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# CHEMICAL COMPOSITION OF GALACTIC H II REGIONS

M. Peimbert
Instituto de Astronomía, Universidad Nacional Autónoma de México

RESUMEN

Se presenta una revisión sobre las determinaciones de la composición química de regiones H II de la vecindad solar: M8, M17 yM42 (Orion). Se presenta evidencia observacional sobre la existencia de variaciones de la temperatura en las regiones H II; dichas variaciones no se pueden explicar a partir de modelos de fotoionización de nebulosas con composición química uniforme. Se analizan posibles causas de estas variaciones. Se presentan tablas de abundancias y errores probables ($1\sigma$) para Orion, M8 y M17. Estas abundancias se comparan con las solares y con las de estrellas B de la vecindad solar. También se hace una comparación con las regiones H II extragalácticas y se discute el enriquecimiento del carbono y el valor de $\Delta Y/\Delta Z$.

ABSTRACT

A review of the chemical compositions of M8, M17 and M42 (Orion) is presented. Observational evidence on the presence of spatial temperature variations inside H II regions is presented; these variations can not be explained by photoionization models of nebulae with uniform distributions of dust and chemical composition. Possible causes of these temperature variations are analized. Abundance tables with probable errors ($1\sigma$) for Orion, M8 and M17 are presented. These abundances are compared with those of the Sun and B stars of the solar neighborhood. The abundances of Galactic H II regions are compared with those of extragalactic H II regions; the enrichment of the carbon abundance and the $\Delta Y/\Delta Z$ value are briefly discussed.

*Key words:* **H II REGIONS — ISM: INDIVIDUAL OBJECTS (M8, M17, M42) — ISM: ABUNDANCES**

## 1. INTRODUCTION

There have been many abundance determinations of the Galactic H II regions M8, M17 and M42 in the last few years. There are controversial results on the ionization correction factors and on the temperature structure of the nebulae. There are two types of abundance determinations: those based on recombination lines that depend weakly on the temperature structure of the nebulae (H, He, C and O) and those based on collisionally excited lines that depend strongly on the temperature structure of the nebulae (C, N, O, Ne, Si, S, Cl, Ar, Fe and Ni). To derive the same abundances of C and O from recombination and collisionally excited lines, values of the mean square temperature variation over the observed volume, $t^2$, of about 0.04 are required.

In §2 a table of the abundances of the elements for nebulae with constant temperature along the line of sight ($t^2 = 0.00$) and for the presence of strong temperature fluctuations ($t^2 = 0.04$ and 0.046) is presented.

In §3 we discuss possible physical processes that could produce the large $t^2$ values measured. In §4 we compare the H II regions with stars of the solar neighborhood and with extragalactic H II regions and derive some consequences.

## 2. ABUNDANCES

Table 1 shows the abundances of M8, M17 and Orion for two values of $t^2$ defined by (Peimbert 1967):

$$t^2 = \frac{\int T_e^2 N_i N_e d\Omega dl - T_o^2 \int N_i N_e d\Omega dl}{T_0^2 \int N_i N_e d\Omega dl}. \quad (1)$$

The values that I favor are: $t^2 = 0.04$ for M17 and Orion and $t^2 = 0.046$ for M8. Abundances for other $t^2$ values can be interpolated or extrapolated from Table 1 or from the original papers (see also Walter et al. 1992). In what follows I will discuss the main issues and controversies regarding the abundance determinations.

TABLE 1
CHEMICAL COMPOSITION FOR ORION, M8 AND M17[a]

| Element | Orion | M8 | M17 | Orion | M8 | M17 |
|---|---|---|---|---|---|---|
| He | 11.02 | 11.02 | 11.02 | 11.00 ± 0.02 | 11.00 ± 0.02 | 11.00 ± 0.012 |
| C | 8.54 | 8.69 | 8.74 | 8.53 ± 0.06 | 8.55 ± 0.10 | 8.73 ± 0.05 |
| N | 7.65 | 7.57 | 7.71 | 7.87 ± 0.08 | 7.80 ± 0.08 | 8.01 ± 0.10 |
| O | 8.51 | 8.50 | 8.51 | 8.76 ± 0.06 | 8.74 ± 0.06 | 8.81 ± 0.06 |
| Ne | 7.79 | 7.85: | 7.80 | 8.07 ± 0.08 | 7.99 ± 0.20 | 8.13 ± 0.08 |
| Si | 6.19 | ... | ... | 6.73 ± 0.10 | ... | ... |
| S | 6.97 | 6.99 | 6.99 | 7.22 ± 0.10 | 7.38 ± 0.08 | 7.32 ± 0.10 |
| Cl | 5.08 | ... | 5.18 | 5.31 ± 0.15 | ... | 5.48 ± 0.20 |
| Ar | 6.41 | 6.47 | 6.38 | 6.54 ± 0.10 | 6.76 ± 0.10 | 6.63 ± 0.10 |
| Fe | 6.43 | 5.93 | 6.62 | 6.64 ± 0.10 | 6.16 ± 0.15 | 6.96 ± 0.20 |
| Ni | 5.15 | ... | ... | 5.25 ± 0.15 | ... | ... |
| $t^2$ | 0.00 | 0.00 | 0.00 | 0.04 | 0.046 | 0.04 |
| References[b] | 1,2,3,4 | 5 | 1,5 | 1,2,3,4,6 | 5 | 1,5,6 |

