one with $X_{Ne} = 10X_\odot$ (aqua and pink, respectively). Effects of interstellar hydrogen absorption have been applied to the model spectra. The unsaturated profiles are very sensitive to the neon abundance, and indicate a super-solar abundance in these objects.

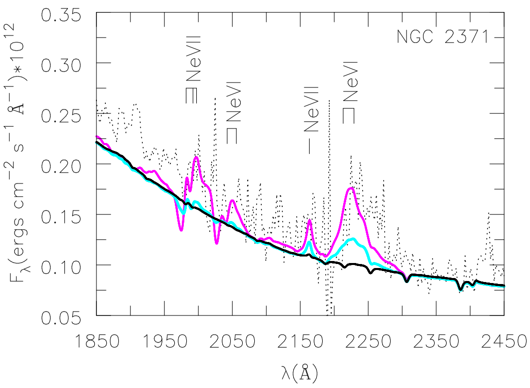

Figure 5: Additional neon diagnostics:IUE observations of NGC 2371 are shown (dotted) along with models with $X_{Ne} = 1X_\odot$ (black), $X_{Ne} = 10X_\odot$ (aqua) and $X_{Ne} = 50X_\odot$ (pink). The labeled features are not apparent in the solar abundance model, but become significant as the neon abundance is increased.

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