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PLANETARY NEBULAE WITH [WR] NUCLEI. A STATISTICAL APPROACH.

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RESUMEN

Se presentan resultados preliminares del análisis de datos espectroscópicos de alta resolución de una muestra de nebulosas planetarias con núcleo WR o estrellas con líneas en emisión débiles. Se han seleccionado objetos con estrellas centrales de diversas características WR. Para todos los objetos, se han calculado las densidades y temperaturas electrónicas así como la composición química y la velocidad de expansión del gas. Los resultados se usan para realizar un estudio estadístico buscando relaciones entre los parámetros estelares y nebulares y el efecto del viento de la estrella WR en la nebulosa planetaria.

ABSTRACT

Preliminary results from high resolution spectroscopy for a selected sample of planetary nebulae with WR nucleus or weak–emission line star (*wels*) are presented. The observed objects spread over a wide range in stellar characteristics: early and late [WC]–type stars and *wels* have been selected. Nebular densities and temperatures, as well as ionic and total abundances and expansion velocities, have been derived. The results are used to perform a statistical study of the objects in order to find possible relationships among the different stellar and nebular parameters and to analyze the effect of the WR wind on the nebular shell.

Key Words: **ISM: ABUNDANCES – ISM: KINEMATICS AND DYNAMICS — PLANETARY NEBULAE: GENERAL — STARS: WOLF–RAYET**

1. INTRODUCTION

Central stars of planetary nebulae (PNNi) are hot pre–white dwarf stars (post–AGB objects) that have recently ejected a substantial amount of mass at low expansion velocities. They consist of dense carbon–oxygen cores of masses around 0.6 $M_\odot$ surrounded by a thin helium shell, and a H–rich outer atmosphere.

Among the known galactic PNNi there are about 50 objects (nearly 10% of the studied sample) that present intense WR features. These WR–PNNi definitely do not fit into the scheme described before. All of them have been reported to be WC–type stars, mostly of [WC 2–4] and [WC 8–11] spectral types, with very few objects in the intermediate classes (Tylenda, Acker & Stenholm 1993). Some of these stars show much weaker emission lines and have been classified as *wels*.

The atmospheres of such stars are almost pure helium and carbon. In mass fraction, it has been found that He $\sim$ 50 – 80%, C $\sim$ 0.16 – 0.50%, O $\sim$ 6 – 15% (e.g., Leuenhagen, Hamann & Jeffery et al. 1996; Koesterke & Hamann 1997):

In the Magellanic Clouds, only a handful of central stars are known to show WR features. All of them but one present also [WC]–type spectra, although in this case they are [WC 4–6]-type stars (Peña et al. 1997a).

To explain the extreme H–deficiency of WR–PNN atmospheres, the most accepted suggestion is the *born–again* scenario (Fujimoto 1977) where a very late thermal pulse, occurring when the central star is near the

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white dwarf cooling track, sends the star back to the AGB. Recently, Iben & McDonald (1995) and Herwig et al. (2000) have computed models, within this scenario, that could reproduce the chemical composition of [WC] central stars.

Regardless of the process that makes the PNN looks like a Wolf–Rayet star, a number of other questions arise. It is not known if WR phenomenon is a transient stage in the evolution of a central star neither are known the main factors which determine that a PNN will be a WR–PNN.

From both, stellar and nebular studies (e.g., Hamann 1997; Acker, Górny & Cuisiner 1996; Górny 1998), it has been suggested that the spectral sequence of [WC] stars corresponds to an evolutionary sequence from late to early types. The main reason for this suggestion is the fact that most [WC–late] stars possess very dense and compact nebulae, while [WC–early] stars are surrounded by extended low–density nebulae. A few counter examples, where the central star is cool while the surrounding nebula is very diluted, have been interpreted as due to a late helium flash (Acker et al. 1996).

On the other hand, Peña et al. (1998) have shown that PNe with nuclei of same [WC] type have very different nebular properties (morphologies, abundance ratios, etc.) suggesting that stars with quite different initial masses can pass through the same [WC] stage. And, additionally, the WR phenomenon is known to be highly variable, at least in a few cases (Peña et al. 1997b; Werner et al. 1992). Thus, it is not really obvious that the stars that now appear as [WC 2-3] were of [WC–late] type before.

