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THE LOW EXCITATION PLANETARY NEBULAE HUDO 1 AND HUBI 1 AND THEIR [WC10] CENTRAL STARS[1]

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RESUMEN

Se analizan datos espectroscópicos de alta y baja resolución de las nebulosas planetarias con estrella central [WC] tardía, HuDo 1 y HuBi 1. Ambos objetos pertenecen al disco galáctico y tienen velocidades radiales heliocéntricas de -12 km s^{-1} (HuDo 1) y 57 km s^{-1} (HuBi 1). El enrojecimiento logarítmico, c(Hβ), es de 2.04 para HuDo 1 y 1.22 para HuBi 1. Se deriva la composición química del plasma, obteniéndose log(O/H)+12 = 8.43 y 8.57, y N/O = 0.2 y 0.1 para HuDo 1 y HuBi 1 respectivamente. HuBi 1 es la única NP excitada por una estrella [WC] muy tardía que muestra líneas intensas de He I. A partir de las líneas estelares, se deriva un tipo espectral [WC 10] para ambas estrellas, aunque la estrella de HuBi 1 debe ser ligeramente más caliente para proporcionar suficientes fotones ionizantes de He^0. Al comparar los parámetros estelares de estos objetos con los de objetos similares, se encuentra que las estrellas de HuDo 1 y HuBi 1 deben ser intrínsecamente más débiles. En particular HuBi 1 parece ser una nebulosa ionizada por una estrella de baja masa que evoluciona lentamente.

ABSTRACT

Low- and high-resolution spectra of the planetary nebulae HuDo 1 and HuBi 1, around [WC-late] stars, are analyzed. The objects belong to the galactic disk, with heliocentric radial velocities of -12 km s^{-1} (HuDo 1) and 57 km s^{-1} (HuBi 1). C(Hβ) reddening values are of 2.04 for HuDo 1 and 1.22 for HuBi 1. Plasma line ratios are used to estimate physical conditions and abundances. We find log(O/H)+12 = 8.43 and 8.57, and N/O = 0.2 and 0.1 for HuDo 1 and HuBi 1 respectively. HuBi 1 is the only PN excited by a very late [WC] star showing intense nebular He I recombination lines. From the stellar lines we derive a [WC 10] type for both stars, although HuBi 1 central star should be slightly hotter to provide a large amount of He^0 ionizing photons. Nebular and stellar parameters of HuDo 1 and HuBi 1 are compared with those of other [WC 10] objects, and we conclude that the stars of HuDo 1 and HuBi 1 should be intrinsically fainter. In particular HuBi 1 seems a low-density evolved nebula around a low-mass slowly-evolving star.

Key Words: **PLANETARY NEBULAE: INDIVIDUAL (HUDO 1, HUBI 1) — STARS: POST-AGB — STARS: WOLF-RAYET**

1. INTRODUCTION

During a spectroscopic survey of protoplanetary candidates, Hu & Bibo (1990) and Hu & Dong (1992) discovered the cool [WC] nature of the central stars of the low excitation planetary nebulae PN G012.2+04.9 (IRAS17514-1555, PM1-188, HuBi 1) and PN G060.4+01.5 (IRAS19367+2458, PM1-310, HuDo 1). Hereinafter they will be called by their usual names: HuBi 1 and HuDo 1. Both central stars were classified by the authors as [WC 11] type stars, on the basis of a qualitative analysis of the stellar spectra which are dominated by C II and C III emission lines. These very late WR type stars of the carbon series are very infrequent. The compilation presented by Gorny (2001) lists only 7 planetary

[1]Based on data collected at the Observatorio Astronómico Nacional, San Pedro Mártir, Ensenada, B. C., México.