[a]Given in $12 + \log N(\text{X})/N(\text{H})$.
[b](1) Peimbert et al. 1992a, hereinafter PTPR; (2) Osterbrock et al. 1992; (3) Rubin et al. 1993; (4) This paper; (5) Peimbert et al. 1993b; (6) Peimbert et al. 1993a.

### 2.1. Helium

From optical and radio observations it has been found that the $He^+/H^+$ ratio decreases with distance from the Trapezium (e.g., Peimbert & Torres-Peimbert 1977, Peimbert et al. 1988, Pogge, Owen & Atwood 1992), this change has been interpreted as due to the presence of neutral helium inside the Orion nebula. From ionization structure models of the Orion nebula, Rubin et al. (1991) find a substantial amount of neutral helium present, while Baldwin et al. (1991) find a negligible amount; this discrepancy needs further investigation.

The variation of the $Ne^{++}/O^{++}$ ratio with O ionization degree seems to be correlated with the $He^+/H^+$ ratio (see §2.4.) indicating that the $He^+/H^+$ variation is real and supporting the presence of neutral helium inside the Orion nebula.

The best He/H optical determination is that of M17, therefore we will compare it with some of the best radio determinations. From radio observations of M17 it is found that there is a trend in the $He^+/H^+$ ratios in the sense that the higher the $n$ value the smaller the $He^+/H^+$ ratio (see Table 2 of this paper and Fig. 16 in

PTPR). Other H II regions also show this trend (Peimbert et al. 1992a and references therein); there are several explanations for this behavior, the main ones are: a) that it is a beam-size effect produced by the smaller size of the $He^+$ zone than the $H^+$ zone, as is the case in the Orion nebula (e.g., Peimbert et al. 1988), b) that for intermediate $n$ values the H lines are closer to case A than the He I lines while for high $n$ values both H I and He I lines approach case B (Ferland & Cota 1988; Baldwin et al. 1991).

TABLE 2
$N(He^+)/N(H^+)$ VALUES FOR M17S DERIVED FROM RADIO DATA

| Line | HPBW | $He^+/H^+$ | Reference[a] |
|---|---|---|---|
| $41\alpha$ | 18″ | 0.122 ± 0.024 | 1 |
| $53\alpha$ | 39 | 0.108 ± 0.004 | 1 |
| $76\alpha$ | 138 | 0.097 ± 0.005 | 2 |
| $86\alpha$ | 210 | 0.102 ± 0.005 | 3 |
| $91\alpha$ | 192 | 0.090 ± 0.013 | 4 |
| $109\alpha$ | 144 | 0.093 ± 0.003 | 5 |
| $114\beta$ | 192 | 0.090 ± 0.011 | 4 |
| $130\gamma$ | 192 | 0.091 ± 0.011 | 4 |

[a](1) Peimbert et al. 1988; (2) McGee & Newton 1981; Lichten et al. 1979; (4) Peimbert et al. 1992b; (5) Churchwell et al. 1978.

There is some confusion in the literature about the case definition for the He I triplets. While some authors (e.g., Brocklehurst 1972; PTPR) mention that the He I triplets are in case A because nebulae are assumed to be optically thin to triplet transitions, other authors (e.g., Ferland & Cota 1988; Baldwin et al. 1991; Smits 1991) argue that the He I triplets are in case B because the $b_n$ computations for an optically thin nebula without transitions to the term $n = 1$ are equivalent to those of hydrogen case B. The criterion used by the second group is better. The discussion by PTPR on possibility b) of the previous paragraph is wrong because they assumed that the $b_n$ computations for the He I triplets are equivalent to those of hydrogen case A. I will discuss possibility b) under the assumption that the $b_n$ computations for the He I triplets are equivalent to those of hydrogen case B.

