THE ULTRAVIOLET SPECTRA OF THE WEAK EMISSION LINE CENTRAL STARS OF PLANETARY NEBULAE

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ABSTRACT

The UV spectra of all “weak emission line central stars of planetary nebulae” (WELSs) with available IUE data are presented and discussed. We performed line identifications and equivalent-width and flux measurements for several features in the spectra. We found that the WELSs can be divided into three different groups regarding their UV spectra: (1) strong P Cygni profiles (mainly in C iv λ1549), (2) weak P Cygni features, and (3) absence of P Cygni profiles. The last group encompasses stars with a featureless UV spectrum or with intense emission lines and a weak continuum, which are most likely of nebular origin. We have measured wind terminal velocities for all objects presenting P Cygni profiles in N v λ1238 and/or C iv λ1549. The results obtained were compared to the UV data of the two prototype stars of the [WC]—PG 1159 class, namely, A30 and A78. For WELSs presenting P Cygni features, most of the terminal velocities fall in the range of ~1000–1500 km s⁻¹, while [WC]—PG 1159 stars possess much higher values, of ~3000 km s⁻¹. The [WC]—PG 1159 stars are characterized by intense, simultaneous P Cygni emissions in the ~1150–2000 Å interval of N v λ1238, O v λ1371, and C iv λ1549. In contrast, we found that O v λ1371 is very weak or absent in the WELS spectra. On the basis of the UV spectra alone, our findings indicate that [WC]—PG 1159 stars are distinct from the WELSs, contrary to previous claims in the literature.

Key words: planetary nebulae: general — stars: atmospheres — stars: fundamental parameters — ultraviolet: stars

1. INTRODUCTION

Central stars of planetary nebulae (CSPNs) that are hydrogen-deficient are generally divided into three main groups: [WR], PG 1159, and [WC]—PG 1159 stars. The first group presents spectra with strong and broad emission lines mainly from He, C, and O, similar to the Wolf-Rayet stars (WR) of Population I. Depending on the ionization stages of the elements dominating the atmosphere, [WR] stars are subdivided into [WCL], [WCE], and [WO] (Crowther et al. 1998; Acker & Neiner 2003). On the other hand, PG 1159 stars are quite distinct objects. They are pre–white dwarfs and show mainly absorption lines of He s and C iv in their spectra (Werner et al. 1997). Only a handful of PG 1159 stars are known to possess wind features (Koesterke et al. 1998; Koesterke & Werner 1998). The [WC]—PG 1159 group presents strong P Cygni lines in the UV (e.g., N v λ1238 and C iv λ1549) and resembles the PG 1159 stars in the optical. Three objects are considered prototypes of this class: A30, A78, and Longmore 4 (at outburst).

The origin and evolution of hydrogen-deficient CSPNs have been investigated from different points of view during the last decade. Evolutionary models are now able to provide a reasonable match to the observed chemical abundances, although the roles of binarity and different thermal pulse models are still debated (De Marco & Soker 2002; Herwig 2001). Nebular analyses, as well as sophisticated non-LTE atmosphere models, have also been very useful in addressing several questions regarding these central stars. It is generally inferred that the groups mentioned above form the following evolutionary sequence: late-type [WR] → early-type [WR] → [WC]—PG 1159 → PG 1159 → non-DA white dwarfs (see, e.g., Zijlstra et al. 1994; Penã et al. 2001; Koesterke 2001). However, this scenario has important unsolved issues, such as the C/He mass ratio and the exact position of [WC]—PG 1159 stars in the H-R diagram (Hamann 1997; Marcolino et al. 2007). Moreover, the evolutionary status of the so-called weak emission line stars and their relation to the [WC]—PG 1159 stars is not at all clear. Let us discuss it now.

In an extensive observational study, Tylenda et al. (1993) analyzed spectroscopic data of 77 hydrogen-deficient CSPNs. In their sample, 39 were classified as [WR] stars. The remaining objects were called “weak emission line stars” (WELSs, or, alternatively, [WC] stars). According to these authors, the WELSs show emission of C iv λ5805 (actually C iv λ5801, 5812) that is systematically weaker and narrower than in [WR] stars and a feature in λ4650 which is possibly a blend of N iii, C iii, and C iv emissions. Moreover, C iii λ5696 is very weak or absent. These optical characteristics were confirmed by Marcolino & de Araújo (2003) with a homogeneous and higher resolution set of data. Interestingly, by comparing a large sample of WELS, [WC]—PG 1159, and PG1159 spectra, Parthasarathy et al. (1998) claimed that the WELSs and the [WC]—PG 1159 stars actually constitute the same class. However, this claim was based solely on comparisons of optical spectra and was not confirmed by further studies. Indeed, some authors argued that this assertion should be taken with caution until an analysis of a larger sample of objects is performed (e.g., Werner & Herwig 2006).

