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ON THE CHEMICAL COMPOSITION OF GASEOUS NEBULAE AND THE PRIMORDIAL HELIUM ABUNDANCE

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RESUMEN

Se discuten determinaciones recientes de temperaturas electrónicas en nebulosas planetarias y regiones H II. Estas determinaciones indican la presencia de variaciones espaciales de temperatura cuya importancia es diferente para cada objeto. Se presentan algunas consecuencias de estas variaciones en la determinación de las abundancias químicas de nebulosas planetarias, regiones H II galácticas y regiones H II extragalácticas. Se hace una revisión somera de las determinaciones de la abundancia primordial de helio.

ABSTRACT

Recent electron temperature determinations of planetary nebulae and H II regions are reviewed, these determinations indicate the presence of spatial temperature fluctuations. The importance of these fluctuations varies considerably from object to object. Some of the consequences of these fluctuations on the determination of the chemical abundances of PNe, galactic H II regions and extragalactic H II regions are discussed. A brief assessment of the primordial helium abundance determinations is made.

Key words: **H II REGIONS — PLANETARY NEBULAE — GALAXIES– ABUNDANCES — COSMOLOGY**

1. INTRODUCTION

Our knowledge of the temperature structure of gaseous nebulae is in general poor. It has been found that in some of the best observed objects the temperature distribution shows variations considerably higher than those predicted by photoionized models of chemically homogeneous gaseous nebulae. This temperature variations affect the determined abundances by amounts that in many cases are not negligible. For a review of this problem see Peimbert (1995).

In this paper I review recent results related to this problem. In § 2 and § 3 PNe and galactic H II regions are discussed. In § 4 the evidence for temperature fluctuations in extragalactic H II regions is discussed. In § 5 the effect of temperature fluctuations in the determination of the primordial helium abundance, Y_p, is evaluated and the constraint imposed by Y_p on big-bang nucleosynthesis is analyzed. The conclusions are presented in § 6.

2. PLANETARY NEBULAE

There are different methods to obtain T_e: $T(O^{++})$ from $I(4363)/I(5007)$, $T(C^{++})$ from $I(4267)/I(1909)$, T(Bac) from I(Balmer continuum)/I(Balmer line), $T(4650/5007)$ from $I(4650)/I(5007)$, T(He) from the ratio of two He I lines, etc. In general $T(C^{++})$, T(Bac), $T(4650/5007)$ and T(He) yield values considerably smaller than $T(O^{++})$ and imply t^2 values in the 0.00 to 0.10 range, with typical values around 0.04 (e.g., Peimbert 1971; Dinerstein et al. 1985; Liu & Danziger 1993; Liu et al. 1995b; Peimbert et al. 1995a; Kingsburgh et al. 1996). Gruenwald & Viegas (1995) and Kingdon & Ferland (1995b) have produced extensive grids of chemically homogeneous photoionized models of PNe to study this problem; they find that: a) in general t^2 increases with Tstar, b) t^2 is different for different ions, c) t^2 increases with metallicity and d) there are many PNe that show t^2 values that are considerably higher than expected from their grids of models.

There are several possible solutions to this problem, two of the more promising are: a) PNe are chemically inhomogeneous due to stellar mass loss episodes with different chemical compositions, or to different fractions of dust destruction as a function of position, and b) the deposition of mechanical energy due to stellar mass

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loss. Peimbert et al. (1995) have studied possible causes for the difference between $T(O^{++})$ and $T(C^{++})$ in PNe and argue that the main one is the presence of large temperature fluctuations. Additional support for their arguments comes from the extensive grid of shock models by Dopita & Sutherland (1996) where it is found that shock waves produce considerably higher $T(O^{++})$ than $T(C^{++})$ values, while $T(C^{++})$ and $T(O^{++})$ are practically the same for the photoionized precursors. For example for models with $v = 200$ kms^{-1} with magnetic parameters between 0 and 4μG they find mean electron temperatures in the ranges $7845 < T(C^{++}) < 16550$ K and $50000 < T(O^{++}) < 64850$ K, alternatively the mean electron temperatures for the photoionized precursor of their shock model with $v = 200$ kms^{-1} are $T(C^{++}) = 6395$ K and $T(O^{++}) = 6353$ K.

