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CHARACTERISTICS OF PLANETARY NEBULAE WITH [WC] CENTRAL STARS

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RESUMEN

Utilizando datos espectro-fotométricos de alta resolución, hemos analizado las condiciones físicas, las abundancias químicas y la cinemática de una muestra amplia de nebulosas planetarias con estrella central de tipo [WC]. Los resultados se comparan con las características de nebulosas planetarias ionizadas por estrellas con líneas de emisión débiles (WELS) o estrellas centrales no-WR. Encontramos que las WRPNe muestran una proporción mayor de nebulosas ricas en nitrógeno. Ninguna de las 9 nebulosas alrededor de WELS analizadas muestran enriquecimiento de nitrógeno. Las WRPNe presentan mayores velocidades de expansión y mayor turbulencia, lo que indica que la energía mecánica del viento estelar masivo ha afectado de manera importante el comportamiento cinemático de la nebulosa. También hemos encontrado que las PNe con estrellas de alta temperatura (por lo tanto más evolucionadas) se expanden más rápido. El efecto es más importante en WRPNe. Esto podría utilizarse para comprobar la secuencia evolutiva, [WC]-tardías $\rightarrow$ [WC]-tempranas, que se ha propuesto para estrellas [WC].

ABSTRACT

We have analyzed the plasma diagnostics (electron densities and temperatures and abundance ratios), and the kinematics of a large sample of planetary nebulae around [WC] stars by means of high resolution spectra. The results have been compared with characteristics of planetary nebulae around WELS and non-WR central stars. We find that the proportion of nitrogen rich nebulae is larger in WRPNe than in non-WRPNe. None of the 9 nebulae around WELS in our sample shows N-enrichment. WRPNe have larger expansion velocities and/or larger turbulence than non-WRPNe demonstrating that the mechanical energy of the massive [WC] stellar wind largely affects the kinematical behavior of nebulae. A weak relation between stellar temperature and expansion velocities has been found for all kind of nebulae, indicating that older nebulae expand faster. The effect is more important for WRPNe. This could be useful in testing the evolutionary sequence [WC]-late $\rightarrow$ [WC]-early, proposed for [WC] stars.

Key Words: **PLANETARY NEBULAE — STARS : AGB AND POST-AGB — STARS : WOLF-RAYET**

1. INTRODUCTION

A small percentage of planetary nebulae (PNe) in our and other galaxies are ionized by central stars showing intense Wolf-Rayet features. In the Galaxy, all these stars belong to the WC-sequence (hereafter [WC] stars), showing almost pure He and C in their atmospheres. Most of the stars belong to the [WC]-early ([WC] 2-4) or [WC]-late ([WC] 7-11) spectral types, with very few objects in the intermediate types. In recent years, many efforts have been devoted to understand the evolutionary status of [WC] stars and to determine the differences between PNe around [WC] stars (WRPNe) and normal PNe.

To the present it is not clear which is the evolutionary process leading to the formation of such H-deficient low-mass stars. A "very late thermal pulse", occurring when the central star is already at the white dwarf cooling phase ("born-again" scenario), was first proposed as the possible mechanism (e.g., Iben et al. 1983). Several authors have demonstrated that such a scenario cannot hold for most of WRPNe, in particular the late ones (e.g., Górny & Tylenda 2000; Peña, Stasińska & Medina 2001; De Marco 2002). Recently, it has been proposed that, for a single star evolution, such a condition could be

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produced by a final thermal pulse either just before the star leaves the AGB or shortly afterwards (e.g., Blöcker 2001 and references therein). Alternatively, it has been suggested that a [WC] central star could be formed as the result of a merger in close binary evolution (De Marco et al., this volume).

In this work we present a brief review of our present knowledge on the nebulae around these uncommon central stars.

A few years ago we started a systematic observational program to obtain high resolution spectroscopic data of a large sample of WRPNe and non-WRPNe. All data have been gathered with the 2.1-m telescope and the echelle spectrograph at OAN, San Pedro Mártir, México. The consistent data set obtained in this way has been used to compare the properties of both kind of nebulae and to analyze the WRPN nebular characteristics and their relation with the stellar properties of [WC] stars. Some results have been already published (Peña et al. 1998; Peña et al. 2001; Medina et al. 2003).