Undoubtedly, the WELSs constitute the least understood class of hydrogen-deficient CSPNs. An important point is that the WELSs might not be descendants of the [WR] stars, as was made explicit in the [WR] → [WC]—PG 1159 (WELS) → PG 1159 evolution. Penã et al. (2003), for example, derived lower average nebular expansion velocities for WELSs than for [WR] stars, while the contrary would be expected from the long-term action of a stellar wind on a planetary nebula during a [WR] → WELS transition. Furthermore, based on a kinematical study of a large sample of planetary nebulae, Gesicki et al. (2006) raised the interesting possibility that some WELSs can be progenitors of the hottest [WR] stars, i.e., the [WO] group (WELS → [WO]). A

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major issue hinders the determination of the evolutionary status of the WELSs: their physical parameters (e.g., $T_{\text{eff}}$, $V_{\infty}$, and $M$) and chemical abundances remain unknown. The properties of A30, A78, and Longmore 4 ([WC] PG 1159 stars) are known (Koesterke et al. 2001), but again, their identity as WELSs is questionable.

So far, most previous studies involving WELSs have been done in the optical part of the spectrum. In fact, the very definition of a WELS is based on the optical features in $\lambda$4650, C iv $\lambda$5805, and C iii $\lambda$5896 (Tylenda et al. 1993). A few studies in the UV including some WELSs can be found in the literature. However, they often include stars of different spectral classes (e.g., Feibelman 2000) and/or are focused on the determination of nebular properties (e.g., Adams & Seaton 1982; Pottasch et al. 2005), without special attention to the WELSs and their evolutionary state. Motivated by this fact and considering the open questions described above, we investigate in this paper the UV spectra of all WELSs with available IUE (International Ultraviolet Explorer) data. Our main aims are to understand their main UV characteristics, identify and measure the most intense spectral lines, measure wind terminal velocities from the available P Cygni profiles, and finally, compare the results to the data of the two prototype [WC]–PG 1159 stars: A30 and A78.

The present paper is organized as follows: In § 2 we present the observational data retrieved from the Multimission Archive at STScI (MAST); a in § 3 we discuss the main characteristics of the UV spectra of the WELSs and present line identifications of the most conspicuous features, as well as equivalent-width and line-flux measurements. In § 4 we empirically measure the terminal velocities for all objects presenting P Cygni profiles in N v $\lambda$1238 and/or C iv $\lambda$1549, from low- and high-resolution data. Finally, in § 5 we discuss and compare the results obtained for the WELSs to the data of A30 and A78 (the two prototype [WC]–PG 1159 stars) and present the main conclusions of our work.

2. OBSERVATIONAL DATA

We used public data from the IUE, which are available at MAST. The total number of WELSs currently known is about 50. Most of them are listed in the work of Tylenda et al. (1993) and Parthasarathy et al. (1998), and 15 were recently discovered in the direction of the Galactic bulge by Görny et al. (2004). Two objects considered to be WELSs in Parthasarathy et al. (1998) (Hen 2-86 and M 2-31) were found to actually be early-type [WR] stars by Marcolino & de Araújo (2003) on the basis of the equivalent width of the C iv $\lambda$5805 line.

We have searched for IUE data for all WELSs known and found spectra for only ~40% of the total WELS population. The list of SWP, LWP, and LWR archives considered in our study, including the ones for A30 and A78 (the two [WC]–PG 1159 stars), is shown in Table 1. The majority of the available spectra are of low resolution (~6 Å). The high-resolution spectra (~0.2 Å) that were used are also shown in the table. Most of the observations were done using the IUE large-aperture mode (10′′ × 20′′).

### 3. THE UV SPECTRA OF WELSs

The weak emission line class of central stars is defined based on the optical spectrum. Tylenda et al. (1993) showed that the WELSs are characterized mainly by a feature in $\lambda$4650 (possibly a sum of N iii, C iii, and C iv) and the C iii $\lambda$5696 and C iv $\lambda$5805 transitions. Because their C iv $\lambda$5805 line is usually weak, a [WCL] spectral classification seems reasonable for these stars at first glance. However, the C iii $\lambda$5696 line is generally strong in the [WCL] class, and it is weak or absent in the WELSs. Conversely, because the C iii $\lambda$5696 line is weak or absent, a [WCE] classification seems plausible. However, the C iv $\lambda$5805 line in [WCE] stars is much stronger than in the WELSs. Besides these characteristics, the WELSs are also known to present some absorption in the optical from lines such as He ii $\lambda$4541 and C ii $\lambda$5412 (Parthasarathy et al. 1998; Marcolino & de Araújo 2003), indicating a stellar wind not as dense as in the case of the [WR] stars, where the photospheric part is completely hidden.

