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OXYGEN RECOMBINATION LINE ABUNDANCES IN GASEOUS NEBULAE

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RESUMEN

La determinación de abundancias de elementos pesados es regiones H II extragalácticas tradicionalmente se ha basado en íneas colisionalemente excitadas. Discutimos la importancia de estudiar las íneas de recombinación para determinar las abundancias de los elementos pesados en nebulosas gaseosas. Las íneas de recombinación más importantes de los elementos pesados son las de oxígeno, y de estas las del multiplete 1 de O II son las más fáciles de observar. Con frecuencia se supone que a partir de la intensidad de una ínea de un multiplete se puede encontrar la intensidad de todas las demás; en estudios recientes hemos encontrado que los cocientes de intensidades entre íneas del mismo multiplete dependen de la densidad; presentamos relaciones empíricas entre la densidad y la intensidad para el multiplete 1 del O basados en observaciones recientes de regiones H II y nebulosas planetarias. A partir las observaciones de las regiones H II encontramos que la densidad crítica asociada a la redistribucion colisional de las intensidades de las íneas del multiplete 1 de O II es de 2800 ± 500 cm^{-3}. Hacemos notar que las abudancias de O obtenidas a partir de íneas de recombinación muestran un acuerdo excelente con las abundancias solares, mientras que las abundancias de O estimadas a partir de íneas de O excitadas colisionalmente están en desacuerdo con las abundancias solares. Presentamos una calibración del método de Pagel para el intervalo $8.2 < 12 + \log \mathrm{O/H} < 8.8$ basada en íneas de recombinación del O.

ABSTRACT

The determination of the heavy element abundances from giant extragalactic H II regions has been generally based on collisionally excited lines. We will discuss the reasons to study the characteristics of recombination lines, and then use these lines to determine chemical abundances. Of these lines the oxygen (specifically the O II) lines are the most important; and, of them, the lines of multiplet 1 of O II are the most accessible. It has often been assumed that by measuring the intensity of a single line within a multiplet the intensities of all the lines in the multiplet can be determined; in recent studies we have found that the intensity ratios of lines within a multiplet can depend on density; we will present empirical density-intensity relationships for multiplet 1 based on recent observations of H II regions and planetary nebulae. From observations of H II regions we find that the critical density for collisional redistribution of the multiplet 1 O II recombination lines amounts to $2800 \pm 500\,\mathrm{cm}^{-3}$. We point out that the O/H recombination abundances of H II regions in the solar vicinity are in excellent agreement with the O/H solar value, while the abundances derived from collisionally excited lines are not. We present a calibration of Pagel's method in the $8.2 < 12 + \log \mathrm{O/H} < 8.8$ range based on O recombination lines.

Key Words: **GALAXIES: ABUNDANCES — ISM: ABUNDANCES — PLANETARY NEBULAE: ABUNDANCES**

1. INTRODUCTION

There are many observations that indicate the presence of large temperature variations in gaseous nebulae. In the case of chemically homogeneous nebulae it can be shown that recombination lines provide us with a better indication of the abundances than collisionally excited lines. In this short review we discuss the information provided by the O II recombination lines on the determination of O/H values in gaseous nebulae. In Section 2 we discuss the derivation of the O/H abundances and their dependence in the electron temperature and the electron density. In Section 3 we discuss two independent methods to estimate the O/H value in the ISM of the solar vicinity. In Section 4 we discuss Pagel's method to determine the O/H abundances in extragalactic nebulae based on the [O II] and [O III] nebular excitation lines and we calibrate it, for the first time based on O II and H I recombination lines. In Section 5 we present the conclusions.

