Chemical Abundances in our Galaxy and Other Galaxies Derived from H II Regions

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Abstract. We discuss the accuracy of the abundance determinations of H II regions in our Galaxy and other galaxies. We focus on the main observational constraints derived from abundance determinations that have implications for models of galactic chemical evolution: a) the helium to hydrogen abundance ratio, He/H; b) the oxygen to hydrogen abundance ratio, O/H; c) the carbon to oxygen abundance ratio, C/O; d) the helium to oxygen and helium to heavy elements abundance ratios, $\Delta Y/\Delta O$ and $\Delta Y/\Delta Z$; and e) the primordial helium abundance, Y_p.

1. Introduction

The H II region abundances provide important observational constraints to test models of stellar evolution, models of the chemical evolution of galaxies, and models of the evolution of the universe as a whole.

Reviews on the abundances of Galactic and extragalactic H II regions have been presented before (e. g. Peimbert, 1993, 1999; Garnett, 1999) Henry & Worthey, 1999.

2. Temperature differences and abundance determinations

From emission line spectra of Galactic and extragalactic H II regions it is possible to determine abundance ratios, good quality spectra usually permit to derive electron temperatures like $T_e(\mathrm{O\ III})$ and $T_e(\mathrm{N\ II})$ from the [O III] 4363/5007 and [N II] 5755/6584 line ratios.

Often only $T_e(\mathrm{O\ III})$ is available and to estimate the temperature of the regions of low degree of ionization photoionization models have been used. For example, to determine $T_e(\mathrm{O\ II})$ Izotov et al. (1997), Izotov & Thuan (1998), and Deharveng et al. (2000) have used the models by Stasinska (1990) that provide a $T_e(\mathrm{O\ III})$ versus $T_e(\mathrm{O\ II})$ relationship. Photoionization models have been used also to estimate the ionization correction factor for those elements that have not been observed in all the stages of ionization present in the nebulae.

There are other methods to determine the electron temperature, like: the ratio of the Balmer continuum to a Balmer line, the ratio of He I/H I

lines, and the ratio of recombination lines of C II and O II to forbidden lines of [C III] and [O III]; these other methods usually yield electron temperatures substantially smaller than those provided by T_e(O III) (e.g. Peimbert, 1967; Peimbert et al., 1993, 1995; Liu et al., 2000). Several explanations have been proposed for the T_e differences, the main ones are: temperature variations, density variations, and chemical inhomogeneities (e.g. Peimbert, 1967, 1971; Torres-Peimbert et al., 1990; Viegas & Clegg, 1994; Liu et al., 2000). Recent discussions on this subject have been presented by Peimbert (1995), Stasinska (1996, 1998, 2000), and Liu et al. (2000).

Detailed photoionization models of I Zw 18, NGC 2363, and NGC 346 yield T_e(O III) values from 10% to 15% smaller than observed, probably indicating that there are additional heating sources not considered by the models, like the deposition of mechanical energy (Stasinska & Schaerer, 1999; Luridiana et al., 1999; Relaño & Peimbert, 2000).

The differences in T_e should be taken into account to derive accurate abundance ratios.

3. He/H

To derive accurate He/H abundance ratios it is necessary to use accurate temperatures and densities. Due to the collisional contribution to the He I line intensities the higher the density the lower the computed He/H ratio. Due to the density variations present in H II regions it is well known that N_e(rms) is smaller than the densities derived from the ratio of two forbidden lines, in general it can be shown that N_e^2(local) $> N_e^2$(rms) $= \epsilon N_e^2$(local), where ϵ is the filling factor and for giant extragalactic H II regions is typically of the order of 0.01. Consequently the use of N_e(rms) yields a higher limit to the He/H ratio.

