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THE TEMPERATURE STRUCTURE IN IONIZED NEBULAE AND THE CHEMICAL EVOLUTION OF GALAXIES

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RESUMEN

Discutimos algunos resultados que indican la presencia de variaciones de temperatura en nebulosas gaseosas. La evidencia se basa en: a) temperaturas obtenidas a partir de métodos diferentes, y b) en la comparación de abundancias predichas por modelos de evolución química de galaxias con abundancias determinadas a partir de observaciones.

ABSTRACT

A few results that indicate the presence of temperature variations in gaseous nebulae are reviewed. The evidence is based on: a) temperatures derived from different methods, and b) on comparisons of abundances predicted by models of galactic chemical evolution with abundances derived from observations.

Key Words: **GALAXIES: ABUNDANCES — GALAXIES: EVOLUTION — H II REGIONS — PLANETARY NEBULAE**

1. OVERVIEW

To constrain models of stellar evolution and of chemical evolution of galaxies it is necessary to derive accurate abundances from gaseous nebulae. Inversely, it might be possible to constrain the assumptions made to derive the abundances from gaseous nebulae based on robust models of stellar evolution and of chemical evolution of galaxies.

The determination of the chemical abundances in gaseous nebulae depends strongly on their temperature structure. By adopting the temperature derived from the 4363/5007 [O III] ratio and assuming that the temperature is constant it can be shown that in the presence of temperature variations the abundances are overestimated (Peimbert 1967; Peimbert & Costero 1969). Typical overestimates of the O/H abundances are in the 1.4 to 3.0 range, with extreme cases reaching overabundances of an order of magnitude.

We compare the predicted abundances based on models of galactic chemical evolution with the abundances derived under the assumption of: a) a constant temperature distribution and b) the presence of temperature fluctuations. We conclude that significant temperature variations are present in gaseous nebulae.

Recent reviews on the temperature structure of gaseous nebulae are those of Esteban (2002), Stasińska (2002) and Peimbert (2002). Recent reviews on the abundances of galactic and extragalactic H II regions are those by Skillman (1998), Peimbert (1999, 2002), Garnett (1999) and Peimbert, Carigi, & Peimbert (2001).

2. TEMPERATURE STRUCTURE

We can characterize the temperature structure of a gaseous nebula by two parameters: the average temperature, T_0, and the mean square temperature fluctuation, t^2, given by

$$T_0(N_e, N_i) = \frac{\int T_e(\mathbf{r}) N_e(\mathbf{r}) N_i(\mathbf{r}) dV}{\int N_e(\mathbf{r}) N_i(\mathbf{r}) dV}, \qquad (1)$$

and

$$t^2 = \frac{\int (T_e - T_0)^2 N_e N_i dV}{T_0^2 \int N_e N_i dV}, \qquad (2)$$

respectively, where N_e and N_i are the electron and the ion densities of the observed emission line and V is the observed volume (Peimbert 1967).

For a nebula where all the O is twice ionized we can derive T_0 and t^2 from the ratio of the [O III] $\lambda\lambda$ 4363, 5007 lines, $T_e(4363/5007)$, and the temperature derived from the ratio of the Balmer continuum to $I(\mathrm{H}\beta)$, $T_e(\mathrm{Bac/H}\beta)$, that are given by

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$$T_e(4363/5007) = T_0\left[1 + \frac{1}{2}\left(\frac{90800}{T_0} - 3\right)t^2\right], \quad (3)$$

and

$$T_e(\mathrm{Bac/H}\beta) = T_0(1 - 1.70t^2), \quad (4)$$

respectively.

It is also possible to use the intensity ratio of a collisionally excited line of an element $p + 1$ times ionized to a recombination line of the same element p times ionized, this ratio is independent of the element abundance and depends only on the electron temperature. In this review we will adopt the view that the C II 4267 and the O II permitted lines of multiplet 1, are produced by recombination only and consequently that other mechanisms like radiative transfer, collisions, and fluorescence do not affect their intensities.

When oxygen is present both in the form of O^{++} and O^{+}, then there will be different T_0 and t^2 values for the O^{++} and the O^{+} zones. A full analytic treatment to second order of this case can be found in Peimbert, Peimbert, & Luridiana (2002).

The comparison of $T_e(4363/5007)$ with $T_e(\mathrm{Bac/H}\beta)$ in planetary nebulae clearly indicates that $t^2 > 0.000$ and that the temperature structure needs to be taken into account to determine the abundances (e.g. Peimbert 1971; Liu et al. 2001; Liu 2002 and references therein).

