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Chemical abundances in planetary nebulae and stellar evolution

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Abstract. I will review basic aspects of galactic Planetary Nebulae focussing on status of art on their chemical abundances and relationship with the stellar evolution theory.

1. Introduction

Planetary Nebulae (PNe) consist of a moderate amount of gas, typically less than $1M_{\odot}$, surrounding a central star with an effective temperature ranging from about 20,000 K up to more than 200,000 K. This wide range in T_{eff} is essentially responsible for an emission line spectrum quite different from object to object, more to my knowledge than in any other single category of astronomical objects. The number of known galactic PNe is of about $\sim$ 2000, with an estimated total of some $\sim 14,000$ (Kwok 1983).

Owing to their characteristic emission line spectrum, they can be observed to fairly distant galaxies, up to the Virgo Cluster and beyond with medium class telescopes. Presently known extragalactic PNe amount to several thousands, with most of them in the Local Group, then to 1−2 Mpc. Many are expected to be discovered with the satellite GAIA in the next years. In the following I will deal only with galactic PNe.

PNe are believed to represent an advanced evolutionary phase of stars of 0.8 to 8 solar masses, when in the Main Sequence (MS). They are important for:

1. Stellar nucleosynthesis in this mass range, which contains the so called low and intermediate mass stars, i.e. all evolved stars which do not end their life as type II SN;
2. chemical enrichment of the interstellar medium (ISM) in nuclearly processed elements as He, C, N, s-elements (Ba, etc.);
3. determining chemical gradients across spiral galaxies 'horizontally and vertically' in nuclearly unprocessed elements (as O, Ne, Ar, S, etc.) at the ages of formation of the progenitors;
4. and so obtain basic constraints for chemical evolution of galaxies, especially for spirals, particularly by combining with similar data from HII regions.

Since PNe can be seen at high distances in galaxies of different morphological types, the above items can be studied in different environments, as different ambient metallicity, a very important point. In this presentation, I will briefly : a) recall properties of macrostructures and microstructures in PNe, because their understanding is essential to understand the evolution of these objects; b) present the status of art in the knowledge of their chemical abundances, a basic tool with points 1 to 4 above and c) illustrate some comparison with predic-

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tions of stellar evolution theory from which in particular an interesting point can be made for the solar abundance of oxygen.

2. Basic morphological structures in PNe

PNe exhibit morphological structures which can be roughly separated into: Macrostructures and Microstructures. The first form the basis of a long standing morphological classification scheme in: a) Round, b) Elliptical, c) Bipolar, d) Irregular. An important work by Schwarz et al. (1993) on 255 PNe classifies in a bit different manner: 64% of them as Elliptical, 14% as Bipolar, 4% as Point-Symmetric and 18% as Irregular. In Macrostructures one can distinguish, particularly in Round/Elliptical PNe, bright inner parts from much fainter external ones. The first include components called SHELLS (single or double) and RIMS (narrow circular bright structures). The external ones contain HALOES (one or more than one). A comprehensive observational study of them is by Corradi et al. (2003)[59 PNe].

Fig. 1 contains a number of representative PNe (images are from the HST telescope). Four of them are Bipolar (easy to recognize for their reduced size normal to the major axis of their globally elliptical shape), three are Elliptical, two are Round (upper and lower right) and one is the Red Rectangle (lower middle). It is evident that the classification just indicates a dominant aspect of the morphology, not being fully mutually exclusive of other aspects, and depends to some extent from the exposure depth of the image. In Fig. 1 the images are essentially in the H−alpha line or in the forbidden [OIII] N1−N2 nebular lines.

In the same Figure a number of quite smaller scale structures are seen, particularly outstanding in NGC 7662 (lower, right), in NGC 7009 (lower left, close to the Red Rectangle) in NGC 6826 (upper left) and in NGC 6543 (middle, central). These are called Microstructures and are prominent in the light of low ionization ions, as [NII], [SII], [OI]. They are small-scale low ionization structures of various shapes named: knots, filaments, ansae, jets, jet-like, etc. They may have a relatively high velocity relative to the ambient gas and then are called FLIERS (Fast Low Ionization Emitting Regions) (Balick 1987a) or a velocity similar to that of the ambient gas and then are called SLOWERS (Slow Low Ionization Emitting Regions) (Perinotto 2000).

