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CHEMICAL ABUNDANCES OF EXTRAGALACTIC H II REGIONS

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RESUMEN

La determinación de las abundancias de los elementos pesados en las regiones H II extragalácticas se obtiene a partir de líneas excitadas colisionalmente. En la presencia de variaciones de temperatura las abundancias que se obtienen son cotas inferiores de los valores reales. Para obtener los valores reales es necesario determinar la estructura de temperatura de las nebulosas. Discutimos la importancia de obtener intensidades de líneas de recombinación de H, He, C, y O para determinar la composición química de estos objetos. Proponemos que el método de Pagel para encontrar la abundancia de O/H sea calibrado a partir de líneas de recombinación observadas y no a partir de modelos de fotoionización o de abundancias obtenidas a partir de líneas excitadas colisionalmente.

ABSTRACT

The determination of the heavy element abundances from giant extragalactic H II regions is based on collisionally excited lines. We argue that in the presence of temperature variations the abundances determined are lower limits to the real heavy element abundances. To determine the real abundances it is necessary to take into account the temperature variations present in these nebulae. We discuss the relevance of obtaining accurate line intensities of recombination lines of H, He, C, and O to determine the chemical composition of extragalactic H II regions. We suggest that Pagel's method to derive the O/H ratio should be calibrated by using recombination lines instead of photoionization models or abundances derived from collisionally excited lines.

Key Words: **GALAXIES: ABUNDANCES — H II REGIONS: ABUNDANCES**

1. INTRODUCTION

The chemical abundances of extragalactic H II regions are paramount for: a) the study of the heavy elements enrichment of a given galaxy as a function of position, and b) the enrichment of the heavy elements in the Universe as a function of time by looking at galaxies at different redshifts.

A powerful tool to determine O/H values is provided by Pagel's method (Pagel et al. 1979) which is based on the [O II] and [O III] collisionally excited lines, these lines are very strong and are easily detected in objects at different redshifts. This method has to be calibrated by matching the [O III]/Hβ and [O II]/Hβ line intensity ratios with abundances derived from empirical methods or with photoionization models. Pagel's method might become paramount for the study of the heavy elements enrichment of the Universe as a function of time.

In this review we discuss briefly some observational evidence in favor of the presence of temperature variations and how large the t^2 values are. It has been shown that in the presence of temperature variations the collisionally excited lines of a given element provide a lower limit to the abundance of this element (Peimbert 1967).

We argue that Pagel's method has to be calibrated with recombination lines of O I and O II. We propose that the recombination lines of H, He, C, and O should be observed for a set of extragalactic H II regions with different heavy element abundances to establish a proper calibration of Pagel's method.

Peimbert (1995, 2002), Peimbert, Carigi, & Peimbert (2001), Esteban (2002), Liu (2002a,b), Stasińska (2002), Torres-Peimbert & Peimbert (2002), and Peimbert & Peimbert (2002) have recently reviewed the temperature structure of gaseous nebulae.

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

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

and

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

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 Paschen continuum to $I(\mathrm{H}\alpha)$, $T_e(\mathrm{Pac/H}\alpha)$, that are given by

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

and

$$T_e(\mathrm{Pac/H}\alpha) = T_0(1 - 1.67 t^2), \quad (4)$$

respectively. A similar equation can be written for the temperature derived from the ratio of the Balmer continuum to $I(\mathrm{H}\beta)$.

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 λ4267 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.

3. OBSERVATIONAL SUPPORT FOR TEMPERATURE VARIATIONS

From photoionization models of chemically and density homogeneous nebulae it has been found that $0.002 \le t^2 \le 0.03$, with typical values around 0.005 (e.g., Gruenwald & Viegas 1992; Kingdon & Ferland 1995; Pérez 1997). These low values of t^2 indicate that to assume $t^2 = 0.00$ is a good approximation to derive abundances. But the observations of many objects, as we will discuss below, indicate significantly larger values of t^2 implying the presence of additional physical processes not considered by the photoionization models. In what follows we will mention some of the observations that imply large t^2 values. A review of possible causes for these large temperature variations is presented elsewhere (Torres-Peimbert & Peimbert 2002).