2. THE SAMPLE

The sample consists of 28 WRPNe (including late and early [WC] stars) and 23 non-WR PNe, 9 of which are nebulae ionized by weak emission line stars (WELS). We have obtained well resolved line profiles for most of the observed objects, in the range from 3500 to 6800 Å, with a typical resolution of 0.2 to 0.3 Å. In this broad wavelength range, several important ratios for plasma diagnostic are observed. Plasma diagnostic and chemical abundances were presented by Peña et al. (2001) for the whole WRPN sample and a few PNe around WELS.

Regarding the kinematics, our spectral resolution (between 10 and 18 km s^{-1}) allows us to analyze resolved nebular lines. We found that 25% of the objects (in general the more extended ones) show the classical split profiles produced by an expanding shell. The others present single line profiles, which occasionally are gaussian lines but, in many cases, asymmetrical or complex profiles (generally produced by knotty nebulae) are found. For some objects, high velocity components or extended wings have been detected (see Peña et al. 2001 and Medina et al. 2003, for a complete description of the kinematical analysis).

3. WRPNE VS. NON-WRPNE

3.1. *The chemical composition*

In 1995, Górny & Stasińska compared the properties of WRPNe with respect to non-WRPNe. From data gathered from the literature, they found no differences in morphologies, average chemical composition, galactic distribution or any other characteristic among WRPNe and non-WRPNe, except for expansion velocities which in average are larger for WRPNe. The analysis of our data confirmed most of their findings and also produced some new results. For instance, Peña et al. (1998) showed that PNe around identical [WC] type stars can present very different N/O ratios, indicating that stars with very different initial masses can evolve through similar [WC] stages.

In Fig. 1 we present the behavior of N/O vs. O/H abundance ratios for the WRPNe and PNe around WELS in our sample (this is the same figure presented by Peña et al. 2001, but with a larger number of objects). The O abundances spread over a range from about $1\,10^{-4}$ to $8\,10^{-4}$, with a mean value of $4\,10^{-4}$, in very good agreement with the values shown by large samples of galactic PNe (see e.g., the sample analyzed by Kingsburgh & Barlow 1994). For a given O/H ratio a large spread in the N/O ratio is found, confirming that stars from low to high initial stellar masses can go through a [WC] phase. However, also it is found that almost 30% of our WRPNe sample presents a N/O ratio larger than 0.8, which corresponds to the definition of Type I PNe as proposed by Kingsburgh & Barlow (1994). None of the 9 PNe around WELS in our sample shows such a high N/O. Normal samples of PNe (like the one of Kingsburgh & Barlow) show no more than 16% of Type I PNe. Therefore among WRPNe there seems to be a larger proportion of Type I objects than in normal PN samples. This is indicating that a high initial stellar mass increases the probability of having a [WC] central star.

An important element to be analyzed is carbon. Unfortunately there are only a few WRPNe where C has been reliably determined. In Table 1 we present the C/O abundance ratios for these objects and their central stars. The small number of objects makes difficult to draw definite conclusions, however, Table 1 shows that [WC] central stars present a large fraction of C in their atmospheres (as expected) and also that most nebulae seem very C-rich, showing C/O much larger than 1. This is a consequence of the so-called “third dredge-up” events,[1] (occurring after each thermal pulse in the AGB phase when freshly-made carbon is dredged up to the surface by deep convection), which seem to have happened in most of these objects.

[1]See e.g., Renzini & Voli (1981) for a description of “dredge-up” events.

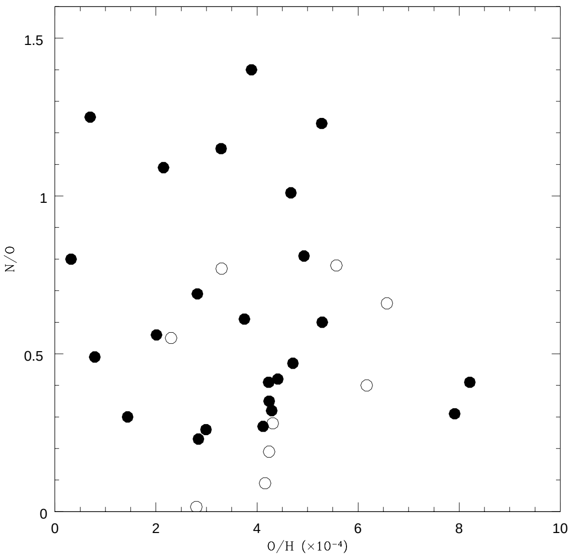

Fig. 1. N/O vs. O/H abundance ratios (figure adapted from Peña et al. 2001). Fill circles represent WRPNe and empty circles, PNe around WELS. For a given O/H, N/O shows a large spread. Also there is a high proportion of WRPNe showing N-enrichment (N/O>0.8), while none of the WELS-PNe in our sample have N/O>0.8.