In H II regions an important fraction of the volume is in the form of O^{+}, and $T_e(\mathrm{Bac/H}\beta)$ has to be compared with a temperature derived from a weighted average of collisionally excited lines in the O^{+} and O^{++} zones. From photoionization models for H II regions by Stasińska (1990) the O^{+} zones are expected to be hotter than the O^{++} zones for objects with $T_0 < 12400$ K, which is the case for galactic H II regions of the solar vicinity, prediction that has been confirmed by observations (Esteban et al. 1998, 1999a, 1999b). From a comparison of $T_e(\mathrm{Bac/H}\beta)$ with a weighted average of colisionally excited lines in the O^{+} and O^{++} zones it is also found that $t^2 > 0.000$.

A large number of papers have been presented in favor and against the idea that the recombination lines of heavy elements can be used to derive the chemical abundances of gaseous nebulae. A strong argument in favor that they are representative of the abundances of gaseous nebulae is given by the work of Liu et al. (2001) where they find a very strong correlation between the O^{++} abundance ratio derived from the O II to [O III] lines and the $T_e(4363/5007) - T_e(\mathrm{Bac/H}\beta)$ values, this correlation has been studied further by Peimbert & Peimbert (2002) who find that it can be explained quantitatively as being due to temperature fluctuations.

From observations it has been found that $0.01 \leq t^2 \leq 0.09$, with typical values around 0.04; while from photoionization models of chemically and density homogeneous nebulae it has been found that $0.000 \leq t^2 \leq 0.020$, with typical values around 0.005. An explanation for the differences in the t^2 values predicted by photoionization models and those found by observations has to be sought (see Torres-Peimbert & Peimbert 2002).

3. O/H IN THE ORION NEBULA AND THE SUN

The determination of the O/H value is paramount for the study of chemical evolution for at least three reasons: a) O is the most abundant heavy element, it comprises about 50% of the heavy elements, b) it is easily observed in the main ionization stages of H II regions and planetary nebulae, c) its atomic physics parameters have been determined with high precision, and d) practically all of it has been produced by supernovae of Type II, therefore in chemical abundance models can be treated under the instant recycling approximation.

A decade ago the O/H solar abundance in the literature was 0.44dex higher than in the Orion nebula (see Table 1), a result of great concern because from galactic chemical evolution models the Orion nebula O/H value is expected to be about 0.05dex higher than the solar value, if the Sun was formed at the same galactocentric distance than the Orion nebula (e. g. Carigi 1996). Note that the Orion nebula is about 0.4kpc farther away than the Sun from the galactic center, and from an O/H gradient of -0.05dex kpc^{-1}, a correction of about 0.02dex has to be made if the Sun were in a circular orbit; nevertheless this correction might be compensated by the ellipticity of the solar orbit that probably implies that the Sun was formed at a larger galactocentric distance, about 0.5 to 1kpc farther away from the galactic center than its present position.

At present the best Orion nebula O/H value in the literature is 0.02dex higher than the solar value, the difference between models and observations is well within the observational errors. The change in the last ten years is due to two recent results for Orion and two for the Sun: a) the 0.15dex increase in the O/H value derived from recombination lines (which implies a $t^2 = 0.024$) relative to that derived from forbidden lines assuming that $t^2 = 0.000$, b) the increase in the Orion O/H value of 0.08dex due

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TABLE 1

ORION AND SOLAR OXYGEN ABUNDANCES

	Orion Nebula[a]	Sun[a]
1980's	8.49[b] ($t^2 = 0.000$, gas)	8.93[d]
1998	8.64[c] ($t^2 = 0.024$, gas)	8.83[e]
now	8.72[c] ($t^2 = 0.024$, gas + dust)	8.73[f]
		8.69±0.05[g]

[a] Given in log O/H + 12.
[b] Shaver et al. 1983; Osterbrock et al. 1992; Rubin et al. 1993; Deharveng et al. 2000.
[c] Esteban et al. 1998.
[d] Grevesse & Anders 1989.
[e] Grevesse & Sauval 1998.
[f] Holweger 2001.
[g] Allende-Prieto et al. 2001.

to the fraction of oxygen embedded in dust grains, and c) the decrease of 0.23dex due to two new solar determinations (see Table 1).