For some objects only the N_e derived from the [S II] lines is available and therefore the N_e(S II) density has been used to determine the He/H ratio. Izotov et al. (1994) pointed out that the region where the [S II] lines originate is not representative of the region where the He I lines originate, and proposed to determine self consistently the density from five of the best observed He I lines, adopting T_e(O III) as the representative temperature for the regions where the He I and H I lines originate.

Most He/H determinations have been made by adopting T_e(O III). T_e(O III) provides us with an upper limit to T_e(He II) for the two following reasons: a) for metal poor H II regions T_e(O III) $> T_e$(O II), and the He I lines originate both in the O III and the O II zones, b) even

if the [O III] and the He I lines originate in the same zone, in the presence of temperature variations it can be shown that $T_e(\text{O III}) > T_e(\text{He II})$.

Peimbert et al. (2000a) from nine He I lines of NGC 346, the brightest H II region in the Small Magellanic Cloud, derived self-consistently $N_e(\text{He II})$, He/H, and $T_e(\text{He II})$. They derived a $T_e(\text{He II})$ value 9% smaller than $T_e(\text{O III})$. The maximum likelihood method implies that the lower the temperature the higher the density and the lower the derived He/H ratio, this is a systematic effect and implies that the He/H ratios derived from $T_e(\text{O III})$ are upper limits to the real He/H value. From photoionization models of giant H II regions based on CLOUDY (Ferland, 1996) it is found that $T_e(\text{He II})$ is from 3% to 12% smaller than $T_e(\text{O III})$ (Peimbert et al., 2000c).

4. O/H

The abundances of the Sun and the Orion nebula have been used as probes of Galactic chemical evolution and as standards for stars and gaseous nebulae of the solar vicinity. Therefore it is important to compare them since they have been derived using different methods.

A decade ago the O/H difference between the Sun and the Orion nebula in the literature amounted to 0.44dex, at present the difference is only of 0.11dex (see Table I). The change is due to two recent results for Orion and one 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 under the assumption of $t^2 = 0.000$, b) the increase of 0.08dex due to the fraction of oxygen embedded in dust grains, and c) the decrease of 0.10dex due to a new solar determination.

Table I. Oxigen abundance for Orion and the Sun (given in log O/H + 12).

Orion Nebula			Sun
(Gas; $t^2 = 0.000$)	(Gas; $t^2 = 0.024$)	($t^2 = 0.024$ + Dust)	
8.49 ± 0.06^a	...	...	8.93 ± 0.04^b
8.47 ± 0.06^c	8.64 ± 0.06^c	8.72 ± 0.07^c	8.83 ± 0.06^d

[a] Shaver et al., 1983; Osterbrock et al., 1992; Rubin et al., 1993; Deharveng et al., 2000.

[b] Grevesse & Anders, 1989.
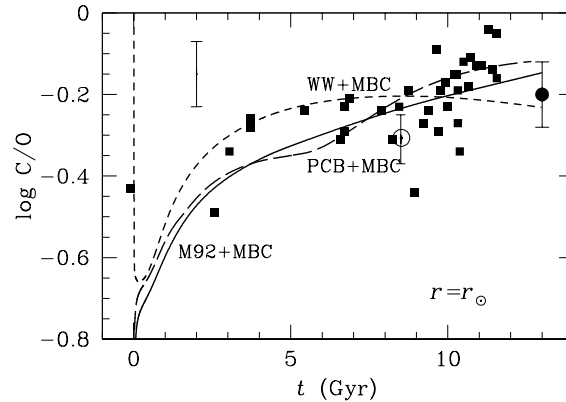
[c] Esteban et al., 1998.

[d] Grevesse & Sauval, 1998.

Figure 1. C/O evolution of the solar vicinity. Open circle, solar value from Grevesse & Sauval (1998). Filled circle, computed value at $r = r_\odot$ from H II region radial gradients by Peimbert (1999). Filled squares, dwarf stars at $r = r_\odot \pm 1$kpc from Gustafsson et al. (1999), the ages of the stars were scaled to the age of the models. Predictions from models assuming yields by Marigo et al. (1996, 1998) for low and intermediate mass stars in combination with yields for massive stars by Woosley & Weaver (1995) and Woosley et al. (1993), Portinari et al. (1998) or Maeder (1992).