Peimbert et al. (1995) find that the use of λ4267 to determine $N(C^{++})/N(H^{+})$ yields values from similar to about thirty times higher than those derived from λ1909. The $N(C^{++}, 4267)/N(C^{++}, 1909)$ ratios correlate strongly with the velocity field of the object indicating that probably the main factor producing the large temperature fluctuations is the deposition of mechanical energy.

3. GALACTIC H II REGIONS

Many determinations of t^2 in the Orion Nebula prior to 1994 gave results around 0.04. For example Walter et al. (1992) based on the $I(1909)/I(4267)$ ratio and the λ4267 effective recombination coefficient by Pengelly (see Seaton 1978) obtain t^2 values of 0.055 ± 0.013 and Peimbert et al. (1993) obtain t^2 values of 0.053 ± 0.013; from the effective recombination coefficient for λ4267 by Pequignot et al. (1991) these values become 0.049 and 0.047 respectively. Peimbert et al. from the O II recombination lines obtain $t^2 = 0.038 \pm 0.011$.

Newer observations of the Orion nebula imply lower values of t^2. Liu et al. (1995a) have derived relatively large T(Bac) values. Their results combined with $T(O^{++})$ and $T(N^{+})$ imply that t^2 in Orion is small, < 0.01. Esteban et al. (1996), from T(Bac) combined with $T(O^{++})$ and $T(N^{+})$ obtain $t^2 = 0.01 \pm 0.01$, from $I(4267)/I(1909)$ 0.034 ± 0.01 (Pengelly) and 0.027 ± 0.01 (Pequignot), and from the O II recombination lines 0.02 ± 0.01.

Like in PNe it is possible that t^2 could vary significantly from object to object, moreover it might also vary for different lines of sight of a given object. A $t^2 = 0.00$ would imply $\Delta Y/\Delta Z$ ratios around 5, that are not explained by recent models of galactic chemical evolution (e.g., Carigi 1994).

4. EXTRAGALACTIC H II REGIONS

By adjusting the nebular lines of [O III] to photoionized models it is found that the O/H values are from 0.2 to 0.4 dex higher than those derived from the $I(4363)/I(5007)$ ratio (Campbell 1988; Torres-Peimbert et al. 1989; McGaugh 1991). These differences have been ascribed to the presence of spatial temperature fluctuations that can not be explained by chemically homogeneous photoionized models (see the grids by Stasinska 1990 and Gruenwald & Viegas 1992).

H II regions contain O stars that evolve through the WR phase and explode as SNe. Very young H II regions are not expected to contain WR stars or SN remnants. Alternatively older H II regions will present stars in the WR phase and some of their most massive stars would have already exploded as SNe. The WR phase and the SNe events will feed the H II regions with processed elements by nuclear reactions. Esteban & Peimbert (1995) and Tenorio-Tagle (1996) have shown, with different arguments, that SN ejecta (in particular the O atoms) escape their parental H II region without mixing. This is a fortunate circumstance because it implies that the H II region abundances are not changed by SNe activities inside them, and consequently that their abundances reflect those of the ISM at the time the ionizing stars were formed. Therefore H II regions are excellent objects to study the chemical evolution of galaxies.

Pagel et al. (1992) have found that H II regions with WR features tend to have higher Y values for their N/H and O/H values than those H II regions without WR features. According to Esteban & Peimbert (1995) this behavior cannot be explained by self enrichment; alternatively they find that by adopting lower temperatures for the H II regions with WR features (higher spatial temperature variations) their Y values become smaller and their O/H and N/H values become higher, placing them on the linear Y versus N/H and O/H fits defined by the objects without WR features. This behavior is expected because H II regions with WR features could be older and with a larger fraction of mechanical energy, due to mass loss, than those without WR features.