Properties of FLIERS in some outstanding PNe have been studied in particular by Balick and his associates (Balick et al. 1987b, 1993, 1994).

For a deep work conducted with HST data on microstructures in NGC 7662 see Perinotto et al. (2004b).

Most of them appear in all types of PNe and thus are not linked to the mechanisms of formation of the associated Macrostructures. For a comprehensive observational work on Microstructures see Gonçalves et al. (2001) [50 PNe].

2.1. Origin of macrostructures

Basic paradigma for the origin of Round and moderately Elliptical PNe is the so called Interacting Stellar Winds (ISW) theory (Mathews 1966; Kwok et al. 1978; Giuliani 1981; Icke 1988, 1991; Icke et al. 1992; Mellema et al. 1991; Mellema 1994; Mellema & Frank 1995; Mellema 1997; Marten & Schönberner 1991; Schönberner et al. 1997, 2005; Schmidt-Voigt & Köppen 1987; Kahn & Breitschwerdt 1990; García-Segura et al. 1999; Perinotto et al. 2004a).

This theory considers that most of the stellar envelope is ejected during the late pulsed AGB phase (Iben & Renzini 1983) in the so called superwind phase at velocities of ~20 km/s. This material progressively expands while the residual central star expands evolving almost horizontally to the left in the HR diagram, up to a point where T_{eff} reaches about ~30,000 K, sufficient to cause a further stellar wind with a typical velocity of 2000 km/s (fast wind). This wind has been extensively observed in central stars of PNe with the IUE satellite (Cerrutti-Sola & Perinotto 1985, 1989; Lamers et al. 1987; Patriarchi & Perinotto 1991, 1995). This wind quickly reaches the previously ejected slow wind producing a pattern which evolves under the action of the fur-

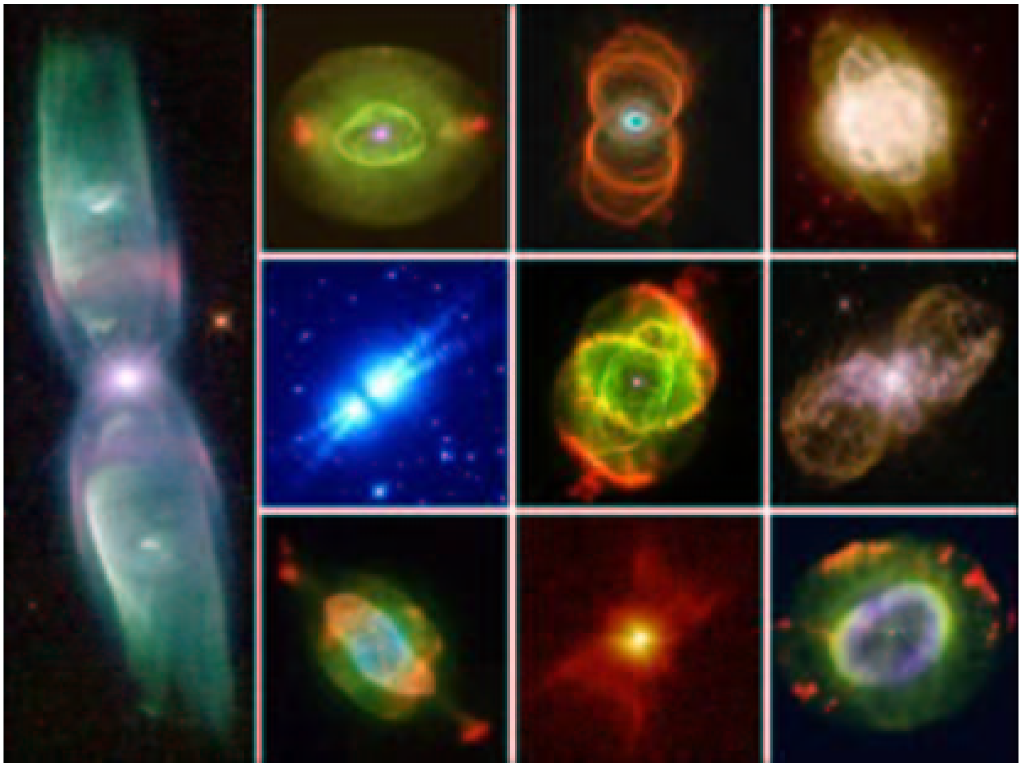

Fig. 1. Images from the HST telescope of some representative PNe.

ther arriving matter (fast wind) from the central star and of the continuously changing photon flux from the central star during its evolution towards final white dwarfs stage, following the evolutionary tracks (e.g. by Blöcker 1995).

