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COMMENTARY ON "ELECTRON TEMPERATURES AND DENSITIES IN PNE" BY PEIMBERT (1971)

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RESUMEN

Presentamos el problema de las discrepancias encontradas en la temperatura electrónica de las nebulosas fotoionizadas cuando se determina con líneas de excitación colisional comparadas con las derivadas de la Discontinuidad de Balmer del hidrógeno. Para el caso de nebulosas planetarias (NPs) estas discrepancias fueron encontradas por primera vez por M. Peimbert en 1971, BOTT, 6, 36, 29 y han sido corroboradas en muchos estudios posteriores. Las discrepancias en temperatura están relacionadas con las discrepancias en abundancias de elementos pesados obtenidas con líneas de recombinación y líneas de excitación colisional. Las primeras son siempre mayores que las segundas, por factores entre 1.6 y 3.2, pero valores mucho mayores se han encontrado en algunas NPs. Hay dos principales propuestas que tratan de explicar estas discrepancias: (a) la presencia de fluctuaciones de temperaturas en el plasma o (b) la existencia de pequeños grumos densos, deficientes en hidrógeno y de baja temperatura, donde se emitiría la mayor parte de las líneas de recombinación. Hasta ahora no hay evidencias claras que permitan descartar alguna de las propuestas.

ABSTRACT

The discrepancies in electron temperatures in photoionized nebulae, as derived from collisionally excited lines and the hydrogen Balmer jump are presented. M. Peimbert in 1971, BOTT, 6, 36, 29 was the first in determining such discrepancies for a sample of PNe. Many authors have confirmed this result in many different samples of PNe. The discrepancies in electron temperatures are related to the discrepancies in the abundances of heavy element when derived from optical recombination lines, ORLs, or from collisionally excited lines, CELs. ORLs abundances are always larger than CELs abundances. For PNe the ratios between both abundances are in the range 1.2–3.2, but much larger values have been found in some PNe. The two main proposals trying to explain these discrepancies are: (a) the presence of temperature fluctuations in the plasma or (b) the presence of small H-deficient low-temperature inclusions, where most of the emission of ORLs would be produced. None of these proposals have been clearly demonstrated so far.

Key Words: H II regions — ISM: abundances — planetary nebulae: general

1. INTRODUCTION

Since long ago, great efforts have been devoted to study planetary nebulae (PNe) and H II regions to obtain elemental abundances in our galaxy and beyond, through the analysis of their emission lines.

In particular PNe, which are observed in all kind of galaxies (ellipticals, spirals and irregulars), are crucial to understand stellar nucleosynthesis of low-intermediate mass stars (LIMS) and the chemical evolution of galaxies, among other problems.

A detailed knowledge of the physical conditions under which the emission lines arise and a full understanding of their excitation mechanisms are of paramount importance for the reliability and accuracy of the results.

In his pioneering work that so far has accumulated more than a hundred citations, many of them in the recent years (2005–2009), Peimbert (1971) analyzed physical conditions (electron temperatures and densities) for 13 bright galactic PNe. Different diagnostic lines were used to derive physical conditions:

- Electron temperatures, $T_{\rm e}$, were calculated from collisionally excited line ratios: [O III] $\lambda\lambda$4363/5007 and [N II] $\lambda\lambda$5755/6583 and also from the ratio of the Balmer continuum (3646 Å) to the Balmer emission line intensities of the hydrogen recombination spectrum.

- Electron densities were obtained from the density sensitive line ratios [O II] $\lambda\lambda$3726/3729, [O II] $\lambda\lambda$(3727)/(7325) and [S II] $\lambda\lambda$4073/6724.

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2. RESULTS BY PEIMBERT (1971)

In Tables 1 and 3 of Peimbert (1971) we find the electron temperatures derived from forbidden line ratios and the Balmer electron temperatures. In addition, electron densities are listed in Table 2. Errors have been quoted. The results shown imply that different indicators provide different values of electron densities and temperatures. Peimbert argues that the differences are larger than the probable errors, and therefore, real differences.