Interestingly, in this Table PB 6 is the only known N-rich WRPN (Peña et al. 1998), all the others do not show N-enrichment and their central stars should have not had a "second dredge-up" event extracting N-rich material to the surface. Such stars should have been of low initial masses (lower than 3.5 $M_{\odot}$). Intriguingly, some nebulae in Table 1 seem to be more C-rich than their central stars but there are large uncertainties in the stellar abundance determinations (compare for instance the two stellar values derived from expanding atmosphere models for NGC 6905 in Table 1) as well as in the nebular C-abundance determinations. Much more good quality data are required in order to better analyze this point.

3.2. *The kinematics*

An important fraction of PN shells seems to be not regular expanding shells. Many of them present knots and filaments and, in many cases, kinematical structures such as ansae, FLIERS, BRETS and others, therefore, the nebular line profiles are usually complex showing asymmetries, wings, shoulders, multiple components, etc. In addition, a nebular line profile also depends on the turbulence, thermal, density and ionization structures and, on the spectral resolution and the slit dimensions. For the above reasons, deriving expansion velocities from nebular line profiles involves somewhat arbitrary choices of criteria (see, for example, Peña et al. 2001; Gesicki & Zijlstra 2000; Neiner et al. 2000) and the velocities obtained with different methods or by different authors cannot be easily compared.

TABLE 1

THE CARBON ABUNDANCE IN WRPNE

Name	[WC]	C/O_{star}	C/O_{neb}
PB6	2	1.7[1]	2.6[2]
NGC 2452	2	2.1[1]	1.1[2]
NGC 2867	2	2.8[1]	3.1[2]
NGC 6905	2-3	1.7[1]-4.1[3]	0.9[2]
He 2-55	3	2.5[1]	1.3[2]
SwSt 1	9p	2.6[3]	0.7[3]
CPD-56°8032	10	5.0[3]	9.8
He 2-113	10	5.5[3]	7.5[3]

[1] Koesterke & Hamann 1997; [2] Peña et al. 1998; [3] De Marco 2003.

Thus, to search for the kinematical effects of the WR winds on the nebular shell, a uniform data set should be analyzed in a consistent way. Such we do in the following. The validity of our results resides on a systematic treatment for all the objects.

As already said, our sample present different kinds of line profiles: split lines, single gaussian, single asymmetrical and complex lines with several components. The interested reader can find the line profiles of our objects in Medina et al. (2003), where the analysis of the expansion velocities of nebulae, measured classically as half the peak-to-peak separation of split lines, or as the HWHM of single lines, is presented.

For this paper we have chosen a slightly different criteria. Considering that the massive [WC] wind might produce more turbulence, asymmetries and high velocity components, we performed the analysis by measuring the widths at the base of the lines. Actually, in order to avoid any noise disturbance at the base of the lines, we have measured the line widths at 1/10 the maximum intensity. Half this value ($\mathrm{HW}\frac{1}{10}\mathrm{I}_{max}$),in km s^{-1}, will be called V_{10} and represents a velocity which includes expansion, turbulence and high velocity components. The values for V_{10}, measured for different ions and corrected for instrumental and thermal widths, are presented in Table 2 for our whole sample of WRPNe, PNe around WELS and normal PNe.