Only in recent years it has been possible to follow in much detail the complete evolution of geometrical regular PNe, reproducing their basic macrostructures as Shells, Rings, Haloes in individual objects. Particularly successful have been the hydrodynamical studies by the group of Potsdam (Schöenberner and associates) with which we have a long standing collaboration (e.g. Marten & Schönberner 1991; Schönberner et al. 1997, 2005; Steffen et al. 1993). In this area we are presently engaged in an extensive work with the fastest supercomputers at CINECA in Bologna to follow in great detail dynamically the evolution of PNe from their origin as Proto-PNe up to their WD phase.

3. Chemical abundances in PNe

The determination of chemical abundances in PNe is an important astrophysical issue, for a number of reasons, as I have mentioned in the introduction. Due to the relative simplicity of the mechanisms responsible for the formation of the nebular emission line spectrum, determinations more accurate than feasible in stellar photospheres are believed to be achieved.

I report here on an effort we have recently made to bring the knowledge of chemical abundances in PNe to quite an high level (Perinotto et al. 2004a,, hereafter PMS2004).

This has, among others, a significant consequence for the so called discrepancy in the abundance of oxygen in most PNe relative to the solar abundance (Perinotto & Morbidelli 2006). It is known that recently (see Asplund et al. 2004) the solar photospheric oxygen abundance has been lowered by a factor of 2 relative to previous assumption (Grevesse & Andres 1989).

3.1. Methods to derive abundances in PNe

While abundances in OB Pop I stars are about the same in different objects, this is not so in PNe. Basically because they are evolved stars in a rather wide stellar mass range. There are two methods to derive abundances in PNe: a) Detailed photoionization method; b) simplified ICFs (ionization correction factors) method. In the first method the nebula is typically approximated by a spherical shell of specified inner and outer radius. The distribution of matter inside the shell must be given. And as well the properties of the central star, including its stellar spectrum, particularly in the UV beyond the Lyman limit. A complete photoionization model, for a set of trial chemical abundances in the nebula, allow to calculate the expected nebular spectrum. The comparison with the observed one, provides the set of 'observed abundances'.

In the simplified method, the nebula is approximated in spherical zones of constant electron temperature and density. Ionic abundances relative to Hydrogen are calculated from the emission line spectrum, essentially using strong collisionally excited forbidden lines for heavy ions. Te and Ne in the different zones are calculated from forbidden line intensity ratios, sensitive to these physical parameters. From the thus 'observed' ionic abundances one evaluate the atomic chemical abundances, allowing for the unobserved ionization stages via the so called ICF factors. These are calculated using a proper set of photoionization models via method a).

Method a) requires to know quantities which are poorly known in PNe, as the distance of the object, and the ionizing spectrum of the central star. Then it is understandable that chemical abundances have been determined in few objects with this method, as NGC 7662 (Flower 1969; Harrington 1969); IC 3568 (Harrington & Feibelman 1983); NGC 7027 (Middlemass 1990). By comparing abundances in these cases with those derived from method b), it has been possible to ascertain that the simplified method, if used with care, gives results of about the same accuracy than method a) (see Pottasch 1984).

I mention that method a) is physically more satisfactory than method b), but it should be improved exploring the relevance of dynamical terms. A first effort in this direction has been made by Perinotto et al. (1998).