3.1. *Extragalactic* H II *regions*

O/H and C/H ratios have been derived from recombination lines in NGC 5461, NGC 5471, NGC 604, NGC 2363 (Esteban et al. 2002), 30 Doradus, NGC 346, and LMC N 11 (Tsamis et al. 2002) and 30 Doradus (Peimbert 2003). Abundances derived from recombination lines are typically 2–3 times higher than those derived from collisionally excited lines, to reconcile these differences it is necessary to adopt t^2 values in the 0.023 to 0.10 range.

Luridiana, Peimbert, & Leitherer (1999) computed photoionization models of NGC 2363 and discuss the variations of the emission spectra obtained with different input parameters. They find that low metallicity models ($Z = 0.10\ Z_\odot$, the value derived with T_e(4363/5007) and $t^2 = 0.00$) do not reproduce the observed features of the spectrum and conclude that a value of $Z \simeq 0.25\ Z_\odot$ is in better agreement with the observational data than the usually adopted value $Z \simeq 0.10\ Z_\odot$.

González-Delgado et al. (1994) made a detailed observational study of NGC 2363. Based on the determination of $T_e(\mathrm{Pac/H}\alpha)$ and T_e(4363/5007), their study found that t^2 is equal to 0.064 for knot A and 0.098 for knot B in excellent agreement with the best model by Luridiana et al. (1999).

In general photoionization models predict values of T_e(4363/5007) smaller than observed, (Stasińska & Schaerer 1999; Luridiana et al. 1999; Relaño, Peimbert, & Beckman 2002; Peimbert, Peimbert, & Luridiana 2002; Luridiana, Peimbert, & Peimbert 2002) indicating the possible presence of an additional heating source not considered by the models.

Peimbert, Peimbert, & Ruiz (2000) have used the maximum likelihood method, to derive $\tau(3889)$, N_e(He II), $\mathrm{He}^+/\mathrm{H}^+$, and T_e(He II) based on nine helium recombination lines of NGC 346. By comparing the T_e(He II) values with the observed T_e(4363/5007) they obtain t^2 in the 0.02 to 0.03 range.

3.2. *Galactic* H II *regions*

Esteban et al. (1999) have found values of t^2 in the 0.024 to 0.044 range for the Orion nebula M8 and M17. The abundance values derived adopting these t^2 values are in agreement with chemical evolution models of the Galaxy while the abundance values derived under the assumption that $t^2 = 0.00$ are not.

The O/H value of the Orion nebula (Esteban et al. 1998) is 0.02 dex higher than the average value from two recent solar determinations (Holweger 2001; Allende-Prieto, Lambert, & Asplund 2001). The Orion nebula value was derived adopting $t^2 = 0.024$ and a correction of 0.08 dex to consider

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the fraction of O trapped in dust grains. This result is in agreement with predictions from models of galactic chemical evolution. Alternatively the adoption of $t^2 = 0.00$ implies a higher O/H value for the Sun than for the Orion nebula.

The O/H abundances for Orion, M8, and M17 derived under the assumption of $t^2 \neq 0.000$ indicate the presence of moderate O/H gradients, while for the O/H abundances derived under the assumption of $t^2 = 0.000$ the gradients disappear. This result supports the contention that temperature fluctuations exist inside gaseous nebulae.

Further discussion and additional arguments in favor of the presence of significant temperature variations inside galactic H II regions is presented elsewhere (Peimbert & Peimbert 2002)

3.3. *Planetary nebulae*

By combining different temperature determinations it has been possible to determine t^2 values in many planetary nebulae. These values are in the 0.00 to 0.15 range, with typical values around 0.04. Recent reviews on temperature variations in planetary nebulae have been presented by Liu (2002a, b), and Torres-Peimbert & Peimbert (2002).