And, most importantly, temperatures deduced from the Balmer continuum are systematically lower than those derived from the forbidden line ratios. This is the first paper where such a result is reported for PNe.

Peimbert (1971) interpreted these results as evidence for the presence of large spatial temperature and density variations inside the nebulae. Moreover, Peimbert argued that the spatial density variations can produce spatial temperature fluctuations.

The temperature fluctuations can be quantified in terms of the t^2 parameter, introduced by Peimbert (1967) and defined as the mean square temperature variations. In PNe such a parameter has a typical value between 0.04 and 0.07, which is much larger than predictions from simple photoionization models (e.g., Gruenwald & Viegas (1995) found t^2 typically of 0.005, in homogeneous models).

2.1. *Density inhomogeneities as possible causes of the temperature fluctuations*

Large density inhomogeneities are evident in PNe when optical high-resolution images are analyzed (see any HST image of galactic PNe, for instance). It is natural to think that all these shells, knots and filaments can produce temperature variations. However, chemically homogeneous models, with large density variations, have been computed (e.g., Mihalszky & Ferland 1989) and values of t^2 of about 0.005 much smaller than required, have been found.

2.2. *The Abundance Discrepancy Factor, ADF*

The results by Peimbert (1971) caused a lot of controversy. Many works have been devoted to analyze this subject. The differences in electron temperatures, as estimated from collisionally excited lines and from Balmer discontinuity, have been corroborated for many PNe. See for instance Figure 9 of Wang & Liu (2007), where they plotted the behavior of the temperature derived from the Balmer Jump, $T_{\rm e}$(BJ), against $T_{\rm e}$([O III]) for a sample of 25 PNe of the galactic bulge and 6 of the galactic disk. Here it is evident that most of the objects have $T_{\rm e}({\rm BJ}) \leq T_{\rm e}([{\rm O\,III}])$.

Other major dilemma, related to the one from temperatures, is that ionic abundances of several species (e.g., C^{++}, O^{++}), derived from optical recombination lines (ORL) are consistently larger than those derived from collisional excitation lines (CEL). These discrepancies are found in PNe as well as in HII regions (Peimbert et al. 1993). The discrepancy is known as the abundance discrepancy factor ADF, and it is defined as the ratio abundances(ORLs)/abundances(CELs). Typical values for PNe are in the range 1.6–3.2, but much higher values have been found in some particular objects: an ADF of 5 is reported for NGC 7009 (Liu et al. 1995); 10 is reported for NGC 6153 (Liu et al. 2000); 35, for NGC 1501 (Ercolano et al. 2004) and 71, for Hf2-2 (Liu et al. 2006).

For a sample of 86 PNe, Liu (2006) shows that ADF(O^{++}) has an average value of 2, and more important, it is directly related to the difference $T_{\rm e}([{\rm O\,III}]-T_e({\rm BJ})$, being larger for a larger difference (see Figure 1 by Liu 2006).

3. INTERPRETATION

So far, it is accepted that the discrepancies are real and not caused by errors in atomic data or observational uncertainties. It has been shown by several authors that $T_{\rm e}$ from different indicators are in general very different and it is found that $T_{\rm e}({\rm CEL}) > T_{\rm e}({\rm BJ})$. Estimates of electron temperature from ORLs indicate very low values, $T_{\rm e} \leq 1000$ K and, abundances from ORLs are, in general, larger than twice the abundances from CELs. Also it has been found that electron densities, $N_{\rm e}$ derived from CEL and BJ are not very different.

To interpret these results, there are two schools. First, Peimbert and co-workers (e.g., Torres-Peimbert & Peimbert 2003; Peimbert & Peimbert 2006, and references therein) have traditionally interpreted these discrepancies as due to temperature fluctuations and density inhomogeneities in the plasma. Torres-Peimbert & Peimbert (2003) identify at least 7 possible mechanisms that could be causing the $T_{\rm e}$ fluctuations. Among others we have:

- Mechanical energy deposited in the plasma (stellar winds, flows, asymmetrical ejections, etc. could be producing shocks and turbulence in the plasma).
- Density variations.
- Chemical inhomogeneities.
- Dust heating.