Finally I underline that, if there are zones in PNe where T_{eff} is quite low (1000-2000 K), upper levels of the usually strong forbidden lines cannot be excited by electron collisions (CEL lines), while they can be populated by radiative recombinations with electrons. The involved atomic data are such that the heavy ions lines formed in this way (RR Lines) are much fainter than collisionally excited forbidden lines. They have however the advantage to be little sensitive to the electron temperature. Such lines have been indeed observed in recent years (Liu et al. 1995,and subsequent papers). The corresponding abundances of heavy elements are between 2 to 20 times higher than CCL abundances in the same nebulae. Present understanding of this discrepancy is that RRL abundances refer to a cold phase representing a few per cent of the mass of the nebula (Liu et al. 2001, 2004). It is then justified to neglect abundances derived this way relative to those derived from CEL lines (Perinotto & Morbidelli 2006).

3.2. New calculations of chemical abundances in PNe

We have recently noted that while a large body of good observations are presently available, essentially from the mid of the seventies when linear detectors become into operation, their analysis for deriving chemical abundances with method b) have been of rather different accuracy, because:

1. different reddening corrections were applied by different authors;
2. different ICF's;
3. different atomic data,
4. often only one ionic temperature has been used;

5. spectra obtained with different apertures had been mixed up;
6. spectra relative to different nebular zones have been averaged.

We have then considered useful not to vaste a quantity of good and costly observations. But instead to reanalyze them with a single well considered procedure. To this aim about 400 papers have been individually examined between the middle of ’70 up to end of 2001 extracting individual line fluxes. The final number of galactic PNe passing the selection procedures, has been of 131. For these PNe we have calculate new high quality homogeneous abundances (PMS2004). Moreover observational flux errors in individual lines have been propagated across the whole procedure, including the ICFs correction factors, to get objective estimates of final errors in the calculated abundances.

It’s interesting to note that with moderate efforts (4 mt class telescopes) the number of chemically well observed PNe could now be brought to 250.

4. Status of art of chemical abundances in galactic PNe

The new homogeneous abundances referred to in Section 3.2., have been analyzed in terms of relationships (correlations and anticorrelations) between individual elements in PMS2004 and compared with predictions of the stellar evolution theory.

In the following I will underline here only a couple of points on this subject.

We mention that I consider the present meeting as a good opportunity to examine in detail the status of art of chemical abundances in PNe in elements relevant to special aspects of stellar evolution theory of low and intermediate mass stars in early and late AGB phases (see in particular the invited papers by Palmerini & Busso 2007; Husti et al. 2007,in this meeting). We plan to do that shortly in cooperations with the groups of Perugia and Torino, aiming to address also new observational projects to pursue these topics.

When dealing with PNe in the context of stellar evolution, it is usual to distinguish PNe of the different classes of Peimbert (Peimbert 1978; Peimbert & Torres-Peimert 1983).

In the presently update ”Peimbert” classification, 5 types are considered:

I) He/H (by number) ≥ 0.125; or $\log(N/O) \geq -0.3$; Kinematics & Galactic distribution: resembling those of Pop I stars;
II) PNe (not He-N rich) in the solar neighborhood with an average height over the galactic plane of 150 pc;
III) PNe not belonging to the Halo with an high velocity ; Kinematics & Galactic distribution: that of Disk stars;
IV) halo PNe, i.e. at high distance from the galactic plane or belonging to Globular Clusters.

PNe of types II and III are similar in chemical composition and thus may be considered together as Disk stars. PNe of type I are related to the most massive progenitors, while those of type IV to the less massive ones. The total number of type I PNe is of the order of 102 (Perinotto 1991), that of type IV of only a dozen. Recently a type V) has been added: it contains the PNe in the Galactic Bulge.

We consider first the important positive correlations between $\log(N/O)$ and He/H, illustrated in Fig. 3 of PMS2004. The upper left panel shows the observed abundances separately for Peimbert type I and types II-III PNe. The upper right and lower left panels of the same Figure shows the expectations from the theory (Marigo 2001) for different metallicity of the progenitors stars. Plotted values indicate the predicted N/O and He/H abundances of the stellar envelope at the moment of its release from the central star, and then the predicted abundances of the ejected PN, for stars having in the Main Sequence the labelled mass. First of all note the high sensitivity of the He/H abundance ratio to the metallicity of progenitors, which makes such type of diagrams particularly interesting in the context of extragalactic PNe (not considered in the present paper).

