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ARE TEMPERATURE FLUCTUATIONS OUT THERE?

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RESUMEN

Los efectos de las fluctuaciones de temperatura sobre el espectro de las nebulosas ionizadas fueron estudiados por primera vez por Peimbert (1967). Desde entonces, su existencia real en nebulosas es todavía una cuestión abierta pues disponemos de observaciones y resultados teóricos a favor y en contra de tales fluctuaciones. En el presente trabajo revisamos las distintas evidencias disponibles, los mecanismos que pueden producir las fluctuaciones y su posible presencia y efectos en objetos extragalácticos.

ABSTRACT

The effect of temperature fluctuations in the spectra of ionized nebulae was firstly explored by Peimbert (1967). Since then, the problem of their existence has remained an open question. In fact, there are observations and models that argue both in favor and against such fluctuations and these are reviewed in this paper. We also discuss the mechanisms that could produce such fluctuations and their possible presence and effects in extragalactic objects.

Key Words: **H II REGIONS — ISM: ABUNDANCES — PLANETARY NEBULAE**

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1. INTRODUCTION

Gaseous nebulae are complex systems and not simple Strömgren spheres. Spatial variations in density and the ionization stratification may naturally produce spatial variations of electron temperature. The emissivity of the different components of the nebular spectrum depend differently on the temperature: recombination lines (hereinafter RLs) and continua depend on a power of the temperature; however collisionally excited lines (hereinafter CELs)—which are so bright in nebulae—depend more strongly, in an exponential form. Therefore, if spatial variations of electron temperature are present inside a nebula they should affect somehow the observed spectrum.

Peimbert (1967) was the first who explored the effects of temperature fluctuations in the derivation of nebular abundances. He introduced a new formalism based on two parameters: the average temperature,

$$T_0(N_{\rm i}, N_{\rm e}) = \frac{\int T_{\rm e} N_{\rm e} N_{\rm i}\, dV}{\int N_{\rm e} N_{\rm i}\, dV}, \qquad (1)$$

and the mean square temperature fluctuation,

$$t^2 = \frac{\int (T_{\rm e} - T_0)^2 N_{\rm e} N_{\rm i}\, dV}{T_0^2 \int N_{\rm e} N_{\rm i}\, dV}. \qquad (2)$$

With these parameters the emissivities of emission lines or continua can be written as Taylor series about T_0.

Photoionization models of chemically and density homogeneous nebulae give typical values of $t^2 \sim 0.01$ (Garnett 1992; Gruenwald & Viegas 1992; Kingdon & Ferland 1995). These results have led many authors to adopt $t^2 = 0.00$.

2. PRACTICAL DETERMINATION OF t^2 AND SOME RESULTS

We need two different methods to derive $T_{\rm e}$ in order to determine T_0 and t^2; one weighting preferentially the high temperature regions (with strong dependence on $T_{\rm e}$: CELs) and one weighting preferentially the low temperature regions (with weak dependence on $T_{\rm e}$: RLs or recombination continua).

The most common procedure is to compare T([O III]) obtained from the λ4363/5007 ratio and T(Bac) determined from the ratio of the Balmer continuum discontinuity and the intensity of a Balmer line. The comparison of both quantities has been carried out for several Galactic objects and T([O III]) is larger than T(Bac) in most cases (Peimbert & Costero 1969; Peimbert 1971; Peimbert et al. 1992; Liu & Danziger 1993) as it is expected if temperature fluctuations are present. However, using this method, some authors obtain very low or negligible t^2 for Orion nebula (Liu et al. 1995; Esteban et al. 1998) and some planetary nebulae, PNe (Peña et al. 1998). These discrepancies are not strange because the determination of T(Bac) is rather difficult. Firstly, the determination of the continuum redwards the Balmer discontinuity could be affected by blending of the Balmer lines. This can be avoided obtaining high-resolution spectra. Secondly, the continuum can be contaminated by other emissions, as He I continuum, sky background and scattered light. Liu & Danziger (1993) have estimated that the statistical uncertainty of T(Bac) determination is of the order of 18%.

Peimbert, Luridiana, & Torres-Peimbert (1995a) introduce another method for estimating t^2 based on the determination of T(He II). These authors obtain that the He^+/H^+ ratios based on different He I lines come into agreement when considering collisional and optical depth effects as well as the presence of t^2. Peimbert et al. (1995a) find that T(He II) is always considerably smaller than T([O III]) for a sample of PNe, as it is expected if temperature fluctuations are present. Peimbert et al. (2000) obtain a similar result for NGC 346, an H II region in the SMC. In this case the values of T(He II) and T(Bac) are almost coincident.