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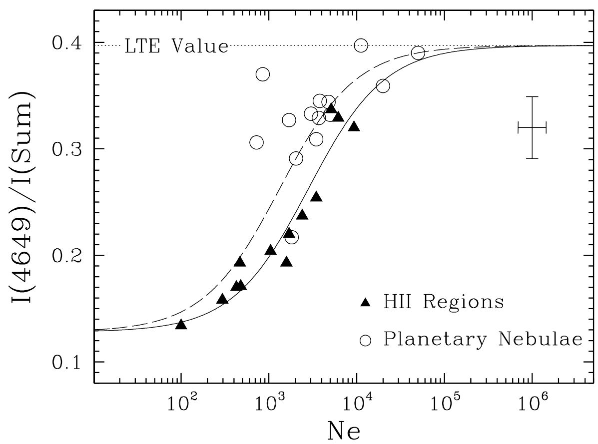

Fig. 1. Intensity ratio of the O II multiplet 1 line $\lambda 4649$ relative to the sum of the intensities of the 8 lines of the multiplet vs. the electron density derived from forbidden line ratios. The solid line represents the best fit to the H II region data, see eq. 4; the dashed line represents a fit to most of the PNe; the dotted line represents where the points would lie if there was LTE.

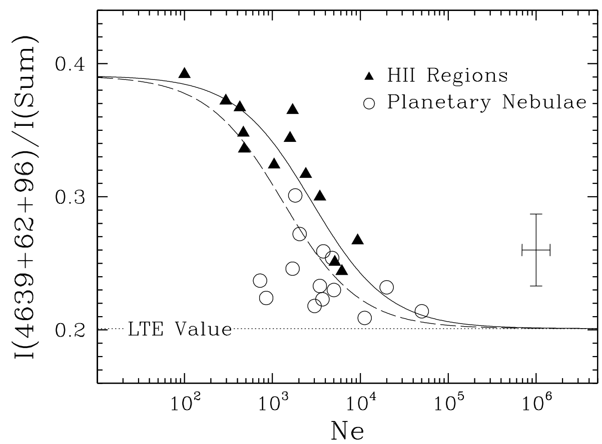

Fig. 2. Same as Figure 1, but for the ratio of $\lambda\lambda 4639 + 62 + 96$ relative to the sum of the lines of the multiplet.

2. OXYGEN ABUNDANCES DERIVED FROM RECOMBINATION LINES

Peimbert, Storey, & Torres-Peimbert (1993), based on the recombination coefficients for O II lines computed by Storey (1994), were the first to determine O/H values for gaseous nebulae. The temperature dependence of the O II lines is relatively weak and very similar to that of the H I lines, therefore the O^{++}/H^{+} ratios are independent of the electron temperature. Alternatively the O^{++}/H^{+} ratios derived from collisionally excited lines do depend strongly on the temperature (e. g.: Peimbert 1967, Peimbert & Costero 1969, Peimbert et al. 2004). In H II regions the recombination lines typically yield abundances higher than the optical collisionally excited lines by factors in the 2 to 3 range. The classical definition of the mean temperature square, t^2, is given by Peimbert (1967) and recent discussions on the presence of temperature variations in gaseous nebulae have been presented by Torres-Peimbert & Peimbert (2003), Ruiz et al. (2003), and Peimbert et al. (2004).

Ruiz et al. (2003) have found that the levels where the O II recombination lines of multiplet 1 originate are not in LTE, therefore to obtain the correct O^{++}/H^{+} value it is necessary to observe the eight lines of the multiplet. For those cases where not all of the lines of the multiplet are observed (due to faintness of some of the lines or due to blending produced by the low spectral resolution used) Ruiz et al. (2003) and Peimbert, Peimbert, & Ruiz (2005) have presented a preliminary set of equations of the multiplet as a function of the critical density. Based on additional observations in what follows we will revise those equations.

In Figures 1 and 2 we present additional observations of H II regions and PNe to those presented by Ruiz et al. (2003) and Peimbert et al. (2005). We have added the H II region values presented by Tsamis et al. (2003a) for LMC11B and by Esteban et al. (2004, 2005) and García-Rojas et al. (2004, 2005) for Orion, M8, M17, NGC 3576, and S 311. We have also added the PNe values presented by Tsamis et al. (2003b) for NGC 2022, NGC 3132, NGC 3234, NGC 5882, IC 4191, and IC 4406 and we have deleted the value for IC 4997. From the best fits to the H II regions in Figures 1 and 2 we have obtained the following equations:

$$\left[\frac{I(4651+74)}{I(\mathrm{sum})}\right]_{obs} = 0.101 + \frac{0.128 \pm 0.010}{[1+N_e(\mathrm{FL})/2800]}, \tag{1}$$

