

# The kinematical behavior of ORLs and CELs in PNe with [WC] central star

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**Abstract.** In Planetary Nebulae (PNe) and HII regions ionic abundances can be derived by using collisionally excited lines (CELs) or recombination lines (ORLs). Such abundances do not coincide for the same ion and usually abundances from ORLs are larger than those from CELs by factors of 2 or larger. The origin of the discrepancy, known as the Abundance Discrepancy Factor is an open problem in astrophysics of gaseous nebulae. It has been attributed to temperature fluctuations in the plasma, tiny metal-rich inclusions embedded in the H-rich plasma, gas inhomogeneities or other processes. In this work we analyze the kinematical behavior of CELs and ORLs in two PNe ionized by [WC] stars, finding that kinematics of ORLs is incompatible with the kinematics of CELs. In particular the expansion velocities from CELs and ORLs for the same ion are different, indicating that ORLs seem to be produced in zones nearer the central star than CELs. This is in agreement with results found by other authors for individual PNe.

**Keywords.** planetary nebulae: general, kinematics and dynamics, planetary nebulae: individual: (Cn 1-5, PC 14)

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## 1. Introduction

PNe are constituted by ionized gas surrounding a low-intermediate mass hot evolved star. The gas was ejected by the star, at low velocity (of about  $10 \text{ km s}^{-1}$ ), in advanced stages of evolution (Giant or Asymptotic Giant Branch (AGB) stars). Thus the nebula is expanding away from the star with a velocity that depends on the ejection processes, the thermal processes and the interaction of the nebula with the interstellar medium.

The ionized gas emits collisionally excited lines (CELs) of ions of heavy element (ions of C, N, O, Ne, S, and others) and recombination lines (ORLs) of H, He and ions of heavy elements. Physical conditions (temperature and density) and ionic chemical abundances can be derived from both types of emission lines. Total abundances are obtained by considering all the ions detected in the gas and including the not visible ions by correcting the partial abundances with ionization correction factors (ICFs) or other procedures.

It is a well known fact that ionic abundances derived by using CELs or ORLs do not coincide for the same ion and usually the abundances from ORLs are larger than those from CELs by factors of 2 or larger. This occurs in HII regions and PNe as well (see e.g., García-Rojas & Esteban 2007). In some PNe such a factor, known as the Abundance Discrepancy Factor (ADF), can rise up to 100 or more but the mean value is around 3 (McNabb *et al.* 2013; García-Rojas *et al.* 2013). The origin of the ADF is, so far, an open problem in astrophysics of gaseous nebulae. It has been attributed to temperature fluctuations (e.g., Peimbert 1967, 1971), tiny metal-rich inclusions embedded in the H-rich

plasma (Liu *et al.* 2006 and references therein), gas inhomogeneities or other processes. These proposals would imply that CELs and ORLs would be emitted in zones of different temperatures in the nebula, as CELs are highly dependent of the electron temperature, while ORLs are much less dependent of this parameter and they would be emitted mainly in low temperature zones.

Since some years ago some authors have indicated that the ORLs and CELs emitted by the same ion seem to show different kinematical behavior or different physical distribution in the nebula. In several objects recombination lines of O II appears to show lower expansion velocities than [O III] collisionally excited lines (e.g., Otsuka *et al.* 2010) or that the emission of ORLs from C<sup>++</sup> and O<sup>++</sup> strongly peak towards the nebular center, see e.g., Liu *et al.* (2000), Liu *et al.* (2006) and references therein.

More recently Richer *et al.* (2013) analyzed in detail the spatially and velocity-resolved spectroscopy of ORLs and CELs for the same ion in NGC 7009, finding that the lines show discrepant kinematics and location. ORLs kinematics is incompatible with the ionization structure given by CELs. These authors find that ORLs arise from a different volume than that giving rise to the forbidden emission from the same ion within this nebula, and suggest that there is an additional H-deficient plasma component.

Also García-Rojas *et al.* (2016) found that the O II  $\lambda$ 4649+50 and the [O III] $\lambda$ 5007 have different spacial distributions in NGC 6778. These authors claim that these differences are consistent with the presence of a H-poor gas where ORLs are being emitted.

We have analyzed the kinematics of ORLs and CELs for some PNe, for which we dispose of very high-resolution spectra, where the lines are well resolved. Most of spectra were obtained with the Magellan Inamori Kyocera Echelle spectrograph (MIKE; Berstein *et al.* 2003), attached to the 6.5-m Magellan telescope Clay, at Las Campanas Observatory, Chile. Most of these data have been already analyzed in order to derive physical conditions and chemical abundances from ORLs and CELs and to determine the ADFs for the objects (García-Rojas *et al.* 2012; García-Rojas *et al.* 2013). In these references the procedures for data reduction can be found. Data for other objects have been collected from the literature. The total sample includes PNe ionized by a [WC] central star, a *wels*, or a normal. The ADFs for the whole sample varies from 1.5 to 5.

In this article we present partial results for Cn 1-5 (PN G002.2-09.4) and PC 14 (PN G336.2-06.9), ionized by a [WC] central star, as examples of the whole sample, which will be presented elsewhere.

