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A *FUSE* View of Winds from the Central Stars of Planetary Nebulae

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Abstract: Since the *IUE* satellite produced a vast collection of high-resolution UV spectra of the central stars of planetary nebulae (CSPNe), there has not been any further systematic study of the stellar winds of these stars. The high spectral resolution, sensitivity and large number of archival observations in the *FUSE* archive allow the study of the stellar winds of CSPNe in the far-UV domain where lines of species spanning a wide excitation range can be observed. We present here a preliminary analysis of the P Cygni profiles of a sample of ~60 CSPNe observed by *FUSE*. P Cygni profiles providing evidence for fast stellar winds with velocities between 200 and 4300 km s^{-1} have been found in 40 CSPNe. In many cases, this is the first time that fast stellar winds have been reported for these planetary nebulae (PNe). A detailed study of these far-UV spectra is on-going.

Keywords: line: profiles — planetary nebulae — stars: winds, outflows — ultraviolet: stars

1 Introduction

Fast stellar winds driven by radiation pressure are characteristics of the central stars of planetary nebulae (CSPNe). These stellar winds, with terminal velocities (v_∞) up to 4000 km s^{-1}, carry large amounts of energy and momentum and interact with the slow, 5–30 km s^{-1} (Eder, Lewis & Terzian 1988), dense wind of the Asymptotic Giant Branch (AGB) phase. This interaction plays an important role in the shaping and evolution of PNe, as recognized by the canonical Interacting Stellar Wind model of formation of PNe (Kwok, Purton & Fitzgerald 1978; Balick 1987).

The fast stellar winds in CSPNe can be discovered through the P Cygni profiles of lines in the UV of high-excitation ions. The International Ultraviolet Explorer *IUE* satellite obtained useful UV spectra in the 1150–3350 Å range for ~160 CSPNe (Patriarchi & Perinotto 1991, and references therein). A significant fraction of these CSPNe presented P Cygni profiles in the N v λλ1239,1243 Å, C iv λλ1548,1551 Å, and O v λ1371 Å lines, among others. These P Cygni profiles implied fast stellar winds with edge velocities ranging from 600 to 3500 km s^{-1} (Cerruti-Sola & Perinotto 1985).

Launched in June 1999, the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) opened a new window in the far-UV range of the spectrum from 905 to 1195 Å. This spectral range includes information on a variety of resonance lines of high-excitation species (O vi, P v, Si iv, C iii, etc.) that can be present in the spectra of CSPNe. The occurrence of P Cygni profiles of these lines and their properties (v_∞, variability, main ionization stage, ...) is a valuable tool to assess the importance of stellar winds in the formation of PNe. We have therefore started a program aimed to use the high-resolution spectra of CSPNe in the final archive of the *FUSE* mission to investigate stellar winds in CSPNe. Here, we present preliminary results of this on-going project.

2 Results

The final *FUSE* archive includes high-resolution spectra for ~90 CSPNe. The inspection of these spectra has revealed P Cygni profiles indicative of stellar winds in 40 PNe. For a dozen of them, this is the first time that fast stellar winds have been reported. The CSPNe with useful *FUSE* observations that do not show evidence of P Cygni profiles overimposed on their stellar continuum are: A 7, A 31, A 35, A 39, DeHt 2, HDW 4, Hen 2–86, Hen 2–138, Hen 3–1357, K 1–26, K 2-2, NGC 1360, NGC 3132, NGC 3587, NGC 7293, Ps 1, PuWe 1, and Sh 2-174. These are either CSPNe of high $T_{\rm eff}$ and g at the center of old PNe (e.g. NGC 7293), i.e. these CSPNe are subdwarfs that have already initiated their evolution towards the white dwarf phase, or post-AGB stars at the center of young PNe (e.g. Hen 3–1357) that have not developed yet a stable wind or whose $T_{\rm eff}$ is not high enough to excite these emission lines in the stellar wind.

We list in Table 1 the CSPNe exhibiting P Cygni profiles and their edge velocities. Previous information obtained by *IUE* has been incorporated into this table to allow the straightforward comparison with the new *FUSE*

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Table 1. Edge velocity of *FUSE* and *IUE* UV lines in CSPNe