Results from grids of photoionization models (Kingdon & Ferland 1995) indicate that the t^2 obtained from the comparison of T([O III]) and T(Bac)—it may be also applied for T(He II)—is not correlated with the t^2 determined from theory. This is because t^2 depends on the ion, and has different values for two ions that are not coextensive, such as H^+ (or He^+) and O^{++} (Gruenwald & Viegas 1992; Kingdon & Ferland 1995).

Another method to estimate t^2, which avoids the aforementioned problem of non coextensive ions, is the comparison of temperatures obtained from emission line ratios of the same ion coming from upper levels of different excitation energy. For example, the combination of FIR fine-structure and optical lines of [O III]. The excitation energy of the fine-structure lines is very small so their strengths are insensitive to T_e; in contrast the auroral lines are extremely sensitive. The most common procedure is to compare values of T_e obtained from [O III] λ4363/5007 and λ5007/52μm ratios. Dinerstein et al. (1985) combine KAO data and integrated optical line fluxes for 6 PNe. They find that the temperatures inferred from the optical line ratios are systematically higher than those inferred from the combination of optical and FIR lines. They obtain a mean value of $t^2 = 0.04$ as a representative for the group. However, more recent similar observations have reported $t^2 \sim 0.00$ for several PNe (Dinerstein et al. 1985; Rubin et al. 1997; Liu et al. 2000). This procedure has the inherent problem of the combination of different instrumentation and apertures for FIR and optical observations. Flux calibration is potentially the main source of uncertainty of this method.

An important observational fact in many ionized nebulae is that ionic abundances from RLs are systematically higher than abundances from CELs of the same ion. This abundance discrepancy was firstly addressed as a possible effect of temperature fluctuations by Torres-Peimbert et al. (1980). C^{++} and O^{++} are the most commonly used ions for this comparison because they have RLs and CELs that can be observed in the UV/optical range. The abundance discrepancy is as large as a factor of 5 or even 20 in some PNe.

3. THE ABUNDANCE DISCREPANCY

Several reasons have been proposed to explain the abundance discrepancy in ionized nebulae: (a) systematic errors in the measurement of the intensity of weak lines; (b) errors in the atomic parameters or unknown excitation mechanisms affecting the line strengths; (c) temperature (or density) fluctuations; and (d) chemical inhomogeneities.

Several authors (Rola & Pelat 1994; Rola & Stasińska 1994; Kholtygin 1998) have claimed that the intensity of emission lines with low S/N (such as RLs of heavy elements) tends to be systematically overestimated in spectroscopic works. However, recent deep high-resolution observations are providing measurements of RLs with relatively high S/N ratio. Mathis & Liu (1999) have performed a useful comparison in this sense; these authors have found that, for a sample of PNe where O II lines have been measured, the observed [O III] λ4391/4959 ratio is very close to the theoretical prediction. Taking into account that the intensity of the O II λ4649 line—the brightest line of multiplet I of O II—is of the order of [O III] λ4391, this indicates that there is no systematic overestimation of line strengths of RLs in the recent sets of observations.

Another important fact is that the atomic parameters of the two most commonly used ions, C^{++} and O^{++}, seem to be well-determined. Moreover, there is no evidence for unknown excitation mechanisms for the lines involved in the comparisons. A proof of the consistency of the abundance determination from RLs and CELs is that the average value of C^{++}/O^{++}(RLs) over C^{++}/O^{++}(CELs) ratio is 1.2 ± 0.6 for a large sample of objects taken from Mathis et al. (1998), Liu et al. (1999), and Esteban et al. (1998; 1999a,b) independently of the degree of the abundance discrepancy of the nebulae. Another useful test is that abundances from lines of the same multiplet and from different multiplets of the same ion agree for several objects (Esteban et al. 1998; Liu et al. 1999). All this evidence strongly suggests that the standard physics of RLs is essentially correct.

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As it has been commented above, Torres-Peimbert et al. (1980) were the first to propose that the abundance discrepancy may be produced by t^2. In fact, while the ratio of two RLs is almost independent of T_e, the ratio of a CEL with respect to a RL is strongly dependent on it. Therefore, the comparison of the abundance determined from both kind of lines for a given ion should provide an estimation of t^2.