4. ABUNDANCE GRADIENTS IN OUR GALAXY

In Table 2 we present average gradients for gaseous nebulae based on results by many authors (see reviews by Esteban & Peimbert 1995, Maciel 1997, Peimbert 1999 and references therein), most of the gradients have been determined from colisionally excited lines. The values come from H II regions of the solar vicinity and for O, Ne and S were derived from more than 40 objects. The planetary nebulae values by Maciel & Quireza (1999) were derived from a data set of 130 planetary nebulae of Type II. Rolleston et al. (2000) from approximately 80 B stars of the solar vicinity derived an O gradient of 0.061 ± 0.005 dex kpc^{-1} , and similar gradients for Mg, Al and Si. Chemical evolution models of the Galaxy predict very similar gradients for the elements included in Table 2 (e.g. Allen, Carigi, & Peimbert 1998; Chiappini, Matteucci & Romano 2001; Alibes, Labay, & Canal 2002), since most of their production is due to massive stars that explode as supernovae of Type II. Therefore for the elements in Table 2 we expect gradients of about — 0.05 to -0.06 dex kpc^{-1}.

There are only three H II regions with good determinations of t^2: Orion, M8, and M17; in Table 2 we present for these H II regions two sets of gradients derived under the assumption of $t^2 = 0.000$ and $t^2 \neq 0.000$. The abundances derived under the assumption of $t^2 \neq 0.000$ indicate the presence of moderate gradients, while for those derived under the assumption of $t^2 = 0.000$ the gradients disappear. This result supports the contention that temperature fluctuations exist inside gaseous nebulae.

5. EVOLUTION OF C/O WITH TIME OR WITH O/H IN THE SOLAR VICINITY

Carigi (2002) has constructed models of the chemical evolution of the Galaxy based on observational yields of carbon derived from recombination lines and from forbidden lines of planetary nebulae, she finds that the models that use the yields based on permitted lines agree better with the observational constrains provided by H II regions and stars of the solar vicinity, than the models based on the yields derived from forbidden lines. This result is also indicative of the presence of temperature fluctuations inside gaseous nebulae.

6. $\Delta Y/\Delta Z$ AND $\Delta Y/\Delta O$ IN OUR GALAXY, M101 AND M33

In Table 3 we present the following values in mass units: helium (Y), oxygen (O), and heavy elements (Z) for M17 computed in this paper. The helium abundance was recomputed from the line intensities presented by Esteban et al. (1999a), the He recombination coefficients computed by Benjamin, Skillman, & Smits (1999), the helium recombination coefficients computed by Storey & Hummer (1995), and the optical depth effects computed by Robbins (1968). The results presented in Table 3 are an average for regions M17-3 and M17-14. The self consistent method (see Peimbert, Peimbert, & Luridiana 2002) based on the $\lambda\lambda$ 3819, 3889, 4026, 4387, 4471, 4922, 5876, 6678, 7065, and 7281 lines yielded $N_e = 800$cm^{-3} and $\tau(3889) = 7.5$ for M17-3, and $N_e = 500$cm^{-3} and $\tau(3889) = 4.5$ for M17-14. The helium values are slightly smaller than those presented by Esteban et al. (1999a).

Also in Table 3 we present the abundance values for NGC 5461 in M101, and for NGC 604 in M33 derived by Esteban et al. (2002).

In Table 4 we present the $\Delta Y/\Delta O$ and the $\Delta Y/\Delta Z$ values derived from a pregalactic helium abundance of $Y_p(+\text{Hc}, t^2 \neq 0.000) = 0.2384 \pm 0.0025$ and $Y_p(+\text{Hc}, t^2 = 0.000) = 0.2475 \pm 0.0025$ (Peimbert, Peimbert, & Luridiana 2002) and the abundance values presented in Table 3, where +Hc indicates that the collisional contribution to the hydrogen Balmer lines has been taken into account.

For M17 the difference between the values presented in Table 4 and those presented by Esteban

TABLE 2

GALACTIC ABUNDANCE GRADIENTS

Gradient (dex kpc^{-1})	Planetary Nebulae[a]	H II Regions[b]	(M17[b], M8[c], Orion[d]) $t^2 \neq 0.000$	$t^2 = 0.000$
O/H	−0.058	-0.055 ± 0.015	−0.049	−0.032
Ne/H	−0.036	-0.062 ± 0.020	−0.045	+0.031
S/H	−0.077	-0.062 ± 0.020	−0.055	+0.006
Cl/H	...	-0.031 ± 0.030	−0.031	+0.021
Ar/H	−0.051	-0.044 ± 0.030	−0.044	−0.004

[a] Maciel & Quireza (1999).
[b] Esteban et al. (1999a).
[c] Esteban et al. (1999b).
[d] Esteban et al. (1998).