With reference to galactic PNe, there is a general agreement of observed and expected data in this relationship, with some discrepancy at lowest and highest observed He/H

Table 1. Peimbert's types

type	Chemistry	Kinematics & Galactic distribution	Morphology	Notes
I	He/He≥ 0.125 or log(N/O)≥ 0.3	Resembling those of Pop I	Filamentary & not central symmetric; bipolar	Pop I most massive progenitors
II	average height over Galactic plane $\|Z\| > 150$pc			Intermediate Pop I Disk
III	Disk $\Delta V > 60$kms^{-1}			Similar to type II
IV	Low metals	High distance from Galactic plane or in Globular Clusters		Pop II less massive progenitors
V		in Galactic Bulge Pottash; Barlow & collaborators		

Number of known type I PNe: 32 objects (Peimbert & Silvia 1983, 1987)
102 objects (Perinotto 1991)

abundances. These indeed had been noted time ago (e.g. Perinotto 1991). At lowest He/H abundances it is known that observed He/H could well be underestimated because the relevant PNe are of quite low excitation, and since neutral He escape detection, the 'observed' elemental He could well be underestimated. The overabundance in He/H of the two PNe with high He/H, i.e. He 2-111 and and He 2-152, is not easily explained, considering that their central stars have not been reported, to our knowledge, to have Wolf-Rayet characteristic, as one might think to be the case. In spite of the general mentioned agreement, it is evident that a one to one individual comparison between observed and calculated abundances to derive e.g. the mass of the specific progenitor star in the MS is still premature. In particular the evaluation of uncertainties of theoretical abundances that we have attempted to derive from the theoretical papers is far from being satisfactory (see PMS2004). We believe instead that the accuracies of observational abundances obtained by PMS2004 are rather meaningful.

Thus we urge theoretical workers to make further efforts in this direction, which would allow to derive very important astrophysical data on low and intermediate mass stars by a closer comparison with observed abundances in individual objects, better than that presently possible.

We underline that the discussed relationship between (N/O) and (He/H) basically reflects the predictions of the second and third dredge-up processes (see Iben & Renzini 1983).

I have made an effort to collect in a single panel (Table 1) the chemical changes expected to be produced by various processes during the evolution of the progenitor stars, which originates PNe. This Table follows from discussion with persons of the theoretical group of the Department of Astronomy of the University of Padova, and is intended as just indicative.

Any mistake or unaccuracy is my responsibility. I hope that experts present in this meeting may contribute in future to improve and update this scheme, which may turn out to be useful in interpreting astrophysically observed abundances in individual PNe.

With regards to Fig. 5 upper left and to Fig. 5 lower left of PMS2004 we see at once an important point that I wish to stress here: if the abundance of solar oxygen is reduced by a factor around 2, predicted abundance of oxygen in PNe would come much closer to the observed values.

It is interesting to note than in a previous paper discussing the same topics of relationships between abundance of elements in PNe (Perinotto 1991), although based on less accurate observed chemical abundances, the suggestion was made that O/H in PNe during the stellar evolution preceding the ejection of the nebula had been reduced by a factor of 1.8, to reconcile the abundance of oxygen in PNe with that in the Sun. But at the same time it was noted that this possibility was inconsistent with other findings in HII regions. Moreover most PNe are Disk population stars, as is the Sun. Their metallicity should not then be smaller than in the Sun (as it was observed) or the Sun should be a 'peculiar' disk star, a concept not easy to accept also on historical grounds. It was then concluded that a deepening of the subject was in order.

Really the existence of an 'inconsistency' between the abundance of oxygen in the Sun and that in most PNe had been noted quite before (see Kaler 1978,and subsequent papers).

A possible solution comes indeed recently with the realization that the abundance of oxygen in the Sun had been in fact overestimated by about of factor of twe (see Asplund et al. 2004).

I must confess however that I doubt the 'story' is ended, for two reasons: i) to some extent the abundance of oxygen can anyhow be modified before and during the ABG evolution (see Table 1), ii) the near IR spectral lines of OH, on which the recent reduced solar abundance of oxygen is based, are really extremely faint.

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