$$\left[\frac{I(4639+62+96)}{I(\mathrm{sum})}\right]_{obs} = 0.201 + \frac{0.190 \pm 0.010}{[1+N_e(\mathrm{FL})/2800]}, \tag{2}$$

$$\left[\frac{I(4642+76)}{I(\mathrm{sum})}\right]_{obs} = 0.301 - \frac{0.049 \pm 0.010}{[1+N_e(\mathrm{FL})/2800]}, \tag{3}$$

and

$$\left[\frac{I(4649)}{I(\mathrm{sum})}\right]_{obs} = 0.397 - \frac{0.269 \pm 0.010}{[1+N_e(\mathrm{FL})/2800]}, \tag{4}$$

where the critical density, N_c(H II regions)$= 2800 \pm 500$ cm^{-3} was obtained from the observed O II line intensities and the N_e values derived from collisionally excited lines, mainly those of [Cl III].

TABLE 1

PLANETARY NEBULA DENSITIES

Object	Forbidden Lines	O II multiplet 1 [a]
NGC 3132	720±300	7500^{+4000}_{-2000}
NGC 2022	850^{+1000}_{-500}	$23000^{+100000}_{-10000}$
M1-42	1690^{+600}_{-400}	8500^{+6000}_{-3000}
NGC 3234	1800^{+1400}_{-700}	1750^{+1000}_{-700}
NGC 5307	2040^{+1350}_{-1050}	4500^{+2250}_{-1250}
NGC 7009	3000±900	15000^{+15000}_{-6000}
IC 4406	3500±2000	7500^{+7000}_{-3000}
NGC 5882	3700±1500	12000^{+10000}_{-4000}
NGC 6153	3830±800	8500^{+7500}_{-3000}
M2-36	4830±1000	9000^{+10000}_{-4000}
NGC 6543	5000±1000	11000^{+15000}_{-4500}

[a]Based on the H II regions density calibration of the O II multiplet 1, average of the values derived from figures 1 and 2.

Similarly from the best fit to the PNe in Figures 1 and 2 we have obtained a critical density, N_c(PNe)= 1325 ± 300 cm^{-3}.

The difference between N_c(H II regions) and N_c(PNe) probably indicates that the density variations present in PNe are more significant than those present in H II regions. For the density fluctuations to be effective in explaining this difference a significant fraction of the emission measure should correspond to densities higher than the O II critical density and a significant fraction to densities smaller than the critical density.

In Table 1, we present the density derived from the forbidden line data for PNe and the density derived from the O II recombination line intensities and equations 2 and 4. The large differences for most of the objects indicate large density fluctuations in the 1,000 to 10,000 cm^{-3} range. These fluctuations will produce underestimations in the heavy element abundances derived from IR collisionally excited lines if they are not taken into account.

The critical density to reach LTE for multiplet 1 of O II, N_c(Atomic Physics) should be estimated from atomic physics computations to see if it agrees with the one derived from observations of H II regions. If N_c(Atomic Physics) turns out to be higher than N_c(H II regions), it would indicate the presence of significant temperature and density variations in H II regions.

As we just saw above, from the observed line intensities of a given object and equations 1-4 it is possible to determine the average density where the O II recombination lines originate. In the presence of strong chemical inhomogeneities, with high density clumps made of H-poor material embedded in low density regions of H-rich material, the density derived from equations 1 - 4 will be higher than the density derived from fitting the ratio of the higher Balmer lines to Hβ or Hα.

3. THE O/H VALUE IN THE SOLAR VICINITY

There are two independent methods to determine the O/H ratio in the ISM of the solar vicinity: a) from the solar ratio by Asplund, Grevesse, & Sauval (2005), that amounts to 12 + log(O/H) = 8.66, and taking into account the increase of the O/H ratio due to galactic chemical evolution since the Sun was formed, that according to state of the art chemical evolution models of the Galaxy amounts to 0.13 dex (e.g. Carigi et al. 2005), we obtain an O/H value of 8.79 dex; and b) from the H II regions O/H value for the solar vicinity by Esteban et al. (2005) based on the O/H galactic gradient determined from O II recombination lines, that amounts to 8.77 dex, in excellent agreement with the value based on the solar abundance.