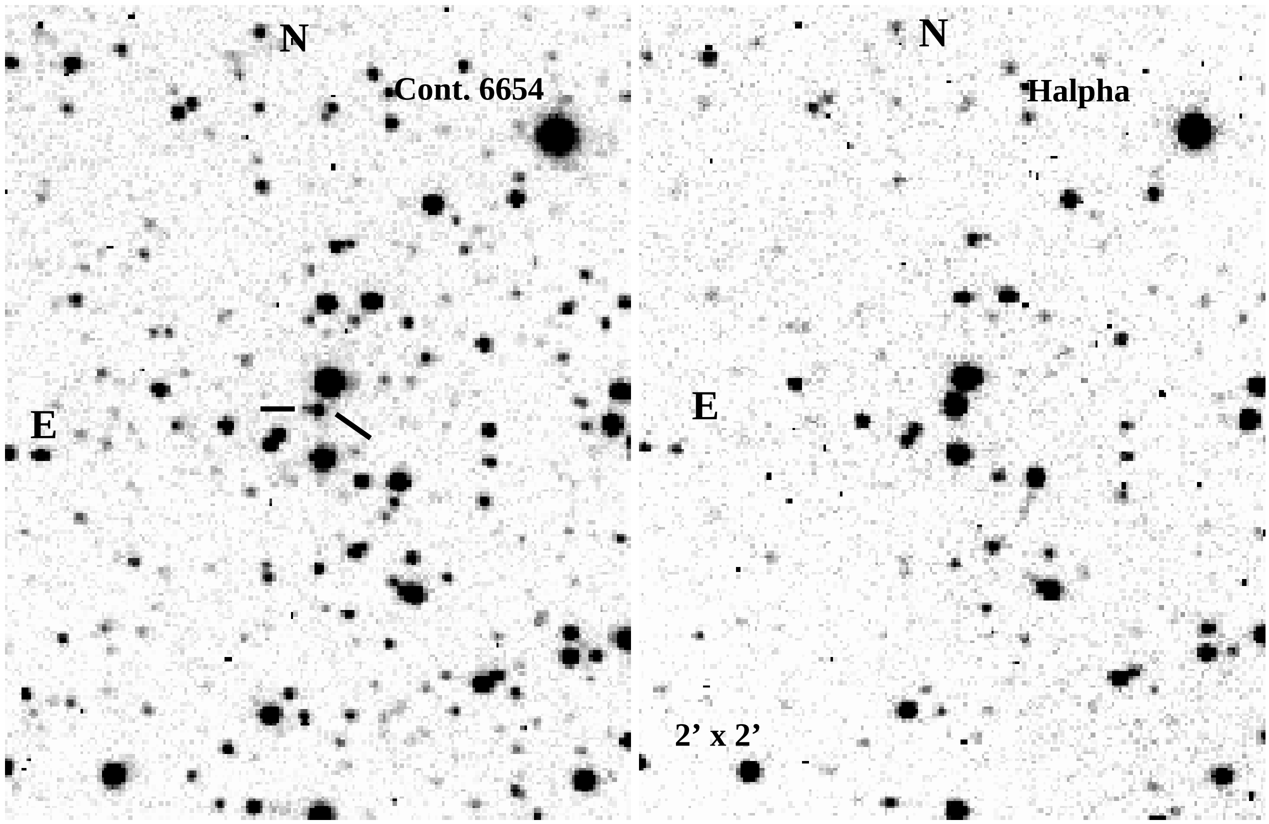

Fig. 1. Continuum (λ6654, 5 min exposure time) and Hα (10 min exposure time) images of a $2' \times 2'$ zone around HuDo 1. The PN is clearly detected as a compact Hα emitting object, with a diameter of about 1.7 arcsec.

nebulae (PNe) with such a central star. In addition to HuDo 1 and HuBi 1, the list includes M4-18, CPD-56^{0}8031, K2-16, He 2-113 and Vo 1. All these central stars were classified as [WC 11] until the new quantitative classification scheme for WC and WO stars was proposed by Crowther, De Marco, & Barlow (1998) who moved most of these objects to the [WC 10] type, K2-16 (PN G352.9+11.4) remaining the only example in their sample of a [WC 11] star. Regarding massive WRs, none so late WC massive star has been found so far.

Another quantitative classification scheme, in principle better adapted for [WC] central stars, was proposed more recently by Acker & Neiner (2003). In this work they also move all the objects previously classified as [WC 11] to the [WC 10] type, except for K2-16 and M4-18. These authors declare that their scheme is coherent with the one by Crowther et al. (1998). There are however some important differences in criteria for all the [WC] types. Unfortunately Acker & Neiner criteria show discontinuities and the primary criteria are not well defined.

In a recent paper Gorny et al. (2004) apparently have found several [WC 11] stars among their sample of PNe towards the galactic bulge. However due to their low signal-to-noise data for the central stars, Gorny et al.'s classification is based on the old qualitative scheme by Hu & Bibo (1990). In addition the authors do not exclude the possibility of these stars being WELS. The classification of these objects needs to be redone on the basis of good quality spectra and using the new quantitative classification criteria.

The [WC]-late objects constitute the first step of the evolutionary path proposed for the WR central stars (e.g., Gorny & Tylenda 2000), which would evolve from cool [WC]s ([WC 10-11]) to hot [WC]s (presently classified as [WO 1-4] by Crowther et al. 1998 and Acker & Neiner 2003) to PG 1159 white dwarfs. It is important therefore to understand the nature and evolutionary status of the [WC 10] stars.

Recent studies of the nebulae and stars for some late [WC] objects have been performed by De Marco, Barlow, & Storey (1997) and De Marco & Crowther (1999) (See Table 6). For HuBi 1, imaging and spec-