5. Y_P: THE THIRD DECIMAL PLACE

Excellent reviews on the determination of the pregalactic helium abundance, Y_p, have been presented by Pagel (1987, 1992, 1995) similarly excellent reviews on the cosmological consequences are present in the literature (e.g, Boesgaard & Steigman 1985; Walker et al. 1991; Copi et al. 1995).

Some of the best determinations of Y_p are presented in Table 1. The determination by Olive & Steigman (1995) includes data from Pagel et al. (1992) and the data by Skillman & Kennicutt (1993), and Skillman et al. (1994, 1996). There are three types of errors involved in the Y_p determinations: a) errors in the determination of the line ratios, that include detector calibration, reddening correction, underlying stellar absorption and signal to noise ratio, b) errors in the interpretation of the line ratios, that include the estimate of the amount of neutral helium, the adopted temperature structure, the accuracy of the atomic data, the correction for the collisional excitation of the He I lines and radiative transfer effects, and c) errors in the extrapolation to $Z = 0$.

TABLE 1

PRIMORDIAL HELIUM ABUNDANCE

Y_p	Method	References
0.230 ± 0.003	$(D/H)_p$ + SBBN	Rugers & Hogan 1996, Walker et al. 1991
0.233 ± 0.003	$(D/H)_p$ + SBBN	Rugers & Hogan 1996, Copi et al. 1995
0.228 ± 0.005	SMC[a] + Orion	Peimbert & Torres-Peimbert 1976
0.231 ± 0.005	SMC[a] + LMC[a]	Lequeux et al. 1979
0.233 ± 0.005	10 Objects	Lequeux et al. 1979
0.245 ± 0.003	12 Objects	Kunth & Sargent 1983
0.230 ± 0.006	4 Objects	Torres-Peimbert et al. 1989
0.228 ± 0.005	19 Objects	Pagel et al. 1992
0.240 ± 0.005	9 Objects	Izotov et al. 1994
0.232 ± 0.003	22 Objects	Olive & Steigman 1995

[a] The SMC and LMC values are based on three and four different H II regions respectively.

Different methods and assumptions have been made to deal with the sources of error mentioned above and consequently most of the systematic errors present are different for each determination in Table 1. It is beyond the scope of this note to discuss the errors involved in each determination of Y_p but I will say a few words on the extrapolation to $Z = 0$ and on the errors related to the interpretation of the line ratios.

Most of the Y_p values derived from H II regions were obtained from the relationships $Y = Y_p + Z(\Delta Y/\Delta Z)$ or $Y = Y_p + O(\Delta Y/\Delta Z)$, where Z and O are the heavy elements and O abundances by mass respectively. Only Kunth & Sargent assumed that $\Delta Y/\Delta Z = 0$.

For the last three determinations in Table 1 the presence of neutral helium would systematically raise the Y_p value, but not for those by Peimbert & Torres-Peimbert (1976) and Lequeux et al. (1979) where a correction for neutral helium was made. In particular for the H II regions in the SMC and the LMC by determining $N(He^+)/N(H^+)$ ratios along different lines of sight of a given object it was found that practically no neutral helium was present in those lines of sight with large $N(O^{++})/N(O)$ ratios. From models it has also been found that objects with a high degree of ionization should have a negligible amount of neutral helium, moreover even if a low degree of ionization H II region is superposed to the main one it would have an insignificant contribution to the Balmer line flux and consequently to the derived $N(He^+)/N(H^+)$ ratio (e.g., Peña 1986; Pagel et al. 1992; Skillman et al. 1994; Pagel 1995).