The possible relation between the abundance discrepancy and t^2 in H II regions has been investigated by Esteban et al. (1998, 1999a, and 1999b) who obtained echelle spectrophotometry for the bright Galactic H II regions M42, M8 and M17. They obtained the abundance from RLs and CELs for several ions in one or two slit positions for the three objects, finding that the abundance discrepancy is rather modest (between 1.2 and 2.2) for that group of nebulae. The results of these studies are very consistent, in the sense that the t^2 values obtained from different ions for the same slit position and the same object are remarkable similar, suggesting that the abundance discrepancy is related to t^2. In general, the values of t^2 found are not very high, in the range 0.018–0.044. Another important result by Esteban et al. (1998) is that only with the assumption of $t^2 > 0.00$ the CNO abundances of the Orion nebula are in good agreement with the CNO abundances of the B stars of the Orion association. Another important conclusion by Esteban et al. (1999b) is that the radial gradients for N, O, Ne, S, Cl, and Ar derived from the data of the three H II regions become remarkable similar only when $t^2>0.00$ are considered. Therefore, all these results suggest that the standard scheme of temperature fluctuations "a la Peimbert" seems to be appropriate for Galactic H II regions.

In the case of PNe, the relation between the abundance discrepancy and t^2 is not so clear. Peimbert, Torres-Peimbert, & Luridiana (1995b) determine $T(\mathrm{C}^{++})$ by combining C III] λ1906+1909 with C II λ4267 line intensities for a large sample of PNe, finding that $T(\mathrm{C}^{++})$ is considerably smaller than T([O III]). This difference is expected if temperature fluctuations are present in the nebulae.

In a series of excellent papers, Liu and collaborators have obtained echelle spectrophotometry for a large number of PNe (Liu et al. 1995; Liu 1998; Liu et al. 1999; Liu et al. 2000). They find some relevant observational results pointing out the problems that the standard scheme of t^2 faces to explain the abundance discrepancy in the case of PNe. They find that: (a) the values of t^2 obtained from the comparison of T([O III]) and T(Bac) cannot account for the large abundance discrepancies derived; (b) the variation of T([O III]) along the slit for two objects (2 arcsec^2 of resolution) has an amplitude of the order of 1000 K, this value leads to very small t^2; and (c) there is no correlation between the abundance discrepancy and the excitation energy of the upper levels of the lines. In particular, the FIR fine-structure lines, which are almost insensitive to T_e, yield abundances very similar to those given by the UV and optical CELs.

A direct evidence that the temperature fluctuations are not large in some PNe is obtained by Lame et al. (1997) who have obtained the map of T([O III]) from *HST* images of NGC 6543. They find that the variation of T([O III]) is only about 12%, which gives a much lower t^2 than the value of 0.057 obtained by Kingsburgh et al. (1996) from the abundance discrepancy of O^{++}.

Therefore, the aforementioned evidences do not support the standard scheme of temperature fluctuations as the main cause of the large abundance discrepancy observed in many PNe.

4. THE ORIGIN OF TEMPERATURE FLUCTUATIONS?

Several mechanisms have been proposed to explain the presence of temperature fluctuations and/or the observed abundance discrepancies in nebulae: (a) presence of high-density condensations; (b) chemical inhomogeneities; (c) contribution of shock excitation; (d) contribution of conduction fronts; and—very recently—(e) magnetic reconnection (see Ferland et al. 2002).

Viegas & Clegg (1994) proposed that in the presence of condensations with densities higher than the critical density of the nebular lines of [O III] (7×10^5 cm^{-3}), those lines are collisionally de-excited but the auroral line (which has a larger critical density of 2.5×10^7 cm^{-3}), is not. As a result, the T([O III]) may be overestimated and $\mathrm{O}^{++}/\mathrm{H}^+$ underestimated. These authors propose that the use of density indicators involving ratios of lines with higher critical density (as [O II] λ7325/3727 and [S II] λ4079/6725) and their comparison with the traditional density indicators could betray the presence of those dense clumps. In this sense, Mathis et al. (1998) have compiled data for a sample of 10 PNe with large abundance discrepancies, finding that the comparison of the [O II] λ7325/3727 and [O II] λ3726/3729 ratios does not indicate the presence of high-density clumps in those objects. Also, Liu (1998) and Liu et al. (2000) do not find evidences of very dense clumps in the PNe NGC 4361 and NGC 6153 respectively. However, positive evidences of high-density clumps have been reported by other authors. From *HST*

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observations, Torres-Peimbert et al. (2002) have determined that PN M 2-29 has at least two density components, one with low density ($N_e = 10^4$ cm^{-3}) and lower temperature than observed from ground-based observations, and another with much higher density ($N_e = 10^6$ cm^{-3}). Moreover, the O/H ratio obtained from ground-based observations is a factor of 10 smaller than the value derived by Torres-Peimbert et al. (2002) adopting the two density component model. Walsh & Rosa (1999) have obtained *HST*/FOS data for Orion nebula, and have found a wide range of T_e and N_e for proplyds and filaments embedded in the H II region, the contribution of these objects might be able to explain the observed values of t^2 in this object.