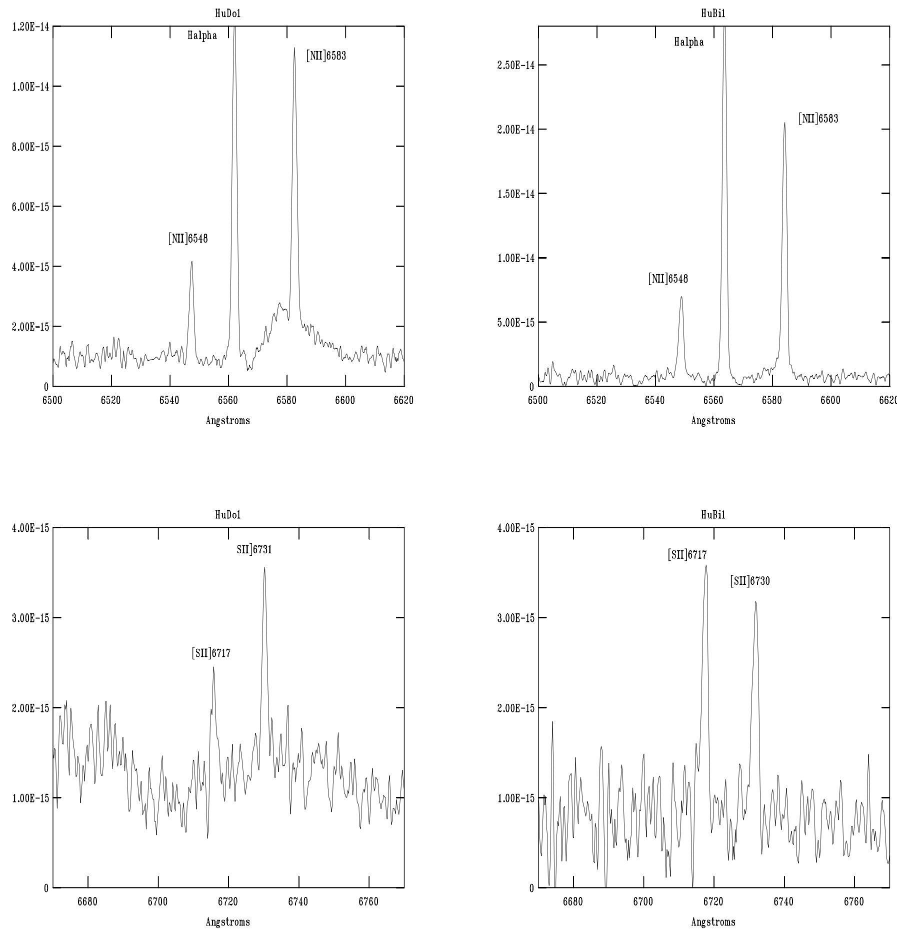

Fig. 2. Hα and [S II] high-resolution spectral zones for HuDo 1 and HuBi 1, obtained in April 2004. Fluxes are in units of erg cm^{-2} s^{-1}. For HuDo 1 the nebular lines are easily deblended from the wide stellar lines and can be measured with high accuracy. The central star of HuBi 1 is much fainter (relative to the nebula) and its lines are not noticeable in the high resolution spectra.

troscopic data were analyzed by Pollacco & Hill (1994) who reported a nebular diameter of about 18″. According to these authors the nebula consists of an external zone showing an electron density of about 50 cm^{-3} surrounding a higher-density central zone. They derived N, O, and S abundances reporting values typical of PNe, but found a possibly enhanced He abundance.

The central star of HuBi 1 was studied by Leuenhagen & Hamann (1998) who, from non-LTE expanding atmosphere models, derived $T_{\rm eff} \sim 35,000$ K, terminal wind velocity $v_\infty = 360$ km s^{-1}, a transformed radius of 7.07 $R_\odot$ and a chemical composition (in mass percentage) of β(H) = 1, β(He) = 42, β(C) = 50, and β(O) = 7. By assuming a stellar luminosity of log $L \sim 3.70$, a distance of 1.5 kpc, a mass loss rate of log $\dot{M} \sim -5.70$, and a stellar radius $R_* = 1.88\ R_\odot$ were derived for the central star by these authors. Crowther et al. (1998) and Acker & Neiner (2003) analyzed the stellar lines; they attribute a spectral type [WC 10] to this star.

In our spectroscopic program for systematically studying a large sample of PNe around [WC] central stars (Peña et al. 1998; Peña, Stasińska, & Medina 2001; Medina et al. in preparation), HuDo 1 and HuBi 1 were included among our targets. High resolution data were obtained for HuBi 1 in 1997 and preliminary results were published by Peña et al. (2001) who reported an electron density lower than 235 cm^{-3}. This density is unusually low for a nebula around such a late [WC] star (see discussion in Peña et al. 2001 and in § 6).

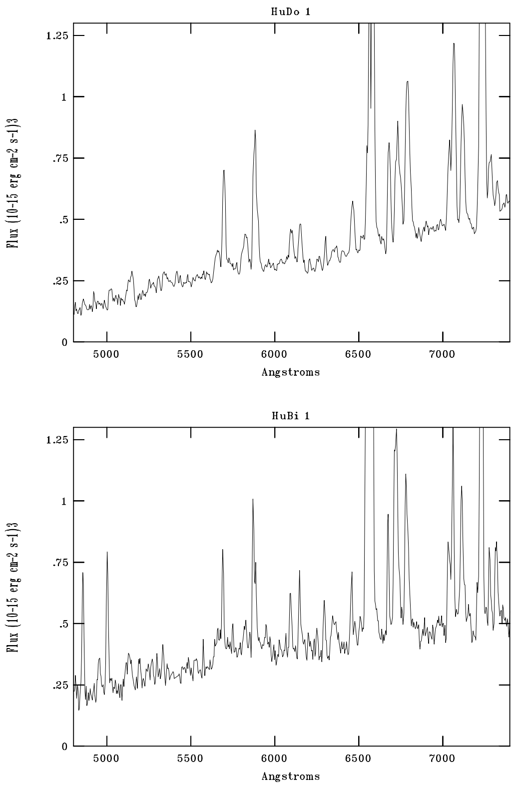

Fig. 3. Low-resolution spectra for HuDo 1 and HuBi 1, obtained in June 2002. Strong stellar lines are blended with the nebular emission, specially for HuDo 1 where the star is relatively much brighter and shows wider lines.