Although we can say that the main characteristics of the WELSs are known in the optical, their UV spectra were never discussed before. As we have mentioned, although some works in the UV involved some WELSs, no attention was given to their evolutionary status or relation to the [WC]–PG 1159 stars. The present paper...
directly addresses this issue. Instead of presenting a homogeneous set of features, we found that the WELSs can be divided into three main groups regarding their UV spectra:

1. Presence of a strong P Cygni feature in $C_{\text{iv}} \lambda 1549$.
2. Weak P Cygni feature in $C_{\text{iv}} \lambda 1549$.
3. Absence of P Cygni features.

In Figure 1 we show stars that are representatives of the first group. The total number of objects is 11: NGC 6629, NGC 6891, Hen 2-12, Pb 8, Hen 2-108, NGC 6543, NGC 6567, NGC 6572, Vy 2-1, Hb 7, and IC 4776. As can be seen, the $C_{\text{iv}} \lambda 1549$ transition is often accompanied by $N_{\text{v}} \lambda 1238$, also in a P Cygni feature. Some other lines present are $He_{\text{ii}} \lambda 1640$ (e.g., Pb 8), $Si_{\text{iv}} \lambda 1394, 1403$ (e.g., Hen 2-108), and $C_{\text{iii}} \lambda 1909$ (e.g., NGC 6891). A feature near $\sim 1720 \text{Å}$ is also exhibited by several objects, and it might be due to $N_{\text{iv}}$ or $Si_{\text{iv}}$. Line identifications, measurements of equivalent widths, and fluxes for all objects are presented in the next section.

Only two stars were assigned to the second group, namely, Cn 3-1 and Hen 2-131. Their spectra are shown in Figure 2 (first and second panels). The $C_{\text{iv}} \lambda 1549$ line is clearly weaker than in
As described in § 4, these two stars also present significantly lower terminal velocities. Despite weakness, the Si $\text{iv} \lambda\lambda 1394, 1403$ transitions can also be identified. The remaining objects are J900, IC 4997, NGC 5873, NGC 6818, NGC 6803, and M 1-71. They constitute the third group, and some of them are also shown in Figure 2 (third, fourth, and fifth panels). The presence of strong emission and a weak and flat continuum can be readily noted. No P Cygni emissions are seen. These characteristics suggest that only nebular features were detected by the $\text{IUE}$ observations. Archives other than those listed in Table 1 were examined, but they all presented similar spectra. An exception is the case of IC 4997. By analyzing another $\text{IUE}$ archival spectrum (SWP 08578) besides the one shown in Figure 2 (SWP 31683), we could see a slightly higher continuum and a N $\text{v} \lambda 1238$ line possibly in a P Cygni feature. We chose to keep this star in group 3, since the C $\text{iv} \lambda 1549$ line is not in a P Cygni feature in any other spectrum, including those in high-resolution mode (e.g., SWP 41947). We have also included the star M 1-71 in group 3, although it shows

Fig. 2.—WELSs presenting weak P Cygni profiles in C $\text{iv} \lambda 1549$ (group 2; first and second panels) and an absence of P Cygni features and very weak continuum (group 3; third, fourth, and fifth panels). These are low-resolution $\text{IUE}$ spectra (~6 Å).
only a featureless UV spectrum. For this object, however, there is only one IUE file available, and it is possible that the central star was not within the IUE aperture during the observation.

One object does not fit in our division scheme, namely, IC 5217. The C iv λ1549 line in this star is intense, but it is not in a P Cygni feature. On the other hand, a P Cygni feature is found for N v λ1238, and also for O v λ1371, although they are somewhat weak. Furthermore, this star does not present a flat continuum. We conclude that the wind spectrum is clearly visible in this star, but it is highly contaminated by nebular emission.

We should emphasize that the three groups above were introduced by analyzing the ~1150–2000 Å interval, and that although

Fig. 3.—Low-resolution IUE spectra of the two prototype [WC]–PG 1159 stars: A30 (top) and A78 (bottom).