- Shadowed regions (as, for instance, those present in the Helix nebula).

According to this interpretation, Peimbert and co-workers, in several papers, have proposed that true chemical abundances in the plasma are those derived from optical recombination lines (which are only faintly dependent on electron temperature) or those abundances derived from collisional excitation lines but corrected by considering a t^2 parameter different from 0. See Peimbert (1967), Torres-Peimbert et al. (1980), Peimbert et al. (2004), and references therein, for a complete description of the procedure.

Interestingly, this implies that derived abundances are, in some cases, larger than the solar values. This occurs in PNe and HII regions as well, e.g., for the Orion nebula, Esteban et al. (2005) derived $12 + \log \mathrm{O/H} = 8.77 \pm 0.05$ from ORL. This is 0.13 dex larger than the present value accepted for the Sun (8.66 ± 0.05). The authors argue that the abundance values for Orion are in very close agreement with recent galactic chemical evolution models, which show that the present interstellar medium is about 0.13 dex richer in O than when the Sun was formed.

For PNe, in strong support of the proposition by Peimbert and co-workers, there is a recent work by Georgiev et al. (2008) where abundances are calculated for the central star and the ionized plasma in the planetary nebula NGC 6543 (nebular abundances are derived from ORLs). Both abundances coincide, showing a value $12 + \log \mathrm{O/H} \sim 9.1$ which is larger than the solar value by a factor of almost 3. The interesting point here is the consistency between nebular an stellar abundances.

The other school (see works by Liu, Barlow, Tsamis, Wesson, Zhang and others, published in 2000, 2003, 2005, 2006 and after) propose that ADFs are caused by the existence of highly He- and heavy elements enriched cold knots of material embedded in the hot plasma. That is, PNe would be extremely chemically inhomogeneous, having small H-deficient inclusions. As many HII regions also present ADFs larger than one, this would indicate the presence of similar inhomogeneities in these nebulae as well.

In this approach, ORLs would be emitted in the dense low-temperature H-deficient small inclusions (electron temperatures of about 1000 K have been proposed for these inclusions). CELs and H lines would be produced in the low-density high-temperature H-rich plasma, which would contain most of the nebular mass. This H-rich zone would not have T_e fluctuations. According to these authors the real abundances in nebulae would be closer to those in the H-rich zone (given by CELs), as the abundances derived from the ORLs are too large for PNe. Liu (2006) shows that O/H abundances deduced from ORLs are higher than the solar value for almost all the analized galactic PNe, up to a factor of 25 in the most extreme case. This is difficult to reconcile with current theory of stellar evolution for low- and intermediate-mass stars.

There are several scenarios proposed as the origin of the H-deficient inclusions. For instance:

- Ejections from born-again H-deficient stars (Iben et al. 1983). However, Wang & Liu (2007) argue against this possibility, as they found that C/O ratios derived from ORLs and CELs are similar.
- Evaporating planetesimals (Liu 2003).
- Novae (as it seems to be the case for A30, A78, A58 and others, Wesson et al. 2003, 2008).

It has been suggested that these H-deficient zones with such low temperatures, should present differences in their line widths, relative to the H-rich zones. Also differences in velocities could be detected, due to H-deficient inclusions would have been ejected from the star at higher velocity than the main body of the nebula. Present works devoted to these subjects are searching for these evidences.

4. THE NEBULAE AROUND [WC] CENTRAL STARS: ARE THEY CHEMICALLY INHOMOGENEOUS?

About 15% of galactic PNe are ionized by [WC] stars. These are H-deficient stars suffering strong atmospheric instabilities which produce huge stellar mass-loss similar to those in massive WR stars. [WC] central stars are He, C and O rich, showing in their atmospheres the abundances resulting from stellar nucleosynthesis. We are seeing the bared nucleus of the star in these objects. As a consequence of the C and He-rich stellar wind one could expect large inhomogeneities in the nebular material. Large H-deficient knots of this type are observed for instance in the highly evolved PNe A30 and A78, both with a H-deficient nucleus.