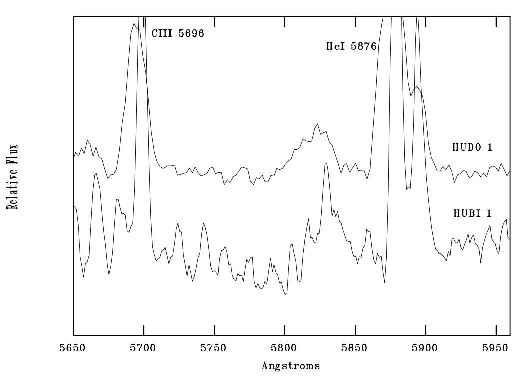

Fig. 4. Low-resolution stellar spectra showing the zone around C IV5801,5812. These lines are in the wing of C III 5826.

For HuDo 1 no quantitative studies have been made apart from the qualitative stellar classification by Hu & Dong (1992). We found that the ID map published by Hu & Dong (1992) is indicating an object which resulted to be a F8 main sequence star, and the ID chart in the Strasbourg-ESO Catalogue of Galactic PNe (Acker et al. 1992) indicates a different but also wrong object whose spectrum corresponds to a late-type star. Consequently we decided to search for the planetary nebula, using direct imaging in Hα and nearby continuum to detect the Hα emitting objects in the field presented by Hu & Dong. With this strategy —very useful to detect emission line objects— we finally found a low excitation PN whose central star, in addition, presented WC-late type emission lines. The right ID chart for HuDo 1 is presented in Figure 1.

Once the right position of HuDo 1 was determined, spectrophotometric data for both objects were acquired to analyze the nebulae and central star parameters. A description of the observations is presented in § 2. In § 3 and § 4 we discuss the nebular properties. The analysis of the stellar data is presented in § 5, and our conclusions are discussed in § 6.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. *Direct Imaging of HuDo 1*

Hα on-band off-band direct images for HuDo 1 were acquired with the 2.1 m telescope of the Observatorio Astronómico Nacional, S.P.M., B. C., México (OAN-SPM). The CCD Site3 detector was used with interference filters centered at Hα (λ6564) and continuum (λ6654) on May 27, 2001. Exposure times were 10 min for Hα and 5 min for λ6654. These images allow us to identify the planetary nebula as an object different from that indicated in the ID charts by Hu & Dong (1992) and Acker et al. (1992). Fig. 1 shows both images. The planetary nebula is the weak object marked. It is a very compact nebula with a diameter of about 1.7 arcsec.

2.2. *Spectrophotometric Data*

Long-slit spectrophotometric data were gathered during different observing runs with two different spectrographs (high and low resolution) attached to the 2.1 m telescope at OAN-SPM. The high resolution echelle REOSC spectrograph allows one to obtain spectra with a resolution of about 20,000 ($\Delta\lambda/\lambda$ better than 0.25) which is very useful to safely deblend the narrow nebular lines from the wide stellar ones, especially in the case of HuDo 1 (see Figure 2). The low-resolution Boller & Chivens spectrograph was used with a grid of 600 l/mm. The spectral resolution for such a set-up is 2–3 Å, depending on the CCD pixel size. For the 4$''$ slit used for our observations, the spectral resolution is about 5–6 Å.

The log of observations is presented in Table 1 where the observing date (ddmmyy), the spectrograph (echelle or Boller & Chivens) and the detector

TABLE 1

LOG OF OBSERVATIONS FOR HUDO 1 AND HUBI 1

Date	Spectr.	Detector[a]	$\Delta\lambda$	Slit Width[b]	HuDo 1[c]	HuBi 1[c]
040897	ech	CCD2k	3360–7360	4″	···	2×15m
250900	BCh	CCD2k	4400–6750	4″	···	2×10m
260900	BCh	CCD2k	4400–6750	4″	···	2×10m
240801	ech	CCD2k	3360–7360	4″	15m, 2×20m	···
260801	ech	CCD2k	3360–7360	4″	2×15m	···
040602	BCh	CCD-S3	3500–7400	4″	3×15m	4×10m
050602	BCh	CCD-S3	3500–7400	4″	10m,15m	2×10m
060602	BCh	CCD-S3	3500–7400	4″	3×15m	3×10m
230404	ech	CCD-S3	3860–6800	2″	···	3×15m
240404	ech	CCD-S3	3860–6800	2″	2×15m	···
250404	ech	CCD-S3	4480–7560	4″	4×15m	···
260404	ech	CCD-S3	4480–7560	2″	···	15m,10m
170804	BCh	CCD-S3	5600–7750	4″	3×10m	···

[a]CCD2k: 2048×2048 pix of 14μ, CCD-S3: 1024×1024 pix of 24 μ. The spectral resolution is about 0.2 Å with echelle and 5–6 Å with B&Ch.

[b]Slit was always oriented E-W.

[c]Number of exposures × exposure time.

TABLE 2

OBSERVED AND DEREDDENED NEBULAR LINE FLUXES, RELATIVE TO Hβ, FOR HUDO 1 AND HUBI 1

	HuDo 1	HuBi 1		
λ(Å) Ion	F/Hβ.F/Hβ	F/Hβ.F/Hβ		
	Observed.Deredd.	Observed.Deredd.		
4340 Hγ	···	···	0.32	0.45
5007 [O III]	< 0.5	<0.4	0.30	0.27
5755 [N II]	<0.6	<0.07	0.04:	0.02:
5876 He I	<0.25	<0.09	0.27	0.15
6548 [N II]	3.34	0.73	1.40	0.57
6563 Hα	13.52	2.86	7.12	2.82
6583 [N II]	10.73	2.26	4.19	1.66
6717 [S II]	1.88	0.38	0.58	0.22
6731 [S II]	2.39	0.48	0.55	0.21
7319 [O II]	0.89	0.12	0.29:	0.09:
7330 [O II]	0.68	0.09	0.32:	0.10:
F(Hβ)(E-15)[a]	1.60	179.5	15.6	259.1
EW(Hβ)	15	···	87	···
c(Hβ)	2.05	···	1.22	···

[a] Flux in erg cm^{-2} s^{-1}.

used are listed in Columns 1, 2, and 3. We present the observed spectral ranges in Column 4, in Column 5 the slit widths, and in Columns 6 and 7, the number of exposures and the exposure times for each object.