To derive the total O/H values in H II regions it is necessary to estimate the fraction of O embedded in dust grains. For the Orion nebula and NGC 346 (the brightest H II region in the SMC) it is found that Fe_{gas}/O_{gas} is 1.2 ± 0.3dex smaller than in the Sun (Esteban et al., 1998; Relaño & Peimbert, 2000; Grevesse & Sauval, 1998). For the Orion nebula and for O poor extragalactic H II regions it is found that Si_{gas}/O_{gas} is 0.46 ± 0.1dex and 0.39 ± 0.1dex smaller respectively than in the Sun (Esteban et al., 1998; Garnett et al., 1995a; Grevesse & Sauval, 1998). From the Si/O and Fe/O underabundances in H II regions it is estimated that the missing Si and Fe fractions are in dust grains in the form of molecules that trap about 20% of the oxygen atoms.

5. C/O

The observed C/O ratios are important to test the different sets of stellar yields present in the literature and the importance of the O-rich galactic outflows.

The increase of C/O with the age of the disk at the time the stars of the solar vicinity were formed is due only to the ejecta of massive stars. Models with yields by Maeder (1992) or yields by Portinari et al. (1998) can reproduce the increase of C/O with age in the solar neighborhood, while models assuming yields by Woosley & Weaver (1995) and Woosley

et al. (1993) do not (Carigi, 2000; Henry et al., 2000; Jinliang et al., 2000).

In Figure 1 we present the evolution of C/O with time for three different sets of yields, from chemical evolution models by Carigi (2000), as well as the C/O values for a group of dwarf stars of different ages.

From chemical evolution models of the Galaxy Carigi (2000) finds that those computations based on yields by Maeder (1992) predict negative C/O gradients while those based on the yields by Woosley & Weaver (1995), Woosley et al. (1993), or Portinari et al. (1998) predict flat gradients. The observations of negative C/O gradients in our Galaxy (Peimbert, 1999 and references therein), M101 and NGC 2403 (Garnett et al., 1999) support those models based on the yields by Maeder (1992).

Table II. α values from models of the Galaxy by Carigi (2000) compared with observations, where α is given by: log C/O $= \alpha$ log O/H.

Observations	α	Model Yields	α
Galactic H II regions	0.93 ± 0.60^a	Woosley & Weaver (1995)	-0.28
Galactic B stars	1.69 ± 2.34^b	Portinari et al. (1998)	0.06
M101 H II regions	1.10 ± 0.29^c	Maeder (1992)	0.94
NGC 2403 H II regions	0.50 ± 0.43^c	Metal independent	0.00

[a] Esteban et al., 1998, 1999a, b; Peimbert, 1999.

[b] Gummersbach et al., 1998; Hibbins et al., 1998.

[c] Garnett et al., 1999.

A powerful way to present the previous result is by means of the parameter α given by log C/O $= \alpha$ log O/H. In Table II we present the α values for models and observations.

In Figure 2 we present the best model for the solar vicinity by Carigi (2000) in the C/O versus O/H plane. In this figure we also present the observed values for the Orion nebula, the Sun, and the extragalactic H II regions.