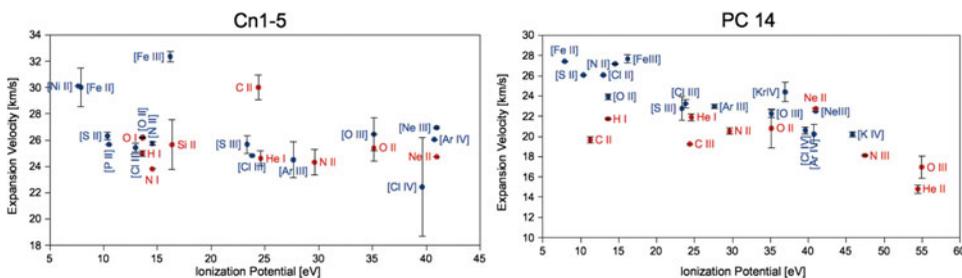
## 2. Data analysis

Due to the high spectral resolution of our data (MIKE has  $R \sim 28,000$  for a 1'' slit width) the lines are well resolved and in several cases they are split showing blue and red components coming from the front and back zones of the expanding shell. In other cases the lines appear as a single component or show evidence of several overlapped components. Cn 1-5 and PC 14 present split lines and we measured both components with IRAF<sup>†</sup> routines by fitting a Gaussian profile to each line. Thus the observed central wavelength and Gaussian Full Width at Half Maximum (*gfwhm*) were determined for several ORLs and CELs in each object. The measured line widths are corrected for the instrumental width, considering that they add in quadrature. Thermal widths are not corrected for, therefore line widths include contributions from thermal broadening,

<sup>†</sup> IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

**Table 1.** Central wavelength ( $\text{\AA}$ ), flux ( $\text{erg cm}^{-2} \text{s}^{-1}$ ) and  $g\text{fwhm}$  ( $\text{\AA}$ ) for some CELs and ORLs in Cn 1-5 and PC 14.  $V_{exp}$  in  $\text{km s}^{-1}$ .

	Cn 1-5			PC 14		
Ion	center	flux	$g\text{fwhm}_o$	center	flux	$g\text{fwhm}_o$
[O II]	3726.04	2.48E-13	0.25	3725.23	4.89E-14	0.29
[O II]	3726.69	1.64E-13	0.25	3725.90	4.74E-14	0.30
[O II]	3728.79	1.24E-13	0.24	3727.99	2.65E-14	0.29
[O II]	3729.44	8.04E-14	0.25	3728.66	2.49E-14	0.29
[O III]	4958.94	1.36E-12	0.47	4957.89	6.49E-13	0.50
[O III]	4959.80	1.09E-12	0.53	4958.63	6.69E-13	0.39
[O III]	5006.88	3.85E-12	0.46	5005.81	2.70E-12	0.46
[O III]	5007.76	3.21E-12	0.55	5006.56	2.96E-12	0.38
O II	4076.35	7.73E-15	0.35	4075.49	1.91E-15	0.48
O II	4077.04	6.02E-15	0.27	4076.21	8.53E-16	0.25
O II	4649.14	1.14E-15	0.37	4648.45	7.08E-16	0.30
O II	4649.91	1.11E-15	0.30	4649.94	3.19E-16	0.25
[N II]	6548.09	7.42E-13	0.54	6546.65	4.27E-14	0.61
[N II]	6549.21	5.59E-13	0.61	6547.84	3.87E-14	0.49
[N II]	6583.47	2.30E-12	0.54	6582.02	1.28E-13	0.61
[N II]	6584.60	1.73E-12	0.61	6583.21	1.15E-13	0.48
N I	8223.12	2.18E-16	0.75			
N I	8224.43	1.66E-16	0.80			
$V_{exp}$ [O II]	26.3 $\pm$ 0.1			23.9 $\pm$ 0.3		
$V_{exp}$ [O III]	26.4 $\pm$ 1.2			22.3 $\pm$ 0.4		
$V_{exp}$ [O II]	25.4 $\pm$ 1.0			20.8 $\pm$ 1.9		
$V_{exp}$ [N II]	25.7 $\pm$ 0.2			27.2 $\pm$ 1.2		

**Figure 1.** Expansion velocity vs. ionization potential for different ions as given by CELs (blue) and ORLs (red).

turbulence and structure. Partial results for the CELs and ORLs emitted by  $\text{O}^+$ ,  $\text{O}^{++}$ , and  $\text{N}^+$  are presented in Table 1, where Column 1 gives the ion ID. In Columns 2, 3 and 4 the observed central wavelength, line flux, and  $g\text{fwhm}$  for lines in Cn 1-5 are presented, and in Columns 5, 6 and 7, the same data are given for PC 14. As usual, CELs are represented with squared parenthesis, and ORLs without parenthesis. CELs and ORLs from several other ions ( $\text{C}^+$ ,  $\text{Fe}^+$ ,  $\text{Fe}^{++}$ ,  $\text{S}^+$ ,  $\text{S}^{++}$ ,  $\text{Ne}^{++}$ , etc.) are also measured.