All the values presented in Table 1 are based on the He I emissivities by Brocklehurst (1972), B72, with the exception of that by Izotov et al. (1994) that is based on the computations by Smits (1996). The new computations of the He I emissivities by Smits (1996), S96, yield practically the same Y_p results than B72, the ΔY changes for the three strongest lines used are (B72-S96)= $-0.0005(\lambda5876)$, $+0.0028(\lambda4471)$ and $-0.0016(\lambda6678)$, these values correspond to T_e = 14 000 K and depend weakly on T_e. On the other hand the ΔY differences between Smits (1991), S91, and S96 are significant and at T_e = 20 000 K are: (S91-S96)= $+0.0089(\lambda5876)$, $+0.0048(\lambda4471)$ and $+0.0078(\lambda6678)$; for smaller temperatures the differences become smaller. From a comparison of B72 with S96 the systematic error in Y_p due to errors in the He I emissivities is expected to be < 0.001; notice, however, that the B72 $\lambda7065$ emissivity is incorrect and should not be used to determine the electron density. Furthermore the collisional contribution to the He I lines is well known (Kingdon & Ferland 1995a) and due to the very small densities of the H II regions used to determine Y_p the collisional contribution is very small and produces errors considerably smaller than 0.001; a similar case can be made for radiative transfer effects.

I will discuss possible effects of temperature fluctuations in the determination of Y_p. Due to a weak but not negligible dependence of the He I/H I line ratios on the electron temperature a value of $t^2 = 0.04$ reduces Y by 0.003 in a given object.

There is one selection effect that operates when looking for the O/H poorest H II regions to derive Y_p. It seems reasonably to look for the objects with the lowest O/H ratios, and consequently with high $I(4363)/I(5007)$ ratios. The objects where mechanical heating is present show a higher 4363/5007 temperature and consequently a smaller than real O/H ratio. In a sample of objects with a real O defficiency of an order of magnitude, those where mechanical energy is playing an important role will show a higher $I(4363)/I(5007)$ ratio producing a spuriously lower O/H ratio and a spuriously higher He/H ratio.

Broad low-intensity components of hydrogen and forbidden lines have been observed in some giant O poor H II regions corresponding to expansion velocities as high as 3000 km s^{-1} (e.g., Izotov et al. 1996 and references therein). Moreover, Izotov et al. find a broad component for 1851+695, an O poor object without WR features, they argue that stars with low metallicities conserve their H-rich envelope until the SN explosion. Therefore O/H poor H II regions might have a high t^2 value that can not be detected based on the presence of WR features. That might be the case for I Zw 18 where Skillman & Kennicutt (1993) find a broad emission component to the Hα profile in the NW region with a full width at zero intensity of about 3600 km s^{-1}; furthermore Martin (1996) finds from long slit spectroscopy that the O/H ratio varies from one end to the other and that there is a velocity of expansion of the shell of about 30 to 60 km s^{-1}.Therefore the best objects to determine the pregalactic helium abundance are not necessarily those with the apparently lowest O/H values.

As mentioned in § 4, Esteban & Peimbert (1995) argue that the anomalous position of the WR galaxies in the sample by Pagel et al. (1992) is probably due to temperature fluctuations. Moreover from the linear fits of Y versus O/H Olive & Steigman (1994) find for their whole sample that $Y_p = 0.234$ while by excluding the objects with WR features they find $Y_p = 0.232$, similarly from the linear fits for Y versus N/H they find for their whole sample that $Y_p = 0.236$, while by excluding the objects with WR features they find $Y_p = 0.233$. These differences could be due to the presence of temperature fluctuations in the H II complexes with WR features. It is possible that the objects without WR features also show some spatial temperature fluctuations which would reduce further Y_p by about 0.002.

From the previous discussion I consider that a value of $Y_p = 0.234 \pm 0.005$ is representative of the H II region results in Table 1, the error is a one sigma error that includes all the sources of error mentioned above.