Fig. 4.—Low-resolution IUE spectra of WELs resembling [WC]–PG 1159 stars: NGC 6543, NGC 6567, and NGC 6572.
| Star           | λ_{obs} | Transition       | W_γ | (10^{-13} ergs s^{-1} cm^{-2}) |
|---------------|---------|------------------|-----|--------------------------------|
| Vy 2-1        | 1246.3* | N v λ1238        | -13 ± 3 | 0.62 ± 0.08                  |
|               | 1552.9* | C iv λ1549       | -6.4 ± 1.6 | 0.56 ± 0.08                  |
|               | 1721.0  | N iv λ1719?, Si iv λ1722? | -4.7 ± 1.1 | 0.42 ± 0.07                  |
|               | 1906.7  | C m λ1909        | -6.8 ± 1.2 | 0.5 ± 0.07                   |
| NGC 6543      | 1243.6* | N v λ1238        | -6.0 ± 0.8 | 540 ± 40                     |
|               | 1376.4* | O v λ1371        | -3 ± 1 | 300 ± 100                     |
|               | 1551.6* | C iv λ1549       | -8 ± 1 | 510 ± 50                     |
|               | 1639.8  | He n λ1640       | -3.7 ± 0.4 | 200 ± 20                     |
|               | 1720.0  | N iv λ1719?, Si iv λ1722? | -2.5 ± 0.3 | 110 ± 10                     |
|               | 1909.7  | C m λ1909        | -4.9 ± 0.8 | 170 ± 20                     |
| NGC 6567      | 1246.5* | N v λ1238        | -6 ± 1 | 7 ± 1                         |
|               | 1336.1  | C ii λ1334, 1336 | -4.3 ± 0.9 | 5.8 ± 0.9                    |
|               | 1377.2* | O v λ1371        | -3.6 ± 0.3 | 4.5 ± 0.3                    |
|               | 1553.4* | C iv λ1549       | -11 ± 1 | 13 ± 1                        |
|               | 1661.7  | O m λ1666–1669   | -1.2 ± 0.5 | 1.2 ± 0.4                    |
|               | 1908.7  | C m λ1909        |  | Saturated                     |
|               | 2326.7  | C ii λ1235       | -27 ± 4 | 6.3 ± 0.4                    |
|               | 2798.4  | Mg ii λ2796–2798 | -15 ± 1 | 6.6 ± 0.4                    |
| NGC 6572      | 1244.6* | N v λ1238        | -7.1 ± 0.9 | 47 ± 4                       |
|               | 1375.4* | O v λ1371        | -1.8 ± 0.4 | 16 ± 3                       |
|               | 1551.5* | C iv λ1549       | -6.4 ± 0.7 | 51 ± 4                       |
|               | 1641.3  | He n λ1640       | -4.5 ± 0.6 | 33 ± 3                       |
|               | 1664.6  | O m λ1666–1669   | -4.2 ± 0.4 | 29 ± 2                       |
|               | 1721.5  | N iv λ1719?, Si iv λ1722? | -1.7 ± 0.4 | 10 ± 2                       |
|               | 1750.7  | N m λ1751        | -4.7 ± 0.4 | 29 ± 2                       |
|               | 1815.3  | Ne m λ1815       | -0.8 ± 0.1 | 4.4 ± 0.5                    |
|               | 1907.9  | C m λ1909        |  | Saturated                     |
|               | 2169.0  | C m λ2163?       | -12 ± 8 | 21 ± 7                       |
|               | 2293.6  | C m λ2291–2297   | -3 ± 1 | 7 ± 2                         |
|               | 2306.8  | C iv λ2305       | -46 ± 5 | 117 ± 10                     |
|               | 2470.3  | O n λ2470        | -18 ± 1 | 59 ± 2                       |
| NGC 6891      | 1245.3* | N v λ1238        | -5.8 ± 0.7 | 45 ± 3                       |
|               | 1434.0  | C i λ1432?       | -1.4 ± 0.7 | 13 ± 5                       |
|               | 1522.9* | C iv λ1549       | -5.1 ± 0.8 | 47 ± 5                       |
|               | 1723.0  | N iv λ1719?, Si iv λ1722? | -1.3 ± 0.2 | 9 ± 1                        |
|               | 1908.0  | C m λ1909        | -6.8 ± 0.5 | 44 ± 2                       |
| NGC 6629      | 1247.8* | N v λ1238        | -5.5 ± 2.4 | 2.3 ± 0.8                    |
|               | 1554.0* | C iv λ1549       | -4.4 ± 0.3 | 4.6 ± 0.2                    |
|               | 1724.3* | N iv λ1719?, Si iv λ1722? | -0.9 ± 0.2 | 0.8 ± 0.2                    |
|               | 1908.5  | C m λ1909        | -4.3 ± 0.6 | 2.5 ± 0.3                    |
| Hen 2-12      | 1246.4* | N v λ1238        | -5.2 ± 0.8 | 17 ± 2                       |
|               | 1554.2* | C iv λ1549       | -5.5 ± 0.4 | 20 ± 1                       |
|               | 1723.4* | N iv λ1719?, Si iv λ1722? | -0.7 ± 0.2 | 2.1 ± 0.7                    |
| Pb 8          | 1245.9* | N v λ1238        | -3.6 ± 0.5 | 2.6 ± 0.3                    |
|               | 1382.2* | O v λ1371?       | -2.2 ± 0.4 | 1.8 ± 0.3                    |
|               | 1397.1* | Si iv λ1394?     | -1.2 ± 0.1 | 1.0 ± 0.1                    |
|               | 1413.1* | Si iv λ1403?     | -1.3 ± 0.3 | 1.1 ± 0.2                    |
|               | 1554.5* | C iv λ1549       | -7.5 ± 0.5 | 7.1 ± 0.3                    |
|               | 1643.4* | He n λ1640       | -2.1 ± 0.2 | 1.9 ± 0.1                    |
|               | 1724.1* | N iv λ1719?, Si iv λ1722? | -2.7 ± 0.5 | 2.2 ± 0.4                    |
| Hen 2-108     | 1245.1* | N v λ1238        | Very weak or absent | Very weak or absent |
|               | 1394.9* | Si iv λ1394      | -1.5 ± 0.5 | 1.8 ± 0.5                    |
|               | 1403.8* | Si iv λ1403      | -1.7 ± 0.4 | 2.2 ± 0.4                    |
|               | 1551.9* | C iv λ1549       | -2.9 ± 0.4 | 4.6 ± 0.5                    |
| IC 4776       | 1245.3* | N v λ1238        | -4 ± 2 | 11 ± 5                       |
|               | 1554.9* | C iv λ1549       | -2.8 ± 0.5 | 7 ± 1                        |
|               | 1751.6  | N m λ1751        | -2.5 ± 0.6 | 5 ± 1                        |
|               | 1909.3  | C m λ1909        | -13 ± 1 | 23 ± 1                       |
|               | 2468.2  | O n λ2470        | -14 ± 1 | 15 ± 1                       |
| Hb 7          | 1245.2* | N v λ1238        |  | Saturated                     |
|               | 1554.3* | C iv λ1549       | -2.7 ± 0.4 | 10 ± 1                       |
|               | 1907.9  | C m λ1909        |  | Saturated                     |