CSPN	*FUSE* lines	Edge velocity (km s^{-1})	*IUE* lines	Edge velocity (km s^{-1})
A 30	O VI, C III	4200	N V, O V, C IV	3400
A 43	O VI, C III	3900	...	
A 78	O VI, C III	4000	N V, O V, C IV	3500
BD+30°3639	S IV, P V, Si IV, C III	850	N V, O V, Si IV, C IV, N IV	1000
Cn 3–1	S IV, C III	530	...	
	Si IV	360	...	
Hb 7	S VI	1000	...	
	O VI	1500	...	
Hen 2–99	P V, C III	1200	...	
	S IV, Si IV	900	...	
Hen 2–131	P V, C III	500	N V, O V, Si IV, C IV, N IV	850
	S IV, Si IV	300	...	
Hen 2–274	S IV, C III	600	...	
Hen 2–341	S VI, O VI	1950	...	
IC 418	S IV, P V, C III λ1175 Å	500	Si IV, C IV, N IV	1050
	O VI, C III λ977 Å	850	...	
IC 2149	S VI, O VI, C III	1050	N V, Si IV, C IV	1300
IC 2448	O VI	2550	...	
IC 2501	S VI, O VI, P V	1400	N V, C IV	1280
IC 2553	O VI	2750	...	
IC 3568	O VI	>1600	N V, O V, C IV	1850
IC 4593	P V, C III	700	N V, O IV, Si IV, C IV, N IV	1100
	O VI	1400	...	
IC 4776	S VI, O VI	2050	...	
IC 5217	O VI	2600	...	
K 1–16	O VI, C III	3700	...	
Lo 4	O VI, C III	3800	...	
LSS 1362	O VI	2630	...	
NGC 40	S IV, P V, C III	1350	N V, O IV, O V, Si IV, C IV	1600
	O VI	1000	...	
NGC 246	C III	4300	C IV	>3300
	O VI	3700	...	
NGC 1535	O VI, S VI	2100	N V, O V	2150
NGC 2371	O VI, C III	4000	C IV	<3750
NGC 2392	O VI, C III	200	N V, N IV	600
NGC 2867	O VI, C III	2600	...	
NGC 5882	O VI, S VI	1950	N V, O V, C IV	1525
NGC 6058	O VI	2750	N V	...
NGC 6543	S VI, O VI	1900	N V, O IV, O V, Si IV, C IV, N IV	1900
	P V	1650	...	
NGC 6826	S VI, O VI, P V, C III	1350	N V, O IV, O V, Si IV, C IV, N IV	1600
NGC 6891	S VI, O VI, P V	1400	N V, O IV, O V, C IV, N IV	1950
NGC 7009	O VI	3000	N V, O V	2750
NGC 7094	O VI, C III	3750	C IV	3600
NGC 7662	O VI	2550	...	
PB 6	O VI	3500	...	
PB 8	S VI, C III	1000	N V, O IV, O V, Si IV, C IV, N IV	1060
	O VI, P V	1250	...	
SwSt 1	O VI	1120	N V, O IV, O V, Si IV, C IV, N IV	1580
	P V	800	...	
	S IV, Si IV	700	...	
	C III λ1175 Å	1400	...	
Vy 2–3	S VI, O VI	1800	...	

measurements. The comparison between *IUE* and *FUSE* data shows general agreement, but there are a few CSPNe where this is not the case. The poorer spectral resolution of the *IUE* data (e.g. NGC 2392) or the difficulties in the determination of the edge velocity in CSPNe severely affected by H_2 and atomic absorptions (e.g. NGC 6826) may be blamed for these differences. There are, however, CSPNe for which the different edge velocities between *IUE* and *FUSE* data seem real (e.g. IC 418).

We note that the terminal velocity of a stellar wind is usually determined from the blue edge velocity (i.e. the maximum velocity at which the P Cygni profile joins

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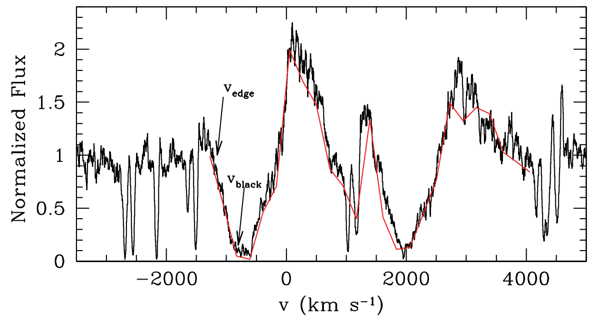

Figure 1 PB 8 P Cygni profile of the P v λλ1118,1128 Å line. The edge and black velocities are marked. The red curve corresponds to a SEI fit of the line profiles.

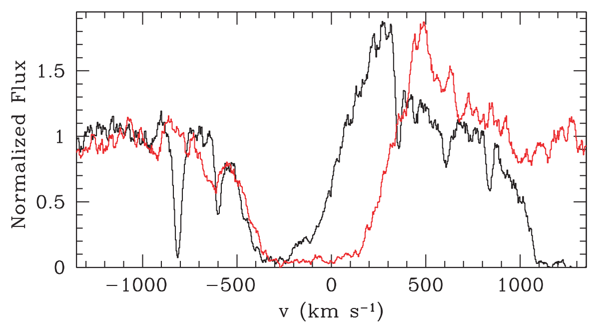

Figure 2 Cn 3–1 P Cygni profiles of the C III λ1175 Å (red) and S IV λλ1073.0,1073.5 Å (black) lines. Note the interstellar/circumstellar absorptions in the blue edge of the S IV P Cygni profile.