In order to provide some answers to these questions, we are systematically obtaining high–resolution spectrophotometric data of a large sample of known planetary nebulae with WR star (WRPNe). The first results with data for five nebulae with [WC–early] nuclei, together with a detailed photoionization modeling of each object can be found in Peña et al. (1998). To date we have observed about 30 nebulae, selected trying to cover a wide range in stellar characteristics: objects with nucleus of different [WC] types and some *wels* among them. This gives us a large sample of WRPNe which can be analyzed in a consistent way.

2. SPECTROSCOPIC DATA

High resolution spectroscopic observations have been performed with the *echelle* spectrograph attached to the 2.1–m telescope at OAN/SPM, in different observing runs. We have chosen a spectral range as wide as possible in order to determine most of the important optical line ratios for nebular diagnostic and ionic abundance determinations. Our observations range from 3600 to 7000 Å with resolution of about 0.2 Å. A representative *echelle* spectrum is shown in Figure 1.

Details of the observing and reduction procedures can be found in Peña et al. (1998) and Peña, Stasińska, & Medina (2001, in preparation). The high spectral resolution allows us to determine radial velocities of the objects and expansion velocities of the nebular material.

The nebular data derived so far can be used to perform a statistical analysis of some nebular parameters, as a function of the [WC] spectral type (which is closely correlated with the effective temperature of the star).

3. PRELIMINARY RESULTS

1.– The analysis of the electron density as a function of [WC] type confirms the trend found by Acker et al. (1996) in the sense that n_e decreases as the [WC] class decreases. That is, most low–excitation nebulae, ionized by [WC 8-11] stars show $n_e \geq 10^4$ cm^{-4}, while [WC 2-4] stars are surrounded by nebulae with $n_e \sim 10^3$ cm^{-3} and the intermediate types show nebulae with intermediate n_e. This well defined trend indicates that most [WC–late] stars possess young nebulae. Thus, the *born–again* scenario, which requires old nebulae around [WC–late] stars, is not supported by observations.

A few [WC–late] objects, however, notoriously deviate from this behavior. For instance K 2-16 and PM 1-188, both ionized by a [WC 11] star, present $n_e \leq 1000$ cm^{-3}. Specially K 2-16 shows a faint and extended shell–like nebula. Therefore the stellar nuclei in these objects could be *born–again* stars. Alternatively, these objects could be low–mass nebulae around low–mass stars evolving slowly in the H–R diagram, as those reported by Dopita et al. (1988) for their sample of PNe in the Magellanic Clouds.

2.– Chemical abundances of He, O, N and Ne have been derived. We find that He/H can be well determined from the He^+/H^+ ratio only for objects with [WC 6] or earlier type star ($T_{\rm eff} \geq 60{,}000$ K). For later stars, a

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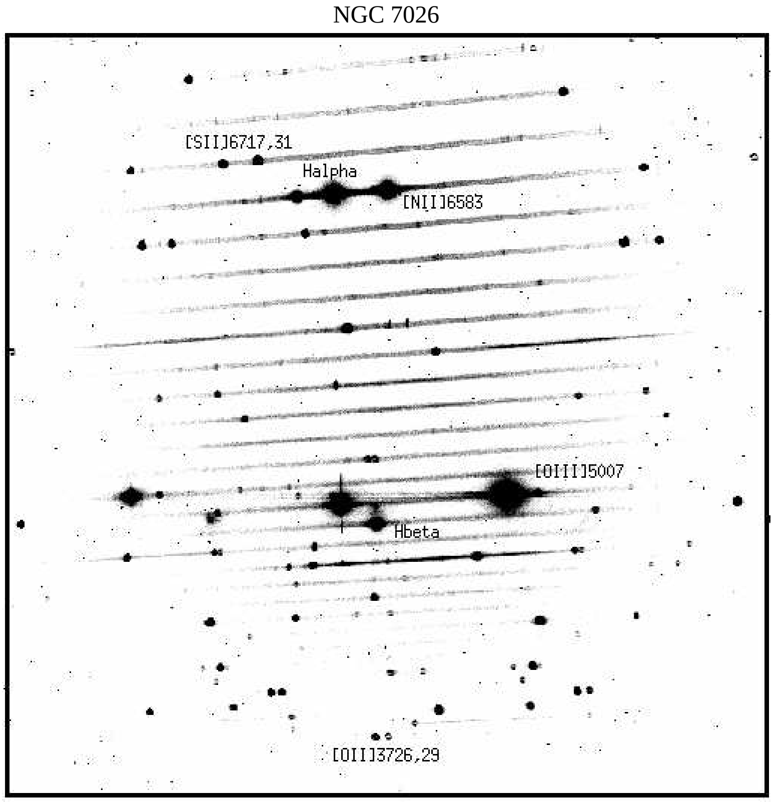