The most spectacular result of recent years in the field of cosmological nucleosynthesis has been the determination of the pregalactic D/H ratio by Rugers & Hogan (1996). They find a D/H value of $(1.9 \pm 0.4) \times 10^{-4}$, that together with standard big-bang nucleosynthesis (Copi et al. 1995) corresponds to $\eta = (1.7 \pm 0.2) \times 10^{-10}$, $\Omega_b h^2 = (6.2 \pm 0.8) \times 10^{-3}$ and $Y_p = 0.233 \pm 0.003$. Support for the result of Rugers & Hogan comes from the observation of an absorption line in the direction of quasar 0420–388 tentatively ascribed to deuterium (Carswell et al. 1996). If the line is due to D and if OI/HI is constant throughout the absorbing cloud it follows that D/H $\sim 2 \times 10^{-4}$; in this quasar O/H is about 1/10 solar.

The predicted Y_p value from the D/H observations and SBBN is in excellent agreement with the best Y_p determinations of the last twenty years. It should be noted that the D/H value by Rugers & Hogan (1996) is a lower limit to $(D/H)_p$ because some D destruction in the absorbing clouds due to stellar evolution could have occurred. $(D/H)_p$ and Y_p provide us with two independent constraints on big bang nucleosynthesis; while $(D/H)_p$ gives us a restriction on η and $\Omega_b h^2$, Y_p gives us a restriction on the number of light neutrino species, N_ν (e.g., Steigman et al. 1977). Each neutrino species increases the value of Y_p by about 0.012 (Walker et al. 1991). From SBBN (Copi et al. 1995), $D/H_p = (1.9 \pm 0.4) \times 10^{-4}$ (Rugers & Hogan 1996) and $Y_p = 0.234 \pm 0.005$ (Table 1), it follows that $N_\nu = 3.1 \pm 0.5$, in excellent agreement with $N_\nu = 2.99 + 0.05$, result derived with high-energy colliders from the properties of the Z^0 boson (e.g., Schramm 1993 and references therein). In Figure 1 the Y_p, D_p and Li_p constraints to SBBN are presented; it is clear from this figure that there is excellent agreement among Y_p, D_p, Li_p and SBBN.

6. CONCLUSIONS

t^2 varies from PN to PN and in general is higher than predicted by photoionization models. The C abundances derived from λ4267 of C II are higher than those derived from λ1909 of [C III] and $T(O^{++})$. The $N(C^{++}, 4267)/N(C^{++}, 1909)$ ratio in PNe is in the 0.6 to 30 range with an average value of 4. The correct abundances are those derived from λ4267 and the difference between both types of determinations is mainly due to spatial temperature fluctuations.

Recent determinations of T(Bac) in the Orion nebula yield smaller t^2 values than those derived from C II and O II recombination lines. These T(Bac) determinations imply large $\Delta Y/\Delta Z$ values that can not be explained by present models of galactic chemical evolution.