Torres-Peimbert et al. (1990) proposed that the presence of chemical inhomogeneities could be a possible origin of t^2 in PNe. In recent papers, Liu et al. (2000) and Péquignot et al. (2002) suggest a possible scenario based on the observed properties of the so-called "born-again" PNe. The scenario is basically the following (for a much more detailed description see paper by Péquignot et al. 2001): RLs are mostly emitted by a population of high-density, metal-rich, and low-temperature condensations produced by recent ejections of stellar material; these clumps are embedded in a diffuse, low-density, high-temperature gas of "normal" metal abundances, which is responsible of most of the emission of CELs. However, a serious problem of this scenario is that it cannot explain that the ionic abundance ratios obtained from RLs and CELs are the same. There is no known nuclear process that produce H-deficient material preserving the heavy-element ratios of the original material.

Peimbert, Sarmiento, & Fierro (1991) explored the effects of shock waves on the spectra of ionized nebulae. They showed that large temperature fluctuations could arise in giant H II regions including SNRs. Using composite models of shocks and H II regions, these authors find that the net effect of the shocks is the increase of the intensity of the auroral lines, in particular [O III] λ4363 while the nebular lines remain unaffected, this produces an overestimate of T_e and an underestimate of the abundances. There are some evidences indicating that the presence of shocks could be affecting the spectral properties of several PNe. Peimbert et al. (1995b) found that those PNe with larger differences between T(O^{++}) and T(C^{++}) are precisely of Type I and show complex gas motions (some of them with velocities larger that 100 km s^{-1}) indicating the presence of shock waves. Another indication of the presence of shock contribution is in the results by Liu (1998) for NGC 4361, who find a correlation between the spatial variation of T([O III]) and the radial velocity and width of He II λ4686 line.

The effect of the contribution of conduction fronts in nebular spectra has been investigated by Maciejewski et al. (1996). These fronts arise in the conductive transition layer between the visible plasma and very hot gas of shocked stellar wind that presumably confines the visible plasma in many ionized nebulae. The effect of these fronts on the spectra is qualitative similar to the shocks. However, estimations by Maciejewski et al. (1996) predict that the increase of [O III] λ4363 is not enough to explain the observed t^2 in the Orion nebula. Therefore, the required number of interfaces is so large that this effect is probably implausible.

5. t^2 IN EXTRAGALACTIC REGIONS

The presence of t^2 in the extragalactic H II regions, is even a more controversial question than in Galactic ones. The first indirect evidence pointing out in this sense was the significant differences between the O/H ratios obtained using the R_{23} empirical calibration based on models and on observations. The differences are in the 0.2 dex to 0.4 dex range. Several authors claimed that such differences could be due to the presence of temperature inhomogeneities over the observed volume (Campbell 1988; Torres-Peimbert et al. 1989; McGaugh 1991). It is worth noting also that Peimbert et al. (1991) indicate that, in the presence of processes increasing the intensity of [O III] λ4363 line (shocks for example) R_{23} is unaffected. Therefore, if t^2 are present in a given object, the abundances obtained from the empirical calibration based on R_{23} should provide a more confident estimation of O/H than the direct determination neglecting such fluctuations.

There are few estimations of t^2 available for extragalactic objects. González-Delgado et al. (1994) find large values of t^2 = 0.064–0.098 for the giant extragalactic H II region (GEHR) NGC 2363 from the comparison of T([O III]) and T(Pac). Moreover, Luridiana et al. (1999) have computed photoionization models for this GEHR and compare them with optical observational data. They reproduce the observed emission-line spectrum and other properties of NGC 2363 only with models assuming a metallicity 2.5 times higher than usually adopted. Luridiana et al. (1999) propose that the presence of temperature fluctuations can explain these facts. Another positive estimation is obtained by Peimbert et al. (2000) who find t^2=0.022 for NGC 346 from the comparison of T([O III]) and T(Bac) and a self-consistent

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determination of T(He II). However, Terlevich et al. (1996) obtain t^2~0.00 for NGC 604 also from the comparison of T([O III]) and T(Pac).