TABLE 3

ABUNDANCES OF HELIUM, OXYGEN AND HEAVY ELEMENTS BY MASS

Object	Y ($t^2 = 0.000$)	Y ($t^2 \neq 0.000$)	O ($t^2 = 0.000$)	O ($t^2 \neq 0.000$)	Z ($t^2 = 0.000$)	Z ($t^2 \neq 0.000$)
M17	0.2766	0.2677	0.00440	0.00849	0.0135	0.0201
NGC 604	0.2705	0.2641	0.00427	0.00634	0.0108	0.0142
NGC 5461	0.2706	0.2612	0.00501	0.00896	0.0115	0.0175

et al. (1999a), in addition to the difference in the Y values mentioned in the previous paragraph, is due to the adoption of two different pregalactic helium abundances, one for the $t^2 = 0.000$ values and another for the $t^2 \neq 0.000$ values, while Esteban et al. (1999a) used the same Y_p for both types of determinations.

Based on their two-infall model for the chemical evolution of the Galaxy Chiappini, Matteucci, & Gratton (1997) find $\Delta Y/\Delta O = 3.15$ for the solar vicinity. Copi (1997) derives values of $\Delta Y/\Delta O$ in the 2.4 to 3.4 range. Carigi (2000) computed chemical evolution models for the Galactic disk, under an inside-out formation scenario, based on different combinations of seven sets of stellar yields by different authors; the $\Delta Y/\Delta O$ spread predicted by her models is in the 2.9 to 4.6 range for the Galactocentric distance of M17 (5.9 kpc), the spread is only due to the use of different stellar yields. The $\Delta Y/\Delta O$ values predicted by the models are in better agreement with the observations derived under $t^2 \neq 0.000$ the assumption than those derived under the $t^2 = 0.000$ assumption.

Similarly the models of chemical evolution of the Galaxy mentioned in the previous paragraph predict $\Delta Y/\Delta Z$ values in the 1–2 range. Again the values derived from observations under the assumption that $t^2 \neq 0.000$ are in better agreement with the models than those derived under the assumption that $t^2 = 0.000$.

7. HE/H ABUNDANCES IN PLANETARY NEBULAE AND GIANT EXTRAGALACTIC H II REGIONS

Each helium recombination line has a different dependence on the density and the temperature, therefore from the helium line intensity ratios it is possible to determine the density and the temperature in gaseous nebulae. Peña et al. (1995) and Peimbert, Luridiana, & Torres-Peimbert (1995) determined T(He II) values considerably smaller than the T(O III) values for a group of planetary nebulae. The extreme object was Hu 1-2, where T(O III) amounts to 19000 ± 500K, while T(He II) derived from the $\lambda\lambda$ 4472, 5876, and 6678 lines amounts to 12500 ± 500K.

From extragalactic H II regions Peimbert, Peimbert, & Ruiz (2000) and Peimbert, Peimbert, & Luridiana (2002) also find that T(H II) is also smaller than T(O III). This difference is paramount for the determination of the primordial helium abundance because the use of T(O III) instead of T(He II) leads to an overestimate of Y_p of about 0.008, a small

TABLE 4

VALUES OF $\Delta Y/\Delta O$ AND $\Delta Y/\Delta Z$

	$\Delta Y/\Delta O$		$\Delta Y/\Delta Z$	
Object	$(t^2 = 0.000)^a$	$(t^2 \neq 0.000)^b$	$(t^2 = 0.000)^a$	$(t^2 \neq 0.000)^b$
M17	6.60 ± 1.25	3.45 ± 0.65	2.15 ± 0.45	1.45 ± 0.30
NGC 604	5.40 ± 2.10	4.05 ± 1.50	2.15 ± 0.85	1.80 ± 0.65
NGC 5461	4.60 ± 1.95	2.55 ± 1.05	2.00 ± 0.85	1.30 ± 0.55

[a] Y_p(+Hc)=0.2475.
[b] Y_p(+Hc)=0.2384.

amount but significant for testing the standard big-bang model and possible deviations from it.

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