6. $\Delta Y/\Delta O$, $\Delta Y/\Delta Z$

M17 is the best H II region to determine the helium abundance because among the brightest Galactic H II regions it is the one with the highest degree of ionization and consequently with the smallest correction for the presence of He^0(Peimbert et al., 1992; Deharveng et al., 2000). By combining the abundances of M17 and NGC 346 the $\Delta Y/\Delta O$ and
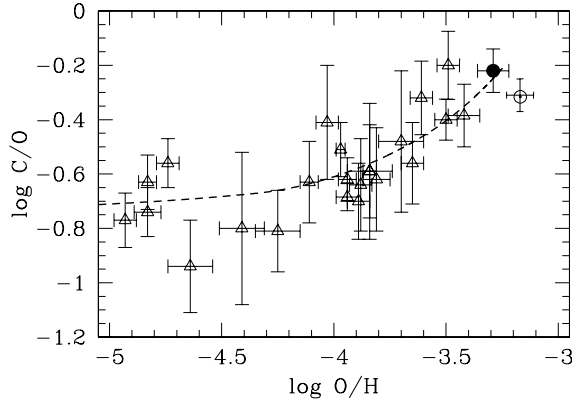
Figure 2. Log C/O versus log O/H relation. Open circle, solar value from Grevesse & Sauval (1998). Filled circle, Orion nebula value from Esteban et al. (1998). Open triangles, observational data for irregular galaxies, M101 and NGC 2403 (Garnett et al. 1995b, 1999; Izotov & Thuan 1999). Dashed line, the prediction of the best model for the solar vicinity by Carigi (2000), which is based on the yields by Maeder (1992) and van den Hoek & Groenewegen (1997).

$\Delta Y/\Delta Z$ values presented in Table III were derived, the recommended values are those for $t^2 = 0.037$.

Based on their two-infall model for the chemical evolution of the Galaxy Chiappini et al. (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. For massive stars $\Delta Y/\Delta O$ increases along the sequence Portinari et al. (1998) $\rightarrow$ Maeder (1992) $\rightarrow$ Woosley & Weaver (1995), while for intermediate mass stars it increases along the sequence van den Hoek & Groenewegen (1997) $\rightarrow$ Renzini & Voli (1981) $\rightarrow$ Marigo et al. (1996). The differences between all the models and the observations for $t^2 = 0.000$ are significant, while the differences between some of the models and the observations for $t^2 = 0.037$ probably are not.

From a group of 10 irregular and blue compact galaxies Carigi et al. (1995) found $\Delta Y/\Delta O = 4.48 \pm 1.02$, where they added 0.2 dex to the O/H abundance ratios derived from the nebular data to take into account the temperature structure of the H II regions and the fraction of O embedded in dust; moreover they also estimated that O constitutes 54% of the Z value. Izotov & Thuan (1998) from a group of 45 supergiant H II regions of low metalicity derived that $\Delta Y/\Delta Z =$

2.3±1.0; we find from their data that $\Delta Y/\Delta Z = 1.46 \pm 0.60$ by adding 0.2 dex to the O abundances to take into account the temperature structure of the H ɪɪ regions and the fraction of O embedded in dust; furthermore from their data we also find that $\Delta Y/\Delta O = 2.7 \pm 1.2$ by assuming that O constitutes 54% of the Z value.

Carigi et al. (1995), based on yields by Maeder (1992), computed closed box models adequate for irregular galaxies obtaining $\Delta Y/\Delta O = 2.95$. They also computed models with galactic outflows of well mixed material that yielded $\Delta Y/\Delta O$ values similar to those of the closed box models, and models with galactic outflows of O-rich material that yielded values higher than 2.95. The maximum $\Delta Y/\Delta O$ value that can be obtained with models of O-rich outflows, without entering into contradiction with the C/O and $(Z - C - O)/O$ observational constraints, amounts to 3.5.

Carigi et al. (1999), based on yields by Woosley et al. (1993) and Woosley & Weaver (1995), computed chemical evolution models for irregular galaxies and found very similar values for closed box models with bursting star formation and constant star formation rates that amounted to $\Delta Y/\Delta O = 4.2$. The models with O-rich outflows can increase the $\Delta Y/\Delta O$, but they predict higher C/O ratios than observed.

O-rich outflows are not very important for the typical irregular galaxy because they predict C/O and Z/O ratios higher than observed. Larsen et al. (2000) reach the same conclusion based on models to explain the N/O ratios.