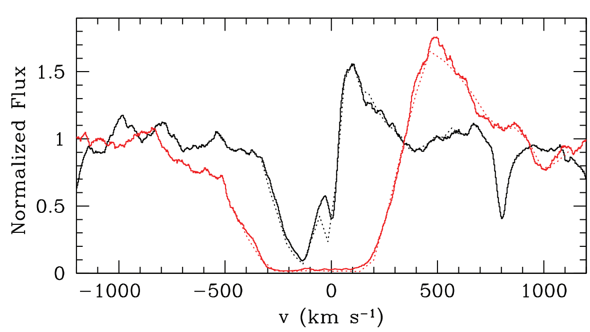

Figure 3 Hen 2–131 P Cygni profiles of the C III λ1175 Å (red) and Si IV λ1122 Å (black) lines. As in Figure 1, the dotted lines correspond to a SEI fits of the line profiles.

back to the stellar continuum). Consequently, we have provided in this work the edge velocity to allow a fair comparison with works in the literature that used *IUE* data (e.g. Patriarchi & Perinotto 1991). Some authors, however, argue that the so-called black velocity describes better v_∞. A detailed modeling using a SEI (Sobolev with Exact Integration) code results in a more accurate determination of v_∞. This method is illustrated in Figure 1 for the CSPN of PB 8. The terminal velocity of the fit, $\sim$1200 km s^{-1}, is very similar in this case to the edge velocity of 1250 km s^{-1} given in Table 1.

As shown in Table 1, many CSPNe have P Cygni profiles of a variety of resonance lines of species of different excitation levels. A close examination of the P Cygni profiles of the different lines for every single CSPN reveals cases when the line profiles are dramatically different. Moreover, as in the case of the comparison between the edge velocities derived from *IUE* and *FUSE* data, there are notable cases of CSPNe for which different edge velocities are associated with different lines in the *FUSE* spectral range.

First, we shall note that the shape of the P Cygni profile depends both on the different components and levels of the line, as well as on the dominant physical processes involved in its formation. The shape of different lines can vary owing to these factors, but their terminal velocities can be the same. This is the case for Cn 3–1 (Figure 2), for which the profiles of the C III λ1175 Å and S IV λλ1073.0,1073.5 Å lines are very different, but the black and edge velocities are similar. The different profile shapes can be explained as a result of the different components that form these two lines: the C III λ1175 Å line is a triplet which has 5 separate, closely spaced levels, while the S IV λλ1073.0,1073.5 Å line is one resonance doublet.

There are more extremes cases on which both the black and edge velocities and the profile shapes are notably different. This situation is illustrated by the P Cygni profiles of the C III λ1175 Å and Si IV λ1122 Å lines of Hen 2–131 shown in Figure 3. The C III λ1175 Å line is a triplet, which can act much like a resonance line in dense winds, scattering radiation in any region wherever C^{++} is present. On the other hand, the Si IV λ1122 Å is a line from a radiatively excited state. As the lower level of an excited state line is the upper level of a resonance line transition, its population depends strongly on the local radiation field and decreases rapidly with distance from the star (Olson 1981). Therefore, the distinct physical processes that dominate these lines determine not only there shapes, but also their terminal velocities.

A statistical comparison of v_∞ with the stellar properties (spectral type, effective temperature $T_{\rm eff}$ and gravity g) is in progress. As it could be expected, stars of high gravity ($\log g > 5$) show the largest v_∞ ($\sim$4000 km s^{-1}). Two of these stars (NGC 246 and Lo 4) are of the PG 1159 type. In contrast, stars of low gravity and effective temperature show low edge velocities. Among these CSPNe, we should mention the low edge velocities of several lines of Cn 3–1, Hen 2–131, and NGC 2392, in the range 200–400 km s^{-1}, whose measurement has been possible because the high spectral resolution of the *FUSE* data.

3 Summary and Future Work

Using *FUSE* data, we have found evidence of fast stellar winds in 40 CSPNe. For a dozen of them, this is the first time that fast stellar winds have been reported. We have determined the edge velocities of these lines, finding notable cases for which different edge velocities are associated to different lines. A more detail modeling using a SEI code and incorporating into the models the absorptions produced by circumstellar and/or interstellar

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H I, H_2, and atomic lines is on-going to determine more accurately v_∞.

A statistical comparison of v_∞ with stellar properties is also underway. The edge velocity is clearly correlated with the surface gravity and effective temperature, with the most evolved CSPNe having the fastest stellar winds. Young post-AGB stars as well as excessively evolved CSPNe do not show evidence of stellar winds.

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