In the previous comparison we are assuming that the solar abundances are representative of the abundances of the ISM solar vicinity when the Sun was formed. There are two other determinations of the present O/H value in the ISM of the solar vicinity that can be made from observations of F and G stars of the solar vicinity. According to Allende Prieto et al. (2004) the Sun appears deficient by roughly 0.1 dex in O, Si, Ca, Sc, Ti, Y, Ce, Nd, and Eu, compared with its immediate neighbors with similar iron abundances, the probable reason for this difference is that the Sun is older than the comparison stars, by adopting the O/H value of the comparison stars we obtain a value of 12 + log O/H = 8.76 dex. A similar result is obtained by Bensby & Feltzing (2005) that find that the most O-rich thin-disk F and G dwarfs have [O/H] $\sim$ 0.15. By adopting their value for the present day ISM of the solar vicinity we find 12 + O/H = 8.81 dex. Both results are in excellent agreement with the O/H value derived from O recombination lines in H II regions of the solar vicinity.

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

The difficulty of measuring $I(\lambda4363)$ (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 $I(\mathrm{H}\beta)$, $R_{23} \equiv$

$I([\text{O II}]\lambda3727+[\text{O III}]\lambda\lambda4959,5007)/I(\text{H}\beta)$, to determine the O/H ratio in giant extragalactic H II regions.

There are four different options to calibrate O/H versus R_{23}: a) from photoionization models where the observed $I([\text{O II}]\lambda3727)/I(\text{H}\beta)$ and the $I([\text{O III}]\lambda\lambda4959,5007)/I(\text{H}\beta)$ values are matched with those predicted by the models, b) from abundances derived from the observed $I([\text{O II}]\lambda3727)/I(\text{H}\beta)$ and the $I([\text{O III}]\lambda\lambda4959,5007)/I(\text{H}\beta)$ values and the observed $T_e(4363/5007)$ under the assumption that $t^2 = 0.00$, c) from O abundances derived from supergiant stars, and d) from O abundances derived from 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 many authors (e. g.: McCall, Rybski, & Shields 1985; Dopita, & Evans 1986; McGaugh 1991; Zaritsky, Kennicutt & Huchra 1994; Kewley, & Dopita 2002; Kobulnicky, & Kewley 2004). This calibration depends on the quality of the models. A good model should include the gaseous density distribution for the nebula and for the ionizing cluster: an initial mass function, the time elapsed since the beginning of the star formation, and a star formation rate.

The photoionization models do not yet include all the physical processes needed to reproduce all the ratios observed in real nebulae. For example they do not include the possible presence of stellar winds due to WR stars nor the possible presence of supernova remnants and related shocks. From a study of NGC 604, a giant extragalactic H II region in M33, Yang et al. (1996) conclude that the velocity width of the Hα line consists of equal contributions from thermal broadening, stellar winds and SNRs, and gravity. 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, Peimbert, & Leitherer 1999, and Relaño, Peimbert, & Beckman 2002), probably indicating the need for additional heating sources. The photoionization models typically predict $t^2 \approx 0.005$, values considerably smaller than those derived from observations that are typically in the $0.02 < t^2 < 0.06$ range.

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

This calibration is based on adjusting the observed R_{23} values with the abundances derived from

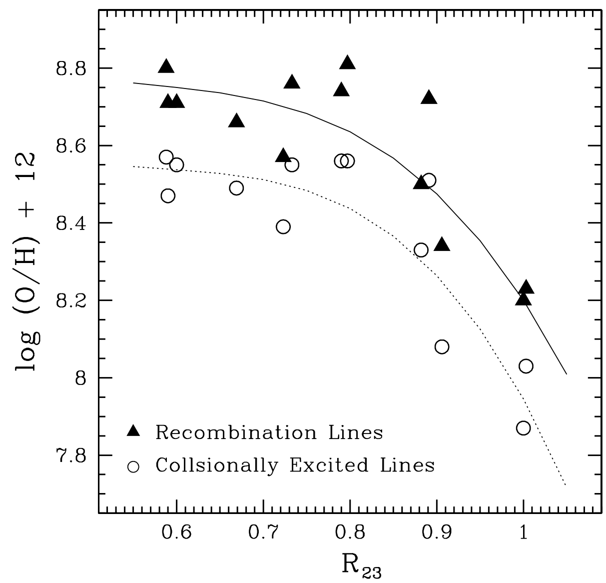

Fig. 3. Pagel's R_{23} method calibration — using abundances determined with recombination lines (solid line) and abundances determined with collisionally excited lines (dotted line).