In Fig. 2 we compare V_{10} obtained from different ions to $V_{10}(\mathrm{H}\beta)$. A very good linear correlation for the velocities of different ions is found for

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TABLE 2

EXPANSION VELOCITIES FOR THE SELECTED IONS

PN G	Main Name	[WC][(1)]	$T_*^{(1)}$	V_{10} (km s^{-1})[(2)]						profile[(3)]
			(kK)	[O II]	[O III	Hβ	[N II]	He I	He II	
001.5 − 06.7	SwSt 1	9	40	29	22	22	30	–	–	s
002.4 + 05.8	NGC 6369	4	150	76:	64	68	57	67	63:	d,c
002.2 − 09.4	Cn 1-5	4	<57	46	42	41	44	–	–	s
003.1 + 29.4	Hb 4	3-4	86	47:	32	32	34	31	42	s,a
004.9 + 04.9	M 1-25	6	60	36	41	41	41	43	–	s
006.8 + 04.1	M 3-15	5	55	–	30	32	29	36	–	s,h
011.9 + 04.2	M 1-32	4-5	66	63	89	62	65	76	–	s,h
012.2 + 04.9	PM 1-188	11	35	–	–	56	70	–	–	s
017.9 − 04.8	M 3-30	–	97	41:	52	49	68	49	52	c
027.6 + 04.2	M 2-43	8	65	26	26	27	30	30	–	s
029.2 − 05.0	NGC 6751	4	135	63	77	72	60:	81:	–	d
048.7 + 01.9	He 2-429	4-5	–	–	52	54	59	–	–	s
061.4 − 09.5	NGC 6905	2-3	141	66	69	66	65	71	70	d
064.7 + 05.0	BD+30°3639	9	47	62	79	43	42	–	–	s
068.3 − 02.7	He 2-459	8	77	–	–	56	60	–	–	s
089.0 + 00.3	NGC 7026	3	130	68	54	55	62	59	52	d,c
096.3 − 02.3	K 3-61	4-5	–	–	48	57	46	51	–	s
120.0 + 09.8	NGC 40	8	78	37:	47	38	36	40	–	d
130.2 + 01.3	IC 1747	4	126	25:	55	54	58	55	56	s,a
144.5 + 06.5	NGC 1501	4	135	–	58	54	51	61	66	d
146.7 + 07.6	M 4-18	11	31	24	–	21	24	–	–	s
161.2 − 14.8	IC 2003	3	88	40	42	39	44	–	–	c
243.3 − 01.0	NGC 2452	2	141	40:	56	58	55:	57	60:	c
352.9 + 11.4	K 2-16	11	30	59	57	55	54	–	–	d
009.4 − 05.0	NGC 6629	wl	<52	34	25	30	–	31	–	s
010.8 − 01.8	NGC 6578	wl	65	32	29	30	34	–	–	c
011.7 − 00.6	NGC 6567	wl	61	38	35	34	–	–	–	d
096.4 + 29.9	NGC 6543	wl	<66	43	34	33	43	33	–	c
100.6 − 05.4	IC 5217	wl	72	62:	38	38	62	39	25	d
159.0 − 15.1	IC 351	wl	85	35	36	26	28:	34	34	s
194.2 + 02.5	J 900	wl	123	–	42	43	49	48	39	s
221.3 − 12.3	IC 2165	wl	153	47	44	43	47	44	43	s
356.2 − 04.4	Cn 2-1	wl	84	28	26	25	34:	29:	32:	s
013.7 − 10.6	YC 2-32	pn	68	–	33	32	40	34	36	s
037.7 − 34.5	NGC 7009	pn	85	36	33	30	38	33	29	d
084.9 − 03.4	NGC 7027	pn	175	53	40	38	51	44	40	s
103.7 + 00.4	M 2-52	pn	–	32	35	35	32	33	39	s
104.4 − 01.6	M 2-53	pn	112	36	30	37	36:	39	39:	s,a
118.0 − 08.6	Vy 1-1	pn	32	36:	21	24	32:	26	–	s
130.3 − 11.7	M1-1	pn	87	36:	57	54	38:	57	–	s
133.1 − 08.6	M 1-2	pn	51	–	48	42	57::	41	49	c
147.4 − 02.3	M 1-4	pn	67	–	27	25	54:	34	19	c
166.1 + 10.4	IC 2149	pn	<49	32	< 18	20	33	26	–	c
196.6 − 10.9	NGC 2022	pn	114	–	43	41	38	47	49	d
215.2 − 24.2	IC 418	pn	53	19	< 18	15	25	21	–	s
243.8 − 37.1	PRTM 1	pn	90	–	56	51	–	–	58	d
294.1 + 43.6	NGC 4361	pn	95	–	54	45	–	–	52	d

(1) Star parameters: a number shows the [WC] type, *wl* is for WELS, *pn* for normal stars. T_* from the literature.
(2) Uncertainties of V_{10} are in average of 10%, and larger if marked with a colon.
(3) Line profile description: *s:* single, *a:* asymmetrical, *h:* high velocity extensions, *d:* double peak, *c:* complex.