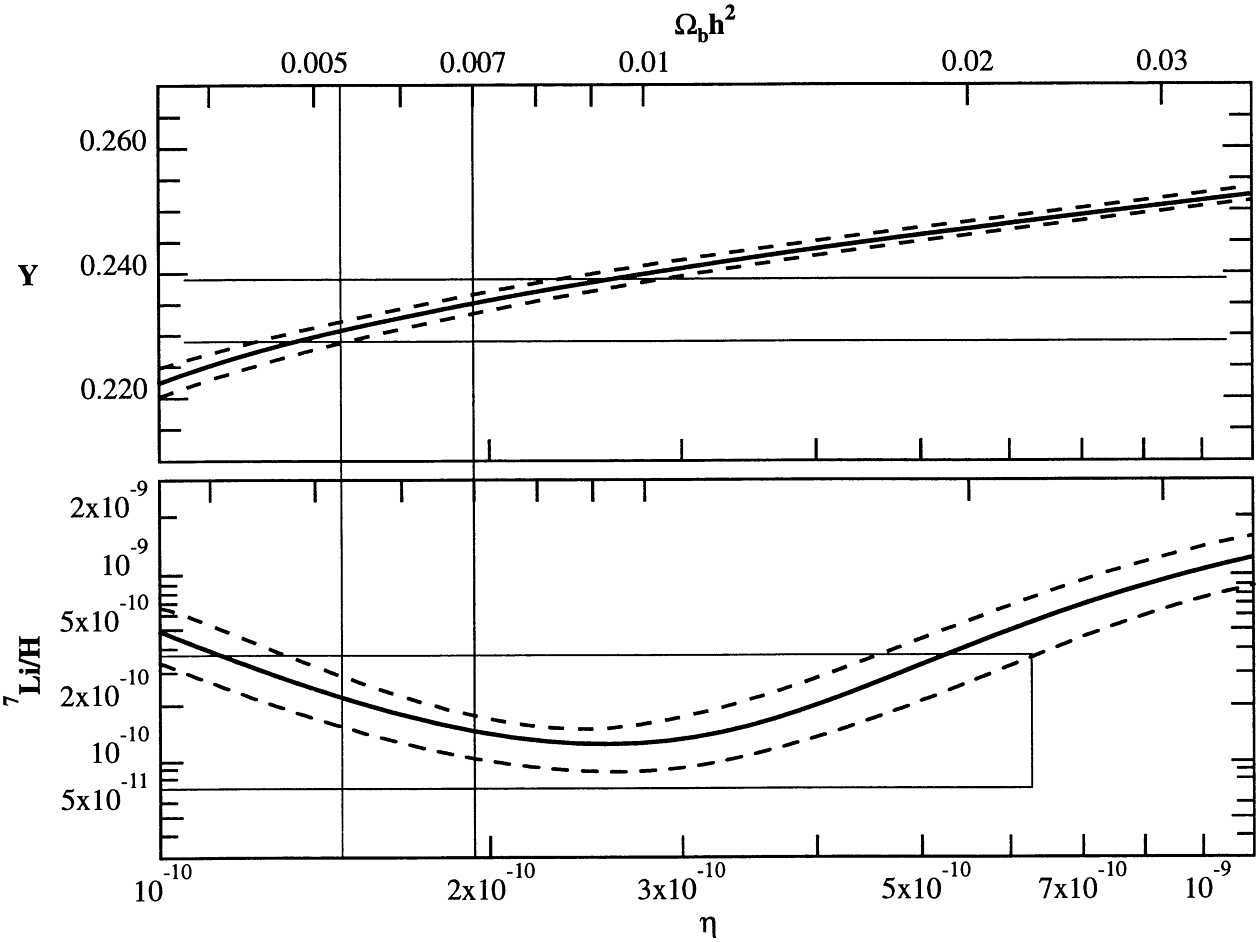

Fig. 1. The full curves in panels one and two are standard, big-bang nucleosynthesis SBBN, predictions from Copi et al. (1995), the dashed curves in both panels correspond to two sigma estimates. The vertical axis in the upper panel is the pregalactic helium abundance by mass Y_p, the vertical axis in the lower panel is the $(^7\mathrm{Li/H})_p$ value by number. The horizontal axis is the baryon to photon ratio, η, or equivalently $\Omega_b h^2$, where h is the Hubble parameter in units of 100 km s^{-1} Mpc^{-1} and Ω_b is the ratio of the baryonic density to the critical density. The vertical constraints are one sigma limits from the $(\mathrm{D/H})_p$ value determined by Rugers & Hogan (1996), while the Y_p horizontal constraints are one sigma values from the Y_p determinations in Table 1. The $(^7\mathrm{Li/H})_p$ horizontal constraints are those adopted by Copi et al.

Photoionization models of extragalactic H II regions do not agree with observations and $t^2 \sim 0.03$ values are needed to reach agreement between models and observations. Even higher t^2 values are needed for some WR galaxies.

Determinations by different groups, are consistent with $Y_p = 0.234 \pm 0.005$. From this Y_p value, $(\mathrm{D/H})_p = (1.9 \pm 0.4) \times 10^{-4}$ and SBBN it follows that $N_\nu = 3.1 \pm 0.5$, in excellent agreement with the Z^0 results.

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