Additional indications of the possible presence of t^2 in GEHR and starburst galaxies have been given by Esteban & Peimbert (1995) and Pérez (1997). Esteban & Peimbert (1995) studied the chemical enrichment produced by massive stars in Wolf-Rayet galaxies, finding that the apparent abnormal position of some of these objects in O vs. Y and N vs. Y diagrams can be explained by the effect of large t^2 in the ionized gas associated with the intense star-forming bursts. Pérez (1997) has investigated the change of the ionization structure during the first Myrs of the evolution of a starburst. He has shown that large temperature fluctuations arise naturally in homogeneous gaseous spheres when the spectral energy distribution of the ionizing cluster hardens at about 3 Myr, coinciding with the onset of the Wolf-Rayet phase.

In a recent review, Stasińska (2000) has discussed the problems that detailed photoionization models face to reproduce the observed [O III] λ4363/5007 ratio of several GEHRs classified as Wolf-Rayet galaxies (García-Vargas et al. 1997; Luridiana et al. 1999; Dufour et al. 1988; Stasińska & Schaerer 1999). The models always predict lower ratios than observed. In the case of I Zw 18, Stasińska & Schaerer (1999) obtain a temperature discrepancy of the order of 30%, which is a rather large value. Stasińska (2000) considers that the classical photoionization models fail and that temperature fluctuations produced by an unknown process could be present in these objects.

Although the evidences are indirect and still scarce, the possibility that t^2 are present in GEHRs may have important consequences in various fields of astrophysics, mainly because most of our knowledge about the chemical content of extragalactic objects comes from the spectra of GEHRs. One of the most dramatic consequences of large t^2 in GEHRs is the determination of primordial helium ($Y_{\rm p}$). Steigman et al. (1997) have explored how the presence of t^2 can affect the determination of $Y_{\rm p}$ in low-metallicity extragalactic H II regions. The net effect is the flattening of the Y vs. Z relation, resulting in a higher inferred value of $Y_{\rm p}$ when t^2 are neglected. In fact, Peimbert et al. (2000) have obtained a relatively low value of $Y_{\rm p}$ (0.2345 ± 0.0026) taking into account the effects of temperature fluctuations in a sample of GEHRs from the literature.

6. FINAL REMARKS

We would like to finish with some personal remarks, which will try to give some kind of answer to the ambitious question posed in the title of the present paper.

In the case of H II regions, we think that the observational results are very consistent indicating that the abundance discrepancy seems to be well correlated with t^2. Temperature fluctuations may be responsible of the differences between the abundances obtained from RLs and CELs. The values of t^2 for Galactic H II regions seem to be rather modest and this facilitates the explanation of their origin. Taking into account the properties of H II regions, we consider reasonable that a combination of density condensations (filaments, globules, proplyds, ...) and shock excitation due to stellar winds could be a major contributor to the values of t^2 reported.

The situation for PNe is much more confusing. Taking into account the results by Liu and collaborators, the standard scheme of t^2 seems to be not appropriate to explain the observed properties. Firstly, the strong abundance discrepancy that some of these objects suffer seems to be not correlated with t^2 (in contrast with the results for H II regions) and the origin of the discrepancy should be, at least partially, due to the action of other phenomena. The presence of chemical inhomogeneities, perhaps in the way proposed by Liu and Péquignot, could be a solution, but further efforts are needed to construct a coherent model. PNe as a group is a mixed-bag of objects with different structure and origin. The different behavior that these objects show in their abundance discrepancy and estimated t^2 may be the reflection of this diversity. Different mechanisms as chemical inhomogeneities, shock excitation due to the stellar wind, and density condensations could be acting in varying combinations in each PNe depending perhaps on their morphological type, origin, and progenitor.

GEHRs are large and very complex systems. They have a hard and evolving ionizing radiation field and the temperature stratification should be important. They show clear spatial density variations, which are reflected in their tortured morphology, dominated by filaments and loops of ionized gas. The contribution of shock excitation must be important due to the presence of the powerful stellar winds of massive stars and supernova explosions. The presence of shocks is suggested not only by their morphology but also by their complex kinematics. Therefore, one may suspect that temperature fluctuations may be present and could have important consequences in the spectra of these objects.

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