4. CALIBRATION OF PAGEL'S METHOD TO DERIVE OXYGEN ABUNDANCES

The difficulty of measuring $I(\lambda 4363)$ (or any other direct temperature indicator) led Pagel et al. (1979) to propose an empirical method based on the ratio of the nebular oxygen lines to $I(\mathrm{H}\beta)$, $R_{23} \equiv I([\mathrm{O\,II}]\ \lambda 3727 + [\mathrm{O\,III}]\ \lambda\lambda 4959, 5007)/I(\mathrm{H}\beta)$, to determine the O/H ratio.

There are three different options to calibrate O/H versus R_{23}: a) from photoionization models where the observed nebular lines are matched with those predicted by the models, b) from abundances based on the observed nebular lines and $T_e(4363/5007)$ under the assumption of $t^2 = 0.00$., and c) from O recombination lines.

4.1. *Photoionization models*

This calibration is based on photoionization models where O/H is an input of the models. Calibrations based on this option have been presented by McCall, Rybski, & Shields (1985), Dopita & Evans (1986), and McGaugh (1991). This calibration depends on the quality of the models. A good model should include an initial mass function, an age for the stellar burst or the beginning of the star formation, a star formation rate, and a gaseous density distribution.

The photoionization models do not yet include all the physical processes needed to reproduce all the ratios observed in real nebulae. For example, even the best photoionization models, those tailored to fit I Zw 18, NGC 2363, and NGC 346 predict $T_e(4363/5007)$ values smaller than observed (Stasińska & Schaerer 1999; Luridiana et al. 1999; Relaño, Peimbert, & Beckman 2002). The models typically predict $t^2 \approx 0.005$, values considerably smaller than those derived from observations.

4.2. *Observations of R_{23} and T_e(4363/5007)*

The calibrations based on observations adjust the observed R_{23} values with the abundances derived from $T_e(4363/5007)$ under the assumption that $t^2 = 0.00$. These calibrations depend strongly on the temperature structure of the nebulae and underestimate the O/H values by factors of about 2 to 3 because, as mentioned before, t^2 is in the 0.023 to 0.10 range.

4.3. *O recombination lines*

There are significant differences between the calibrations of Pagel's method based on models (McCall et al. 1985; Dopita & Evans 1986; McGaugh 1991) and the calibrations based on observations and $T_e(4363/5007)$ (Edmunds & Pagel 1984; Torres-Peimbert, Peimbert, & Fierro 1989; Pilyugin 2000; Castellanos, Díaz, & Terlevich 2002). The differences in the O/H values are in the 0.2 dex to 0.4 dex range and could be caused mainly by the presence of temperature inhomogeneities over the observed volume (Campbell 1988; Torres-Peimbert et al. 1989; McGaugh 1991; Roy et al. 1996; Luridiana et al. 1999). These differences need to be sorted out if we want to obtain absolute accuracies in O/H of the order of 0.1 dex or better.

We consider that the option to calibrate Pagel's method based on the O recombination lines is superior to the other two for the following reasons: a) it is better than the one based on photoionization models because even the best available models are not yet able to reproduce all the observed emission line ratios, b) it is better than the option based on the observationally determined $T_e(4363/5007)$ because the abundances derived from the nebular lines and $T_e(4363/5007)$ are very sensitive to the t^2 value while the O/H values derived from recombination lines are independent of it.

5. DISCUSSION AND CONCLUSIONS

To be able to constrain the models for the evolution of galaxies as a function of redshift it is crucial to have good determinations of their heavy element abundances, and Pagel's method might be the best tool to determine these abundances.

Some determinations of the O/H values based on recombination lines are already available for giant extragalactic H II regions. They yield values in the $8.2 < log\ \mathrm{O/H} + 12 < 8.8$ range. In the near future it will be possible to increase the quality of these determinations and to increase the available range of O/H values.

We propose to calibrate Pagel's method using O recombination lines. The O recombination abundances are from 2 to 3 times higher than those derived from R_{23} and $T_e(4363/5007)$. The GTC can be used for this calibration. A spectrograph with a resolution higher than 5000 would be needed for this project.

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