So far, very few planetary nebulae around [WC] stars have been analyzed searching for evidence of large ADFs. Ercolano et al. (2004) analyzed in detail the case of NGC 1501, ionized by a [WC4] star. The central star present photospheric mass-fraction abundances He:C:O of 36:48:16, therefore it is a He-C star. The nebula shows large ADFs of 32 and 33 for O^{++} and Ne^{++}, respectively. Ercolano et al. argued that the presence of a H-deficient metal-rich component is necessary to explain them.

García-Rojas et al. (2009) have computed detailed abundances from CELs and ORLs for two PNe ionized by a [WC] central star: NGC 2867 ([WC4] central star) and PB8 ([WC8] central star). The stars themselves have been analyzed and their surface abundances determined. In NGC 2867 the star presents a He:C:O mass-fraction abundances of 65:26:9 (Todt et al. 2008). Then, it is a He-C star with C/O = 3.2 (by mass). For PB8, the He:C:O mass-fraction abundances of the star are 82:1:1. This is a Helium star with 15% of H and C/O=1.3 (Todt et al. 2010). Therefore He and C-rich inclusions, and thus very low temperature knots in the nebulae, would be expected for these objects. García-Rojas et al. (2009) determined relatively modest ADF(O^{++}) values for these objects: 2.57 for PB8 and about 1.57 for NGC 2867 and temperature fluctuation parameters, t^2, of 0.03 and 0.044, respectively. The ADF values are in the range of typical ADFs observed in PNe. Also they found that C/O(ORL) / C/O(CEL) ratios are smaller than 1 in both nebulae. These results are against the presence of "C-rich knots ejected in a late thermal pulse" in these objects even when the central stars are H-deficient.

5. CONCLUSIONS

The discrepancy between electron temperatures, as derived from CELs (T_e([O III]) and from hydrogen Balmer jump to hydrogen Balmer line intensities (T_e(BJ)) in PNe, has been known since long (Peimbert 1971). T_e(BJ) are systematically lower than T_e([O III]. It has been shown that this discrepancy is related to the discrepancies in abundances as derived from ORLs and CELs. Abundances from ORLS are always larger than those derived from CELs, this ratio is known as ADF. Similar to PNe, most HII regions also present ADFs larger than one, therefore similar mechanisms should be required to explain the same phenomenon in both type of nebulae.

We have presented the two main different views trying to explain these discrepancies. Peimbert and co-workers, in several papers since 1967, have proposed that temperature fluctuations in the plasma could be responsible for both discrepancies. They suggest that the real abundances in the plasma are those derived from ORLs, or those derived from CELs but considering a temperature fluctuation parameter, t^2, different than cero.

The other proposition suggests that plasma in PNe is highly inhomogeneous, containing H-deficient low-temperature high-density inclusions. ORLs would be originated mainly in these cold inclusions, while CELs are emitted in the low-density hot plasma. These authors consider that abundances from ORLs may not reflect the bulk composition of the nebula, which would be closer to the one derived from CELs.

So far there are not clear evidences in favor of any of the propositions. Temperature fluctuations have not been detected in some well analyzed objects nor H-deficient inclusions are evident in the analyzed objects, except for the well known cases of A30, A78 and A56, where the large C-rich knots might be the results of nova type explosions. It is worth notice that, even when H-deficient inclusions could be expected in PNe ionized by a [WC] central star, García-Rojas et al. (2009) did not detect such a type of inclusions in two of these objects, although they could be present in NGC 1501, ionized by a [WC 4] star, which shows a very large ADF (Ercolano et al. 2004).

Both views on these discrepancies have their own predictions that should be tested with much better and deep data. Studies of a larger number of objects is required for a more conclusive analysis.

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