$T_e(4363/5007)$ 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 typically in the 0.02 to 0.06 range.

There are significant differences between the calibrations of Pagel's method based on models (e. g. McCall et al. 1985; Dopita & Evans 1986; McGaugh 1991) and the calibrations based on observations and $T_e(4363/5007)$ (e. g. Edmunds & Pagel 1984; Torres-Peimbert, Peimbert, & Fierro 1989; Pilyugin 2000, 2003; Castellanos, Díaz, & Terlevich 2002). The differences in the O/H values are in the 0.2 - 0.4 dex range and could be due mainly to the presence of temperature inhomogeneities over the observed volume (e. g. Campbell 1988; Torres-Peimbert et al. 1989; McGaugh 1991; Roy et al. 1996; Luridiana et al. 1999; Kobulnicky, Kennicutt, & Pizagno 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.

4.3. *O recombination lines*

We have discussed previously the need to calibrate Pagel's method with O recombination lines (Peimbert & Peimbert 2003); in Figure 3 we present a calibration of Pagel's method based on recombination line observations of galactic and extragalactic

H II regions obtained by the following authors: Esteban et al. (2002, 2004, 2005), Peimbert (2003), Tsamis et al. (2003a), García-Rojas et al. (2004, 2005), and Peimbert et al. (2005). Also in this figure we present the abundances derived from the O collisionally excited lines and $T_e(4363/5007)$ under the assumption of constant temperature, i. e. $t^2 = 0.00$. The average difference between both methods amounts to 0.21 dex. Notice that we are presenting for both methods the gaseous abundances without correction for the fraction of O embedded in dust grains.

We consider that the option to calibrate Pagel's method based on the O recombination lines is superior to the one based on fitting the 5007 and 3727 O lines to those predicted by photoionization models because even the best available models are not yet able to reproduce all the observed emission line ratios. The O recombination method is also 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 from it.

5. CONCLUSIONS

The O II relative line intensities from multiplet 1 might deviate from the LTE predictions. If that is the case equations 1 - 4 should be used to estimate the intensities of the unobserved lines of the multiplet.

If the density derived from equations 1 - 4 is larger than that derived from the high n Balmer lines, this would indicate that the O II lines originate in high density H-poor gas embedded in a low-density H-rich gas.

The N_c(PNe) that we derive from the multiplet of O II and forbidden lines is considerably smaller than the N_c(H II regions) one, which implies that PNe show larger density fluctuations in the 1,000 to 10,000 cm^{-3} range than H II regions.

The typical densities for PNe from the O II multiplet 1 calibrated based on H II regions (equations 2 and 4) are about a factor of two of three larger than those derived from forbidden lines of PNe (see Table 1). This result has to be taken into account in the determination of heavy element abundances from collisionally excited lines in the IR.

The abundances derived from O recombination lines are typically from 0.2 to 0.3 dex higher than those derived from O collisionally excited lines and the adoption of $T_e(4363/5007)$ under the assumption of $t^2 = 0.00$.

For galactic H II regions the abundances derived from recombination lines by Esteban et al. (2005) are about 0.2 dex smaller than those derived by Deharveng et al. (2000) and Pilyugin, Ferrini, & Shkvarun (2003) from O collisionally excited lines and the adoption of $T_e(4363/5007)$ under the assumption of $t^2 = 0.00$.

We present for the first time a calibration of Pagel's method to derive the O/H ratio in the 8.2 $< 12 + \log$ O/H < 8.8 range based on recombination lines. This calibration is about 0.21 dex higher than that based on $T_e(4363/5007)$ under the assumption of $t^2 = 0.00$. Alternatively, the O recombination lines calibration is in fair agreement with those calibrations based on grids of models that fit the R_{23} observed values like the one by McGaugh (1991); the main reason for the better agreement is that the 5007[O III]/Hβ and 3737[O II]/Hβ ratios depend to a considerably lesser extent on the t^2 value than the 4363/5007 ratio (see Peimbert & Costero 1969 and Peimbert et al. 2004).

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