Fig. 1. An *echelle* spectrum of the planetary nebula NGC 7026, from 3600 to 7000 Å is shown. The main lines have been marked. Notice the strong WR features of the central star.

large fraction of neutral helium can be present in the nebula. The bulk of objects present an average He/H $\sim$ 0.120, with a few of them possibly showing He enrichment.

Oxygen abundance values, log O/H +12, are between 8.4 and 8.9, with a large scatter for a given [WC]–type. No tendency in O abundance with spectral type is found. *Wels* abundances do not deviate from this or other WRPN abundance behavior.

In the case on N, a faint tendency of increasing N/O abundance ratio with decreasing spectral type is found, with a large scatter in N/O abundance ratios at a given [WC] spectral type. This is consistent with the idea already expressed by Peña et al. (1998) that stars with very different initial masses can pass through the same [WC] phase.

Neon abundances in WRPNe show the same trend found for general samples of PNe in various environments: Ne/O $\sim 0.2 - 0.3$ (Henry 1986, 1990).

Carbon abundances are expected to be enhanced in WRPNe, due to the [WC] nature of the central star, possibly varying from point to point inside the objects. Acker et al. (1996) suggest that [WC] central stars come from C stars. Unfortunately, C abundances have been confidently derived only for very few objects (Peña et al. 1998). With a few exceptions, most studied WRPNe show a large C–enrichment, but this result cannot be generalized until more objects have been studied. This is an important work for the future.

The comparison of our average values for He/H, O/H, N/O and Ne/O ratios with those obtained by Kingsburgh & Barlow (1994) shows no significant differences between our sample of WRPNe and their sample (which includes all kind of PNe). Thus, as already concluded by Górny & Stasińska (1995) from data collected from the literature, WRPNe do not present significant differences in chemical abundances compared to non–WRPNe.

3.– Expansion velocities are an important parameter for understanding the dynamical evolution of planetary nebulae. We have estimated $V_{\rm exp}$ for our sample from the nebular line profiles and by adopting a simple and arbitrary method to define $V_{\rm exp}$, similar to that described by Dopita et al. (1988). Thus, we are able to analyze $V_{\rm exp}$ as a function of the [WC]–type from consistent data.

The expansion velocities spread over a large range, from $\sim$ 20 to 70 km/s, and in average, $V_{\rm exp}$ (WRPNe) $\geq V_{\rm exp}$ (*wels*).

There is a large dispersion of $V_{\rm exp}$ values for a given [WC] class and, surprisingly, no special trend of $V_{\rm exp}$ with [WC] type is found. The latter fact would indicate that there is no sequence [WC–late] $\rightarrow$ [WC–early]. Otherwise, due to the action of intense stellar winds blowing for long periods, one should expect larger $V_{\rm exp}$ for [WC–early] objects.

4. CONCLUSIONS

Preliminary results from high resolution spectroscopy for a sample of 30 WRPNe and *wels* show that:

- WRPNe do not present significant differences in chemical abundances compared to non–WRPNe.
- There is no evidence for WRPNe being produced in a *born–again* scenario, except possibly for a few [WC–late] stars surrounded by diluted nebulae.
- Expansion velocities measured for WRPNe are, in average, larger than in *wels*. The lack of correlation of $V_{\rm exp}$ and [WC] type do not support the suggestion of an evolutionary sequence: [WC–late] $\rightarrow$ [WC–early]. However, a detailed comparison with dynamical model predictions is required.

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