Data were reduced using IRAF [2] package. Spectra were bias- and flat-field corrected; afterwards they were extracted using an extraction window of 10 pixels, equivalent to 3.2 arcsec for the Site3 detector and 2 arcsec for the CCD2k. Due to the small extension of HuDo 1, the extraction window includes the whole object. This is not the case for HuBi 1, where only the central zone was extracted. A He-Ne-Ar lamp was employed for wavelength calibration and several standard stars from the list by Hamuy et al. (1992) for echelle spectra, and Oke (1990) for low resolution spectra, were used for flux calibration.

Portions of the high-resolution spectra are shown in Fig. 2. The zones around Hα and [S II] 6717,6731 are displayed showing the narrow nebular lines. The wide stellar lines are only noticeable for HuDo 1, which has a brighter star with stronger lines. The central star of HuBi 1 is almost undetectable in the echelle spectra. Notice how the high resolution allows to safely deblend the narrow nebular lines from the wide stellar lines for HuDo 1. This is very important to obtain reliable diagnostic line ratios for plasma analysis. Figure 3 presents calibrated low-resolution spectra for both objects, not corrected for reddening. In this case the stellar lines are highly blended with the nebular ones for both objects, but especially for HuDo 1 which presents much wider stellar lines. Since these objects belong to the galactic disk, they are heavily extinguished and reddened and there is hardly a detection in the blue zone ($\lambda \leq$ 4200 Å) of spectra.

3. RADIAL VELOCITIES AND NEBULAR EXPANSION

The high-resolution spectra allow us to determine the radial velocity of objects with good accuracy. From the observed nebular lines we have determined heliocentric radial velocities of -12 ± 8 km s^{-1} for HuDo 1 and 57 ± 8 km s^{-1} for HuBi 1. These low values are indicating that both objects are in the solar neighborhood.

The nebular lines present, in both cases, a single but well-resolved component. Therefore the FWHM can be used as an indicator of the nebular expansion. After subtracting the instrumental and thermal widths (by assuming they add in quadrature and that the electron temperature is 9400 K) the expansion velocity, $V_{\rm exp}$, for HuDo 1 is about 30 km s^{-1} (or lower if part of the FWHM is caused by turbulence). The lines of HuBi 1 are slightly wider showing a FWHM of 65 km s^{-1}, therefore $V_{\rm exp}$ is $\leq$ 33 km s^{-1}. Peña et al. (2001) reported a FWHM of 61 km s^{-1} for Hβ in very good agreement with the value derived here.

[2]IRAF is distributed by NOAO, which is operated by AURA, Inc. under contract with the National Science Fundation.

TABLE 3

IONIC AND ELEMENTAL ABUNDANCE RATIOS

Line	Ratio	HuDo 1	HuBi 1
5876	He^+/H^+	<0.06	0.11
7319	O^+/H^+	2.6E-4	3.2E-4
7330	O^+/H^+	2.5E-4	4.1E-4
5007	O^{+2}/H^+	1.7E-5	1.2E-5
6583	N^+/H^+	5.4E-5	3.9E-5
6717	S^+/H^+	5.3E-6	1.4E-6
6731	S^+/H^+	5.1E-6	1.3E-6
log O/H + 12		8.43	8.57
log He/H + 12		>10.8	>11.04
N/O		0.21	0.11

4. NEBULAR PARAMETERS

4.1. *Line Fluxes*

All the nebular lines detected were measured in both low and high resolution spectra. High resolution data were used especially when, in the low resolution case, the nebular lines appear blended with stellar lines. Thus we derived useful line ratios for plasma diagnosis.

The observed nebular fluxes, relative to Hβ, are presented in Table 2. Hα to Hβ ratios were used to derive the logarithmic reddening correction at Hβ, c(Hβ), by assuming case B recombination theory according to Storey & Hummer (1995). The values for c(Hβ) are listed at the end of the same table and were used to deredden the line flux ratios, by employing the galactic reddening law of Seaton (1979). The dereddened flux ratios are listed in Columns 3 and 5 of Table 2. These values have an uncertainty better than 20%, except for those cases marked with a colon, which have an uncertainty of a factor of 1.5.

Both nebulae present a very similar low-excitation degree, with [O III] 5007 flux smaller than 0.5 Hβ flux (this is only an upper limit for HuDo 1, where the line is not detected), and [N II] 6583 about twice Hβ. However in HuBi 1 the nebula is much brighter, relative to the central star, than in HuDo 1 (see the equivalent widths of Hβ, EW(Hβ), at the end of Table 2). Another interesting difference is the nebular He I 5876 line, which is perfectly visible and presents a large intensity in HuBi 1, while it is not detected in HuDo 1. We will discuss this in the next section.