**Notes:** An asterisk denotes P Cygni emission components. Lyα is present in several spectra and has a geocoronal origin.
we have shown low-resolution spectra in Figures 1 and 2, the characteristics of these groups are confirmed from the available high-dispersion data. We chose the \( \sim 1150-2000 \) Å region for two reasons. First, it is in this wavelength range that we have found practically all the P Cygni lines. Obviously, such profiles are formed in the stellar wind of the central star, which is our main interest, and not in the nebula. Second, the \( \sim 2000-3000 \) Å interval sometimes has no or very few features (see next section), whose nature (nebular or stellar) we cannot determine from low-resolution data. The exception is the third group, where we have found various transitions, but as we previously argued, they are most likely nebular.

In addition to Figures 1 and 2, we show in Figure 3 the IUE spectra of the two prototype [WC]–PG 1159 stars, A30 and A78, also at the same resolution. It is clear that these two objects have a spectrum that is remarkably different from the WELS spectra. The three P Cygni lines \( \text{N} \\lambda 1238 \), \( \text{O} \\lambda 1371 \), and \( \text{C} \ IV \ \lambda 1549 \) are simultaneously present and more intense than in the WELSs. Furthermore, the absorption parts of these P Cygni profiles (mainly in \( \text{C} \ IV \ \lambda 1549 \)) are considerably broader, suggesting large terminal wind velocities (see \S 4). Although the \( E(B-V) \) values for these stars have a role in determining the slope of the continuum, it is also evident that the flux is higher in the blue (\( \sim 1150 \) Å) than in the red part of the IUE spectrum (\( \sim 2000 \) Å). This is not seen in most of the WELSs, and it might indicate that [WC]–PG 1159 stars have higher effective temperatures.

We have assigned the stars NGC 6567, NGC 6572, and NGC 6543 to the group presenting intense \( \text{C} \ IV \ \lambda 1549 \) in a P Cygni feature. However, in addition to the \( \text{C} \ IV \ \lambda 1549 \) line exhibited by the stars in group 1, these three objects also simultaneously show \( \text{N} \ \lambda 1238 \) and \( \text{O} \ \lambda 1371 \) P Cygni emissions. This characteristic resembles the [WC]–PG 1159 class and is shown in Figure 4. Thus, although a comparison between spectra shown in Figures 1–3 argues against those WELSs being [WC]–PG 1159 stars, we cannot be sure regarding the objects shown in Figure 4. In fact, the central star of NGC 6567, for example, was already considered as a [WC]–PG 1159 object by Hamann (1996). This point is addressed later in the paper.