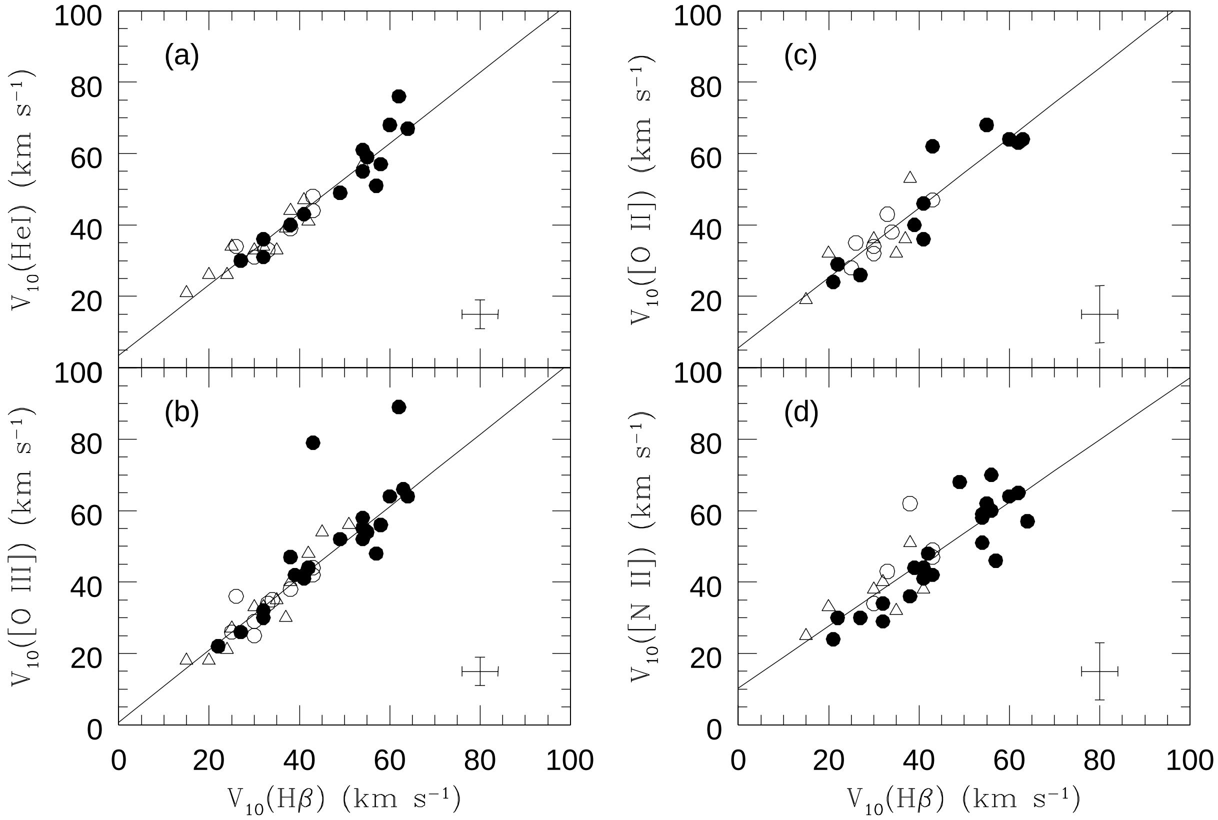

Fig. 2. V_{10} from Hβ are compared to velocities from: a) He I, b) [O III], c) [O II] and d) [N II]. Fill circles are WRPNe, WLPNe are marked with open circles and ordinary PNe are marked with open triangles.

all kind of nebulae (regardless if they are WRPNe or not). It is worth to notice however that low ionization species (O^+ and N^+) present large dispersion and also higher velocities. This indicates that the outside parts of the nebulae are accelerating relative to the inner zones. Such an effect is predicted by hydrodynamical models.

In this figure it is evident that, in average, WRPNe present larger V_{10} than PNe around WELS and non-WR PNe; that is, our results indicate that WRPNe expand faster and/or have larger turbulence. This is in agreement with the results by Górny & Stasińska (1995) and with hydrodynamical models for WRPNe (Mellema & Lundqvist 2002). The faster velocities in WRPNe are a consequence of the large mechanical energy of the [WC] stellar winds deposited on the nebular shells.