4.2. *Plasma Diagnosis: Electron Temperatures and Densities*

Plasma diagnosis was performed with the help of the task NEBULAR of IRAF. For HuBi 1 the temperature-sensitive line ratio [N II] 5755/6583 $\sim$ 0.012$\pm$0.003, indicates an electron temperature T_e $\sim 9400 \pm 1500$ K. The auroral line is very faint providing a large uncertainty in the temperature. [N II] 5755 was not detected for HuDo 1, and its upper limit indicates an upper limit of 14,000 K for T_e which is certainly too high. We will adopt T_e = 9400 K for both nebulae.

From the density sensitive [S II] 6731/6717 line ratio (obtained from high resolution observations of April 2004), we derive for HuDo 1 N_e $\sim$ 3300$\pm$500 cm^{-3} and 800$\pm$300 cm^{-3} for HuBi 1. This latter value is larger than the values derived by Peña et al. (2001) and Pollacco & Hill (1994). This could be due to the fact that we are not measuring the same nebular zone in this extended nebula. In any case, the derived density values are unusually low for a such a late [WC] object.

4.3. *Chemical Abundances*

Ionic abundances for the visible ions: O^+, O^{++}, N^+, S^+, and He^+ were computed by assuming electron densities of 3300 cm^{-3} and 800 cm^{-3} for HuDo 1 and HuBi 1 respectively, and T_e = 9400 K for both objects. The results are listed in Table 3 where estimates for the O and He abundances and the N/O ratios are also included by assuming that O/H = $O^+/H^+ + O^{++}/H^+$, He/H > He^+/H^+, and N/O = N^+/O^+. The derived oxygen abundances and the N/O abundance ratios are about solar. The chemical abundance pattern indicates that both objects are disk planetary nebulae.

The He^+/H^+ abundance ratio equal to 0.11 derived for HuBi 1 (which is indicating a large He enhancement in this nebula), deserves a separate discussion. First, this is the only nebula around such a late [WC] star presenting detectable He I recombination lines (we confirmed the presence of nebular He I 5876 by extracting the nebular emission outside the star and found a nebular spectrum similar to that presented by Pollacco & Hill 1994 with a strong 5876 Å; see their Figure 2b). For none other studied PN of this kind, the nebular He I lines have been observed (for instance, De Marco et al. 1997 and De Marco & Crowther 1999 considered that all the He I 5876 emission detected in M4–18, CPD-56^{0}8031 and He2–133, has a stellar origin) indicating that the amount of He^+ is very low and that most of the nebular helium should be in neutral form. This is expected due to the low effective temperature (about 30 to 32 kK) determined for these central stars. The central star of HuBi 1 should be hotter (Leuenhagen & Hamann 1998 determined 35 kK) and in some way the He^0 ionizing photons should not be totally consumed by the He- and C-rich stellar atmosphere, providing enough photons to partially ionize the nebular helium. The grid of photo-ionization models computed by Stasińska (1982) shows that in a nebula with solar abundances and a density of 10^3 cm^{-3}, a star with $T_{\rm eff} \geq 35{,}000$ K (black-body distribution) can produce a He^+ fraction of about 0.6, leaving 40% in He^0. Lower stellar temperatures produce much smaller He^+ fractions, while higher $T_{\rm eff}$ produce O^{++} fractions which are too large. If we adopt the model with $T_{\rm eff}$ = 35 kK for HuBi 1, its He/H abundance would be as large as 0.18! In § 6 we discuss a compendium of nebular and stellar parameters, including the He abundance, for all the well-studied [WC 10] objects.

5. THE CENTRAL STARS

5.1. *Stellar Lines*

These lines were measured on the low resolution (Boller & Chivens) spectra because in the high resolution ones only the strongest stellar emission lines were detected. The measurements were relatively straightforward for HuBi 1 which shows narrower stellar lines. For HuDo 1, in many cases the lines appear heavily blended (see Figs. 3 and 4) therefore we used the high resolution spectra as an indication to disentangle the components.

Equivalent widths, and observed and dereddened fluxes for stellar lines (relative to C III λ5696) for both objects are listed in Table 4. As expected, stellar spectra are dominated by C II and C III lines and some He I lines are also detected. Some of the lines are blends of several components and they have been marked with a *b*, immediately after the wavelength.

From the comparison of different observations we have estimated the uncertainties in stellar fluxes as follows: for observed fluxes lower than 0.3 (relative to C III 5696) the uncertainties are about 20–25%; for fluxes between 0.3 and 0.8, uncertainties are about 15%; the uncertainties are lower for brighter