### 3.1. Line Identifications and Measurements

In Tables 2–5 we present line identifications, measurements of equivalent widths, and line fluxes of all IUE low-resolution spectra considered in this work. For completeness, we have included IC 5217 in Table 4, although this object does not belong to the group of WELSs without P Cygni emissions (group 3). The equivalent widths were measured by the conventional method of adjusting a Gaussian function to the line profile. When this was not possible, we have computed the line area above the adopted continuum. In the case of a P Cygni profile, only its emission feature was considered in the measurement. We emphasize that our intention is not to construct a UV atlas for the WELSs. Therefore, we have only listed and measured the most conspicuous lines in their spectra. It should also be kept in mind that throughout this paper we make reference to lines such as \( \text{C} \ IV \ \lambda 1549 \) and \( \text{N} \ \lambda 1238 \), but the exact atomic transitions might be slightly different. In these two cases, for example, the carbon and nitrogen lines are actually doublets: \( \text{C} \ IV \ \lambda 1548, 1551 \) and \( \text{N} \ \lambda 1238, 1242 \).

Previous studies have investigated the UV spectra of some stars seen in Tables 2–5. In general, we have found a good agreement between our results and those that also present line measurements. For \( \text{V} \ \lambda 2-1 \), NGC 6629, M 1-71, and Hen 2-108, we found no reference in the literature regarding their IUE spectra from the MAST database. Although we can find references for the stars Cn 3-1, NGC 6891, J900, Hen 2-12, NGC 5873, and NGC 6803, they generally involve a large sample of objects and are not focused on line identifications, measurements, or the WELS evolutionary state. Details concerning some individual objects are discussed below.

#### NGC 6567:

Although there are four references regarding this object in the MAST database, only that of Hyung et al. (1993) has focused in some detail on the main features of its UV spectrum. For \( \text{C} \ IV \ \lambda 1549 \), these authors found a line flux (in units of \( 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1} \)) of 12.8, while we have measured 13 \( \pm 1 \). Taking into consideration the uncertainty in the line measurements of their work (\( \sim 15\% \)), our results present a very reasonable agreement for this line and others, such as \( \text{N} \ \lambda 1238 \), \( \text{O} \ \lambda 1371 \), \( \text{C} \ \Pi \ \lambda 2325 \), and Mg \( \Pi \ \lambda 2798 \).

#### NGC 6572:

There are several references to the UV spectrum of this object. The most important to our discussion is that of Hyung et al. (1994), which presents a detailed high-resolution spectral study from the UV to the optical, with several line identifications and measurements. Their main aim was, however, to explore diagnostic lines in the rich spectrum of NGC 6572 in order to determine plasma parameters, not to discuss its evolutionary status.

#### NGC 6543:

The IUE spectrum of this star was studied before by Bianchi et al. (1986) and Perinotto et al. (1989). Both works heavily focused only on the determination of stellar and wind parameters (e.g., \( T_{\text{eff}} \) and \( M \)). No comparison to other objects as in the context of the present paper was made.

#### Pb 8:

This planetary nebula was studied together with seven other objects by Feibelman (2000). Line fluxes provided in his work are in good agreement with our measurements. For \( \text{N} \ \lambda 1238 \), for example, we encountered \( \sim 2.6 \) (units of \( 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1} \)), while Feibelman derived 2.4. Although the emission in \( \sim 1724 \) Å was identified in his work as \( \text{N} \ \lambda 1719 \), it is possible that it actually arises from \( \text{Si} \ IV \ \lambda 1722 \). In fact, we have also identified two lines in 1394 and 1403 Å which are likely to stem from \( \text{Si} \ IV \).

#### Hen 2-131:

This object’s IUE spectra were briefly discussed by Adams & Seaton (1982). However, attention was given to the determination of the C/O ratio in the nebula, not to the central star.

#### IC 4776:

This object was studied by Herald & Bianchi (2004) by means of expanding atmosphere models, and its physical parameters and chemical abundances were obtained. As far as we are concerned, their work constitutes the first to analyze the stellar wind of a WELS with a state-of-the-art non-LTE code (CMFGEN; Hillier & Miller 1998). The same main observed wind emissions were identified in their paper and ours. The \( \text{O} \ \lambda 1371 \) line is predicted by their model, but it is very weak or absent in the IUE spectrum. Herald & Bianchi (2004) have also analyzed the star A78, and a [WC]–PG 1159 classification was
Notes.—An asterisk denotes P Cygni emission components. Lyα is present in several spectra and has a geocoronal origin.
confirmed. Surprisingly, the physical parameters obtained for A78 and IC 4776 are quite different. A78 is almost twice as hot ($T_{\text{eff}} \sim 113$ kK) and presents a larger terminal velocity (3200 km s$^{-1}$) than IC 4776. These findings support the idea that these two stars do not belong to the same spectroscopic class, i.e., that WELSs are not [WC]–PG 1159 stars (see § 5).