Expansion velocities ( $V_{exp}$ ), as given by each CEL and each ORL, were calculated as half the difference between the red and blue components of each line. The final adopted  $V_{exp}$  for each ion, is the average of velocities given by its different CELs and ORLs. They are given at the end of Table 1.

In Fig. 1 we present graphs showing the average  $V_{exp}$  for each ion given by CELs (in blue) and ORLs (in red) as a function of the ionization potential (IP) of the ion which, considering the stratification in the ionization structure usually found in a nebula, in some way represents the distance of the zone where the ion resides, relative to the central star.

### 3. Results

Fig. 1 shows evidence of the structure of the velocity field inside the expanding nebulae, in the sense that  $V_{exp}$  is lower near the central star and increases outwards. It is expected that low ionization species, which are farther away from the central star, have larger  $V_{exp}$  than highly ionized species which lie nearer the star. In Fig. 1 this is particularly true for velocities given by CELs, where a clear gradient is evident for both nebulae. In Cn 1-5  $V_{exp}$  increases from about  $24 \text{ km s}^{-1}$  for the highly ionized species ([ClIV], [ArIV]) to about  $30 \text{ km s}^{-1}$  for [NII] and [FeII] and the same happens with the CELs in PC 14. For the case of ORLs, there is either no gradient or a very flat one. Low- and high-ionization species show about the same  $V_{exp}$ . In addition,  $V_{exp}$  of ORLs are smaller than  $V_{exp}$  of CELs, at the same ionization potential. This is very clear if one considers for instance  $V_{exp}[\text{OIII}]$  and  $V_{exp}(\text{OII})$  in an object. In both cases presented here  $V_{exp}[\text{O,III}] > V_{exp}(\text{OII})$ , and the same occurs for  $V_{exp}[\text{NII}]$  and  $V_{exp}(\text{NI})$ .

This result recurs in most of the objects under study (Peña *et al.*, in preparation).

### 4. Discussion

From the results shown above, it seems evident that, as far as CELs and ORLs of the same ion do not share the same kinematics, these lines are not being emitted in the same zone of the nebula. Considering the expansion velocity field in the nebula and the fact that ORLs show lower  $V_{exp}$ , they seem to be emitted in an inner zone. In this sense we are finding the same results reported by Liu *et al.* (2000), Richer *et al.* (2013) and García-Rojas *et al.* (2016) for NGC 6153, NGC 7009 and NGC 6778 respectively, where ORLs are being mainly emitted in an inner zone than CELs. And that kinematics of ORLs is incompatible with that of CELs.

In Cn 1-5 and PC 14, the zones where ORLs are mainly emitted are not expanding in the same way as the zones where CELs are emitted, and show lower  $V_{exp}$ . It is tempting to say that ORLs come from H-deficient zones which were ejected by the star after the H-rich gas where CELs are emitted. However at this point this is mainly speculative. Much more analysis is needed, for a larger number of objects.

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### References

- Berstein, R. A., Sackett, S. A., Gunnels, S., *et al.* 2002, *Proc. SPIE* 4841  
 García-Rojas, J. & Esteban, C. 2007, *ApJ*, 670, 457  
 García-Rojas, J., Peña, M., Morisset, C. Mesa-Delgado, A., & Ruiz, M. T. 2012, *A&A*, 538, 54  
 García-Rojas, J., Peña, M., Morisset, C., *et al.* 2013, *A&A*, 558, 122  
 García-Rojas, J., Corradi, R. L. M., Monteiro, H., *et al.* 2016, *ApJ*, 824, 27  
 McNabb, I. A., *et al.* 2013, *MNRAS*, 428, 3443  
 Liu, X.-W., Sorey, P. J., Barlow, M. J., *et al.* 2000, *MNRAS*, 312, 585  
 Liu, X.-W., Barlow, M. J., Zhang, Y., *et al.* 2006, *MNRAS*, 368, 1959  
 Otsuka, M., Tajitsu, A., Hyung, S., & Izumiura, H. 2010, *ApJ*, 723, 658  
 Peimbert, M. 1967, *ApJ*, 150, 825  
 Peimbert, M. 1971, *Bol. Observatorios Tonantzintla y Tacubaya*, 6, 29  
 Richer, M. G., Georgiev, L., Arrieta, A., & Torres-Peimbert, S. 2013, *ApJ*, 773, 133

**Discussion**

BARLOW: Are your spectra capable of being used to measure the ADFs as a function of angular radius in the nebulae?

PENA: It is possible to measure ADFs as a function of radius in extended nebulae. Anyway we are measuring an average over the line of sight.

LIU: Long-slit observations of NGC6153 (Liu *et al.* 2000) do show that ADF increases towards nebular centre.

PENA: Thank you. I will check it.

BARLOW: Two comments. 1) How valid is to plot H I velocity in your diagrams, considering that this ion is by definition present in all the region under consideration? 2) It is not surprising that the FWHM of ORL is lower than the one of CELs; this can be interpreted as corresponding to a lower temperature region.

PENA: 1) H I velocity represents the average over the nebula and it can be interpreted as the expansion velocity of the nebula, so it is important; 2) I agree. FWHM(CELs) are larger due to temperature, than FWHM(ORLs).