TABLE 4

OBSERVED AND DEREDDENED STELLAR LINE FLUXES, RELATIVE TO C III 5696 Å

λ (Å) Ion	HuDo 1			HuBi 1		
	EW[a]	F(obs)[b]	F(dered)	EW[a]	F(obs)[b]	F(dered)
4267 C II	21	0.20	0.94	20	0.47	1.23
4618 C II	10	0.1:	0.3:	4	0.13	0.25
4650[b] C III	25	0.20	0.61	15	0.50	0.93
4686 He II	8:	0.1:	0.2:	2	0.1:	0.2:
4922 He I	8	0.1:	0.2:	7	0.19	0.30
5015 He I	15	0.12	0.25	8	0.21	0.29
5034[b] C II	16	0.16	0.32	10	0.33	0.46
5140[b] C II	32	0.60	1.16	40	1.37	1.76
5261 C II	15	0.20	0.34	8	0.31	0.37
5305 C III	8	0.1:	0.16:	4	0.16	0.18
5340 C II	14	0.23	0.35	8	0.23	0.26
5474 C II	6	0.1:	0.14:	...	...	...
5540 C II	2	0.04:	0.06:	2	0.13	0.14
5656 C II	24	0.48	0.52	12	0.77	0.79
5696 C III(log flux)	40	−14.07	−12.40	21	−13.70[c]	−12.72[c]
5806 C IV	8	0.22	0.19	7	0.25	0.23
5826 C III	14	0.50	0.47	14	0.79	0.75
5876 He I	20	0.70	0.63	29	1.39	1.31
5880 C II	18	0.80	0.66	24	1.00	0.89
5894 C II	10	0.40	0.30	8	0.50	0.45
6097 C II	13	0.45	0.37	14	0.88	0.74
6151 C II	15	0.58	0.47	14	0.90	0.70
6206 C III	4	0.10	0.07	3	0.19	0.14
6255 C II	7	0.18	0.11	4	0.28	0.21
6462 C II	17	0.62	0.37	18	0.92	0.64
6512	4	0.17	0.09	3	0.1:	0.07:
6578 C II	67	3.20	1.65	54	2.29	1.46
6678 He I	37	1.06	0.52	20	1.48	0.92
6746 C II	54	1.70	0.84	6	0.37	0.21
6789 C III	57	2.53	1.19	26	1.85	1.03
7035 C II	16	0.73	0.30	12	1.90	0.97
7065 He I	50	2.16	0.81	21	2.99	1.52
7116 C II	35	1.48	0.55	20	2.59	1.28
7235[b] C II	280	14.2	5.27	129	19.0	9.15
7282 He I	13	0.78	0.29	6	0.52	0.27
7580 C III	10	0.45	0.14	...	...	...

[a] Equivalent width in Å.

[b] Uncertainties are discussed in the text.

[c] Value for September 2000. See discussion in § 5.1.

TABLE 5

STELLAR LINE PARAMETERS FOR SPECTRAL CLASSIFICATION

	HuDo 1	HuBi 1	[WC 10][a]
log F(C III 5696)[b]	-12.40	-12.77	$\cdots$
FWHM(C III 5696) (Å)	14	7	3–6
log F(C IV 5808)/F(C III 5696)	-0.72 ± 0.10	-0.64 ± 0.10	-1.2 to -0.7
log F(C IV 5808)/F(C II 4267)	-0.69 ± 0.13	-0.73 ± 0.13	-1.5 to -0.2
log F(He II 4686)/F(He I 5876)	-0.50 ± 0.20	-0.82 ± 0.20	≤ -0.8

[a] Classification criteria by Crowther et al. (1998).

[b] Dereddened fluxes in erg cm^{-2} s^{-1}.

lines. Lines marked with a colon show uncertainties of a factor of 1.5.

The stellar line fluxes, relative to C III λ5696, were dereddened assuming the Seaton (1979) reddening law and a logarithmic reddening correction at Hβ as derived from the nebular lines. Once dereddened we proceeded to classify the stars following the criteria proposed by Crowther et al. (1998) (see Table 5). We have not used Acker & Neiner's (2003) scheme because, as mentioned in the Introduction, their suggested criteria show discontinuities and the primary ones are not well defined.

Unfortunately, the primary criteria proposed by Crowther et al. (and also Acker & Neiner's), fall mainly on the C IV 5801,5812 lines, which are extremely faint for very late [WC] stars. In addition, with our spectral resolution these lines are almost blended with (or at least lie in the wing of) the strong C III 5826 and show P Cygni profiles (see Fig. 4), rendering their measurements difficult. All this causes the main uncertainty in our classification of HuDo 1 and HuBi 1 central stars. However, within the uncertainties, both objects can be classified as [WC 10] stars, although the FWHM(C III 5696) for HuDo 1 is too large. Considering this primary criterion and taking into account the (very uncertain) He II/He I ratio, the central star in HuDo 1 could be nearer the [WC 9] spectral type, but all the other primary criteria point to the [WC 10] type. In general, the equivalent widths and the FWHM of lines in HuDo 1 are larger than in other [WC 10] stars, probably indicating a more massive wind with a larger expansion velocity, or larger turbulence. In this sense, HuDo 1 is a peculiar [WC 10] object, in a similar sense to the peculiar [WC 9] SwSt 1 which has narrower stellar lines than other [WC 9] objects (Crowther et al. 1998).

5.2. *Is the Central Star of HuBi 1 Variable?*

In Table 4 we present for HuBi 1 a dereddened log F(C III 5696) = -12.72, from the B&Ch data obtained in September 2000. From the literature, we found that, from observations performed in July 1996, Crowther et al. (1998) reported a dereddened log F(C III 5696) = -11.85, while Acker & Neiner (2003) reported a value of -12.24, from observations performed between 1994 and 1995. Our observations of June 2002 show a fainter star, with log F(C III 5696) = -13.50. However, the stellar line ratios seem not to change significantly. Of course much of the flux variation could be caused by the differences in the slit widths or observing conditions, but it would be worth while to perfom a long-term photometric analysis of HuBi 1, in order to verify the possibility of stellar variations. It is known that the [WC 10] star CPD-56^{0}8032 varies with ΔV$\sim$1 mag (Pollacco et al. 1992) and small variations (ΔV$\sim$ 0.03 mag) have been reported for M4–18 (Handler 1996).