NGC 6818: The spectrum of this object (nebular plus central star) was extensively studied by Hyung et al. (1999). We refer the reader to their work for a more detailed analysis than that presented here. The chemical composition of the planetary nebula was further explored by the work of Pottasch et al. (2005).

IC 5217: A very similar analysis to that of NGC 6818 (Hyung et al. 1999) was done in the case of IC 5217 by Hyung et al. (2001). Again, we refer the reader to their work for detailed line identifications and measurements. We highlight that in both references the identity of these two stars as WELSs is not discussed, and emphasis is given mainly to the determination of plasma parameters such as the electronic temperature, density, ionic concentration, and chemical abundance.

4. TERMINAL VELOCITIES

In this section we derive terminal velocities ($v_{\infty}$) for all WELSs presenting P Cygni profiles in N $\lambda$ 1238 and/or C IV $\lambda$ 1549. The $v_{\infty}$, together with the mass-loss rate ($\dot{M}$), constitute the most important physical parameters describing the stellar winds of hot stars. Their empirical determination is often used to test the theory of radiatively driven stellar winds, to compare stars of different spectral classes, and as an input in stellar evolution models and interstellar medium studies (see, e.g., Prinja et al. 1990; Lamers & Cassinelli 1999). The determination of $\dot{M}$ for the WELSs presenting wind features is beyond the scope of the present paper, since it requires sophisticated non-LTE expanding atmosphere models for reliable estimates. Work is under way by our group to accomplish this goal.

Because only a few high-resolution spectra are available, most of the terminal velocities of the WELSs can only be obtained from low-dispersion IUE spectra. A priori, an accurate determination of $v_{\infty}$ from an $\sim$6 Å resolution spectrum is a complicated task, since we generally do not see an extended and saturated absorption in a P Cygni line. Nevertheless, in order to overcome this difficulty, Prinja (1994) provided a relation between $\Delta \lambda$ (defined below, obtained at low resolution) and $v_{\infty}$ (obtained at high resolution) by analyzing a large sample of different hot stars (O, B, WR, and CSPN). The resulting calibration of his work is represented by

$$v_{\infty} = a_1 + a_2(\Delta \lambda) + a_3(\Delta \lambda)^2.$$

In this equation, $\Delta \lambda = (\lambda_{\text{peak}} - \lambda_{\text{min}})$ is the wavelength difference between the peak and the absorption minima of a low-resolution P Cygni profile, and $a_1$, $a_2$, and $a_3$ have different values for C IV $\lambda$ 1549 and N $\lambda$ 1238 (see Prinja 1994). This calibration is perfectly suitable for our purpose and obeys the definition of the terminal velocity from the black absorption core ($v_{\infty, \text{black}}$) of a P Cygni line (Prinja et al. 1990).

In Table 6 we present the terminal velocities derived for the WELSs and for the [WC]–PG 1159 stars A30 and A78. We used the usual method for WELSs with high-resolution spectra (using the Doppler effect and $v_{\infty, \text{black}}$) and the equation described above for low-resolution spectra. We estimate the errors in the determination of $v_{\infty}$ to be $\sim$20%.

The most important thing to be noted in Table 6 is that A30 and A78 have much higher terminal velocities than the WELSs. While the majority of WELSs have values concentrated in the $\sim$1000–1500 km s$^{-1}$ interval, these two [WC]–PG 1159 stars have a terminal velocity of $\sim$3000 km s$^{-1}$ (from C IV). Such high differences cannot be explained by the uncertainties in the measurements. Although different works in the literature have estimated $v_{\infty}$ for A30 and A78, we have also measured this quantity in their low-resolution spectra to follow the same method applied for the other stars (Prinja’s calibration). Among the previous studies regarding A30, we highlight the work of Harrington & Feibelman (1984), who obtained a terminal velocity of $\sim$4000 km s$^{-1}$. At that time, however, the $v_{\infty}$ determination was based on the largest negative velocity seen in a P Cygni profile (when the line returns to the continuum). This procedure tends to obtain larger values.
than the black method (Prinja et al. 1990). The central star of A78 was recently analyzed by sophisticated non-LTE atmosphere models by Herald & Bianchi (2004). These authors found that a velocity of \(~3200\) km s\(^{-1}\) could satisfactorily represent \(v_\infty\), a value slightly higher than ours.