Interestingly, expansion velocities of PNe around WELS are in general similar to those of normal PNe. This kinematical behavior and the fact that none PNe around WELS in our sample shows N-enrichment (in contrast with the 30% of N-rich WRPNe found) discard the possibility of WELS being a more evolved stage of [WC] stars as it has been proposed in the literature.

3.3. *Nebular expansion and stellar temperatures*

Looking for a relation between the [WC] stellar type and the nebular velocity field, we have analyzed the behavior of V_{10} as a function of the stellar temperature T_* (listed in Table 2), as derived from non-LTE expanding model atmospheres for [WC] stars (see compilation by Koesterke 2001) or from the He II Zanstra temperature for the other objects. The results are presented in Fig. 3, where a weak correlation in found for all kind of objects: WRPNe and non-WRPNe with higher T_* are expanding faster. Considering that T_* is an indicator of the stellar age, then the more evolved PNe (around older stars) are expanding faster, but this effect is considerably more important in WRPNe. In apparently young WRPNe

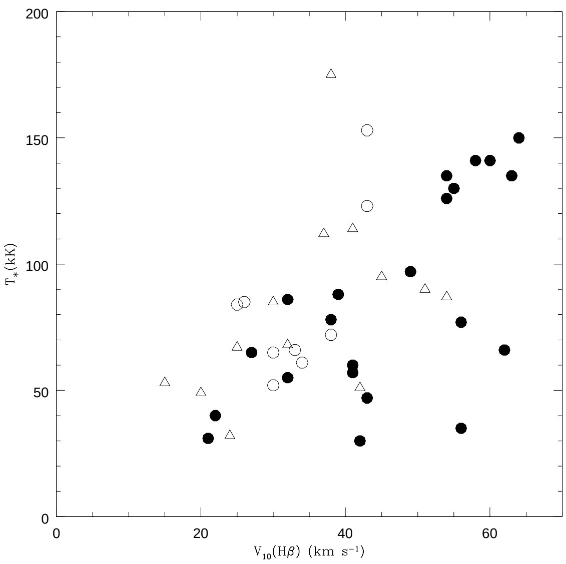

Fig. 3. Stellar temperatures are plotted versus V_{10} from Hβ. Symbols are as described in Fig. 2.

(with low T_*) V_{10} covers the whole range of velocities from 20 to 60 km s^{-1}, but for WRPNe with T_* larger than 100 kK, V_{10} is always larger than 50 km s^{-1}. Thus, the velocity fields of evolved WRPNe seem to have been accelerated by effects of the large mechanical energy of the [WC] stellar wind, although at this point we cannot distinguish if such an effect is producing larger expansion, larger turbulence or high velocity components.

The increase in V_{10} for evolved WR planetary nebulae could indicate that we are witnessing the effects of a massive stellar wind lasting for the whole PN phase. Possibly the analysis of the evolution of the expansion velocities as a function of age in WRPNe, would allow us to test the validity of the evolutionary path: **[WC] late → [WC] early stars**, which has been suggested by several authors (e.g., Hamann 1997; Acker et al. 1996).

A dynamical evolutionary model analyzing the effects of a long-term [WC] stellar wind on a planetary nebula shell is in progress (Medina et al., in preparation) and it will help to elucidate this question.

4. CONCLUSIONS

From a consistent data set of high resolution spectroscopic data for WRPNe and non-WRPNe we have found that:

- WRPNe seem to have a larger proportion of N-rich objects than non-WRPNe and, in particular, PNe around WELS in our sample do not show N-enrichment.
- WRPNe with reliable measurements of the C/O abundance ratio are very C-rich, showing the efficiency of the “third dredge-up” event in these objects.
- WRPNe present higher expansion velocities and probably more turbulence than non-WR planetary nebulae.
- PNe around WELS show a kinematical behavior more similar to normal PNe than to WRPNe, demonstrating that WELS are not a more evolved stage of [WC] stars.
- Expansion velocities for evolved WRPNe are larger than for younger objects. This could be indicating that the velocity field in WRPNe accelerates with time as a consequence of a long-term massive stellar wind.

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