6. DISCUSSION AND RESULTS

From stellar spectroscopic data and applying recent criteria for WR spectral classification, we have found a spectral type [WC 10] (peculiar) for HuDo 1 and we confirmed a [WC 10] type for HuBi 1. This locates these objects among the coolest [WC] stars.

Interestingly, both PNe, but in particular HuBi 1, show relatively low nebular density for such late [WC]-type objects. Several authors (e.g., Acker, Gorny, & Cuisinier1996; Gorny & Tylenda 2000; Peña et al. 2001) have shown that nebulae around [WC] stars follow a density-spectral type relation, with the electron densities decreasing from nebulae around late [WC] stars (young objects showing $N_e \geq 10^4$ cm^{-3}) to nebulae around early [WC] stars (evolved objects). Nevertheless there are some exceptions to this rule. The case of HuBi 1 was al-

TABLE 6

NEBULAR AND STELLAR PARAMETERS FOR ALL STUDIED [WC 10] PNE

log(X/H)+12	HuDo 1	HuBi[a]	M4–18[b]	CPD–56[c]	He2–113[c]
He	>10.8	>11.04	···	···	···
O	8.43	8.57	8.62	8.68	8.68
N	7.75	7.61	7.60	7.91	7.82
C			9.08	9.80	9.70
N_e (cm^{-3})	3300	800	5011	60,000	60,000
T_e (K)	···	9400	8200	9300	8400
diameter ($''$)	∼1.7	18	1.85	1.7×2.1	1.4×1.1
c(Hβ)	2.05	1.22	0.81	1.00	1.47
log F(Hβ)$^{(d)}$	−12.75	−12.59	−11.43	−11.03	−10.21
distance (kpc)	···	···	6.8	1.35	1.2
V_*($^{\rm d}$)	14.4	15.8	12.5	9.5	8.9
T_* (kK)	···	35	31	30	30
log $L_*/L_\odot$	···	(3.7)	3.72	3.7	3.72
log ($\dot{M}/M_\odot$ yr^{-1})	···	−5.70	−6.05	−5.4	−6.1
v_∞ (km s^{-1})	···	360	160	225	160

[a]Stellar wind data for HuBi 1 are from Leuenhagen & Hamann (1998).

[b]Data for M4-18 are from De Marco & Crowther (1999).

[c]Data for CPD-56^{0}8032 and He2–113 are from De Marco et al. (1997).

[d]F(Hβ) and stellar V magnitudes have been corrected for reddening.

ready pointed out by Peña et al. (2001). This nebula and K2–16 ([WC 11] central star) are the only [WC-late] ones presenting densities lower than 10^3 cm^{-3}. It has been suggested that this kind of objects could represent born-again planetary nebulae or, alternatively, low-mass slowly-evolving stars. Gorny & Tylenda (2000) and Peña et al. (2001) have argued in favor of the latter suggestion. The case of HuDo 1 (also M4–18, see below) is only marginally out of the density-[WC] type relation.

In Table 6 we present a compendium of the known parameters for the up-to-now 5 well-studied PNe around [WC 10] central stars. For HuDo 1, we have estimated the dereddened apparent visual magnitude, V_*, from the continuum flux at 5500 Å. The value for HuBi 1 is from Hu & Bibo (1990) after dereddening. An analysis of Table 6 gives the following results:

1. All the PNe have O/H abundance ratio between 8.4 and 8.7, typical of disk PNe (see Kingsburgh & Barlow 1994). The N/O ratio is between 0.1 and 0.2, which is slightly low for typical PNe but similar to the solar value. That is, none of these nebulae seems to be N-rich (curiously, no Peimbert Type I PN are found in this sample, although there are several among the [WC-early] types), and the only three for which C has been measured seem very C-rich. Regarding He, we found that HuBi 1 is the only nebula ionized by a cool [WC] star, showing He$^+$ recombination lines. This indicates that HuBi 1 is very probably a He-rich nebula and its central star should be slightly hotter than the other objects, for which most of the nebular helium is in neutral form and its abundance cannot be measured.

2. The apparent magnitudes for the Hudo 1 and HuBi 1 central stars are much fainter than the values of the other [WC 10] stars (HuBi 1 has the apparently faintest star). Assuming that all of them have a similar luminosity would imply that HuBi 1 and HuDo 1 should be at larger distances. However, if we suppose a distance of 6.8 kpc (the same as for M4–18) for HuBi 1, the nebular diameter would be 0.6 pc, which seems too large for a nebula with an apparently young central star. Therefore, at least for HuBi 1 we should conclude that its star is intrinsically fainter and, consequently, of lower mass. This

represents an evidence that the masses of WR central stars even with very similar effective temperatures, span a large range of post-AGB masses. The same conclusion was derived by Peña et al. (1998) from the analysis of nebulae with [WC-early] stars.

3. Due to its large diameter, higher excitation and low density HuBi 1 seems the more evolved object, with probably the largest dynamical age. It is the only object for which a "born-again" scenario is plausible but, as suggested by Peña et al. (2001), most probably it is a low-mass slowly-evolving post-AGB object. There are some indications that HuBi 1 star could be variable. This particular object certainly deserves a close follow-up.

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