Other information can be obtained by analyzing Table 6. It is clear, for example, that Ch 3-1 and Hen 2-131 have lower terminal velocities than most of the WELSs. Indeed, as we have shown in § 3 (Fig. 2), their UV spectra are quite different.

In order to further illustrate the differences between the terminal velocities of the WELSs and the two prototype [WC]—PG 1159 stars, A30 and A78, as shown in Table 6, and to compare the results obtained for other hydrogen-deficient CSPNs, we present in Figure 5 the \(v_\infty\) distribution for several stars belonging to the spectroscopic classes [WCL], [WCE], [WC]—PG 1159, WELS, and PG 1159. Once again, it can be seen that the terminal velocities measured for the WELSs are mainly concentrated between \(~1000\) and \(1500\) km s\(^{-1}\). Moreover, their \(v_\infty\) tends to be higher and lower than in the [WCL] and [WCE] classes, respectively. It is also clear that the [WC]—PG 1159 class (represented by the two prototype stars, A30 and A78) and the few PG 1159 stars that show a stellar wind have the highest terminal velocities among the hydrogen-deficient CSPNs.

5. DISCUSSION AND CONCLUSIONS

From a comparison between several optical spectra of WELS, [WC]—PG 1159, and PG 1159 stars, Parthasarathy et al. (1998) have proposed that the WELSs are actually [WC]—PG 1159 stars. This claim was not confirmed by further studies, and as we mentioned, some authors have warned that this assertion should be taken with caution until a more comprehensive study is achieved (Werner & Herwig 2006). After an analysis of the main UV characteristics of the WELSs and the two prototype [WC]—PG 1159 stars, A30 and A78, our next step was to compare the results obtained for these two classes of objects in order to address this important issue.

As we have shown, most of the WELSs present a UV spectrum considerably different from the [WC]—PG 1159 stars. While this last class simultaneously presents P Cygni profiles in N \(\lambda 1238\), O \(\lambda 1371\), and C \(\lambda 1549\), the majority of WELSs present very weak or no O \(\lambda 1371\) (see Fig. 1). The same is true, at least for some objects, regarding the N \(\lambda 1238\) line. The only exceptions are the objects NGC 6543, NGC 6567, and NGC 6572. Their spectra in fact resemble those of the [WC]—PG 1159 stars (see Figs. 3 and 4): their O \(\lambda 1371\) line is clearly visible, as are the other transitions mentioned.

Besides the spectral differences found in the UV part of the spectrum, we have also found that the terminal velocities of the WELSs are considerably lower than in [WC]—PG 1159 stars. Our Table 6 shows that the bulk of the WELSs have \(v_\infty\) between \(~1000\) and \(1500\) km s\(^{-1}\), and A30 and A78 have values of about \(3000\) km s\(^{-1}\). This difference might represent different physical parameters underlying these two classes of stars. The theory of radiatively driven stellar winds, for example, predicts that the terminal velocity of a star is related to the escape velocity (\(v_\text{esc}\)), which in turn depends on other physical parameters (e.g., mass and radius; Abbott 1978; Lamers & Cassinelli 1999). Moreover, \(v_\infty\) is also known to correlate with the effective temperature (\(T_{\text{eff}}\)) in several classes of stars (see Fig. 8 of Prinja et al. 1990). The \(T_{\text{eff}}\) tends to be higher for stars with high terminal velocities.

From the considerations described above, we conclude that the [WC]—PG 1159 stars are distinct from the WELSs, in contrast with the claim made by Parthasarathy et al. (1998) on the basis of optical spectroscopy. It should be noted, however, that the situation for the central stars NGC 6543, NGC 6567, and NGC 6572 is ambiguous. On one hand, they have a spectrum compatible with the [WC]—PG 1159 class. On the other hand, they do not present high terminal velocities, as in the cases of A30 and A78. From both low- and high-resolution data we obtain \(v_\infty\) values less than \(2000\) km s\(^{-1}\) for these three stars (see Table 6).

If the WELSs are not [WC]—PG 1159 stars, what is their role in the evolutionary sequence [WR] — PG 1159? Do they form an alternative channel of evolution? In order to elucidate these and other similar questions, and to further clarify the differences between the WELSs and the [WC]—PG 1159 stars, we clearly need to determine their physical parameters and chemical abundances. Non-LTE expanding atmosphere models are being computed for this purpose by our group with the CMFGEN code of Hillier & Miller (1998). In this way, their position in the H-R diagram could be determined, a more efficient comparison to [WR], [WC]—PG 1159, and PG 1159 stars could be made, and their evolutionary status could be better determined.

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