Table III. Helium to oxygen and helium to heavy element ratios by mass: $\Delta Y/\Delta O$ and $\Delta Y/\Delta Z$.

Object	$\Delta Y/\Delta O$	$\Delta Y/\Delta Z$
M17 $(t^2 = 0.000)$[a]	13.3 ± 2.7	3.8 ± 1.1
M17 $(t^2 = 0.037)$[a]	5.4 ± 1.1	2.1 ± 0.6
Solar vicinity models[b]	$2.4 - 4.6$	$1.1 - 2.1$
Irregular galaxies, observations[c,d]	3.5 ± 1.1	1.9 ± 0.6
Irregular galaxies, models[c,e]	$2.9 - 4.2$	$1.6 - 2.3$

[a] Peimbert et al., 1992, 2000a; Esteban et al., 1999a.

[b] Copi, 1997; Chiappini et al., 1997; Carigi, 2000.

[c] Carigi et al., 1995.

[d] Izotov & Thuan, 1998.

[e] Carigi et al., 1999.

7. Primordial Helium Abundance, Y_p

Recent discussions on the determination of Y_p have been presented by
Thuan & Izotov (2000) and Peimbert & Peimbert (2000). Izotov &
Thuan (1998), from the Y – O/H linear regression for a sample of 45
BCGs, and Izotov et al. (1999), from the average for the two most
metal deficient galaxies known (I Zw 18 and SBS 0335–052), derive Y_p
values of 0.2443±0.0015 and 0.2452±0.0015 respectively. Alternatively,
Peimbert et al. (2000a, b), based on NGC 346, NGC 2363, and I Zw 18,
derive $Y_p = 0.2351 \pm 0.0022$. Most of the difference is due to the $T_e(\mathrm{He\ II})$
used by both groups, while Izotov & Thuan and Izotov et al. assume
that $T_e(\mathrm{He\ II})$ equals $T_e(\mathrm{O\ III})$, Peimbert et al. find that $T_e(\mathrm{He\ II})$ is
about 9% smaller than $T_e(\mathrm{O\ III})$.

Under the framework of standard Big Bang nucleosynthesis compu-
tations it is possible to compare the Y_p, D_p, and Li_p values through the
predicted Ω_b values.

The high Y_p determination of $0.2452 \pm 0.0015(1\sigma)$ combined with
standard Big Bang nucleosynthesis computations (Thomas et al., 1994;
Fiorentini et al., 1998) implies that, at the 1σ confidence level, $\Omega_b h^2$ is
in the 0.0139 to 0.0190 range. For $h = 0.65$ the Y_p value corresponds to
$0.033 < \Omega_b < 0.045$, a value in very good agreement with that derived
from the primordial deuterium abundance, D_p, determined by Burles
& Tytler (1998) that amounts to $0.041 < \Omega_b < 0.047(1\sigma)$ for $h = 0.65$.

The low Y_p determination of $0.2351 \pm 0.0022(1\sigma)$ implies that, at
the 1σ confidence level, $\Omega_b h^2$ is in the 0.0060 to 0.0081 range. For $h =
0.65$ the Y_p value corresponds to $0.014 < \Omega_b < 0.019$, a value in good
agreement with that derived from the primordial lithium abundance,
Li_p, determined by Suzuki et al. (2000) that amounts to $0.015 < \Omega_b <
0.033(2\sigma)$ for $h = 0.65$, in very good agreement with the low redshift
estimate of the global budget of baryons by Fukugita et al. (1998)
who find $0.015 < \Omega_b < 0.030(1\sigma)$ for $h = 0.65$, and consistent with
their minimum to maximum range for redshift $z = 3$ that amounts to
$0.012 < \Omega_b < 0.070$ for $h = 0.65$.

The discrepancy between the low Y_p value and the D_p value should
be studied further.

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