In radio determinations of $He^+/H^+$ values the same emissivity has been assumed for the He I and H I recombination lines that originate in the same $n$ level and consequently that

$$\frac{N(\mathrm{He}^+)}{N(\mathrm{H}^+)} = \frac{I(\mathrm{He}^0, n\alpha)}{I(\mathrm{H}^0, n\alpha)}. \qquad (2)$$

There are two extreme situations: a) when the H I lines are in case B, the He I singlets and triplets are in case B and equation (2) is correct and b) when the H I lines are in case A, the He I singlets are in case A and the He I triplets are in case B. Since about one fourth of the recombinations go to singlet states and three fourths go to triplet states the H I emissivities relative to those of He I are reduced by 3/4 of the difference between cases B and A. ¿From the computations by Hummer & Storey (1992) the maximum reduction in the emissivities of H I between cases A and B for $n > 10$ amounts to 15%, which for $10^2 < N_e < 10^4$ cm$^{-3}$, the value for M17, corresponds to $30 < n < 50$; therefore 3/4 of this difference corresponds to a maximum reduction of 11%. For higher $n$ values ($n > 50$) and for intermediate situations between case A and case B for the H I lines, the reduction of the H I line emissivities relative to those of He I is considerably smaller than 11% and equation (2) yields slightly higher $N(He^+)/N(H^+)$ ratios than the real ones.

For M17 the $53\alpha$ $I(He^+)/I(H^+)$ value of $0.108 \pm 0.004$ yields an upper limit to the N(He)/N(H) value due to possible deviations from case A of the H I lines. Moreover, based on infrared observations of Ne II and S IV lines in M17S it has been found that the most highly ionized material lies in the region comprised by the 39″ beam size of the $53\alpha$ observatios and that in this region the $He^+$ and $H^+$ Stromgren spheres coincide (Lester et al. 1983). Alternatively the average of the observations with $n \geq 76$ yields $N(\mathrm{He}^+)/N(\mathrm{H}^+) = 0.095 \pm 0.002$, in this case the deviations of the H I lines from case A are negligible, on the other hand the beam size goes from 138″ to 210″ and neutral helium is expected, therefore this result is a lower limit to the $N(\mathrm{He})/N(\mathrm{H})$ ratio. ¿From these considerations we conclude from the radio data that for M17S $0.108 \geq N(\mathrm{He})/N(\mathrm{H}) \geq 0.095$ and consequently that $N(\mathrm{He})/N(\mathrm{H}) = 0.102 \pm 0.006$, in excellent agreement with the optical determinations presented in Table 1.

### 2.2. Carbon

The $C^{++}$ abundance can be derived from the C II $\lambda$4267 recombination line and from the C III $\lambda\lambda$1907+1909 collisionally excited lines. Frequently the abundances derived from $\lambda$4267 are higher than those derived from $\lambda\lambda 1907 + 1909$ if a value of $t^2 = 0.00$ is assumed. To reconcile both $C^{++}$ abundances, values of $t^2$ different from zero are needed. The relatively high C abundances derived from the $\lambda$4267 C II line have been controversial and the presence of an unknown mechanism strengthening it has been sought without success. Storey (1981) finds that at nebular temperatures the dielectronic contribution to $\lambda$4267 amounts to less than 0.2 per cent. To reach agreement between the $\lambda$4267 and $\lambda\lambda 1907 + 1909$ $C^{++}$ abundances, values of $t^2 = 0.053 \pm 0.013$ for the Orion nebula and of $0.046 \pm 0.01$ for M8 are needed. For M17 the $\lambda\lambda 1907 + 1909$ lines have not been detected.

The C/H values in Table 1 are based on the $\lambda$4267 line and are almost independent of the $t^2$ value for Orion and M17 because most of the C is in the $C^{++}$ ionization stage. Alternatively there is some $t^2$ dependence for M8 because the ionization correction factor, $i_{\mathrm{cf}}$, to the $C^{++}$ (4267) abundance is based on the $[C^{++}(1909) + C^{+}(2326)]/C^{++}(1909)$ ratio.

### 2.3. Oxygen

Peimbert, Storey, & Torres-Peimbert (1993a) have derived $O^{++}/H^+$ ratios from O II recombination lines, they have compared these abundances with those derived from [O III] collisionally excited lines. The recombination abundances are higher than the collisional ones for $t^2 = 0.00$. To reach agreement between both types of determinations values of $t^2 = 0.038 \pm 0.011$ for Orion and of $0.030 \pm 0.012$ for M17 have been derived. The O II line intensities have not been measured for M8. The O abundances presented in Table 1 are based on the [O II] and [O III] line intensities.

### 2.4. Neon

The Ne/H abundance ratio has been often derived from (e.g., Peimbert & Costero 1969)

$$\frac{N(\mathrm{Ne})}{N(\mathrm{H})} = \frac{N(\mathrm{O})}{N(\mathrm{O}^{++})}\frac{N(\mathrm{Ne}^{++})}{N(\mathrm{H}^{+})} = i_{\mathrm{cf}}(\mathrm{Ne}^{++})\frac{N(\mathrm{Ne}^{++})}{N(\mathrm{H}^{+})}. \qquad (3)$$

In Figure 1 we present the $Ne^{++}/O^{++}$ versus $O^{+}/O^{++}$ ratio from the data of Peimbert & Torres-Peimbert (1977), a clear relation is present in the sense that the higher the O degree of ionization the higher the $Ne^{++}/O^{++}$ ratio. A similar dependence was found for M17 (see Figure 9 in PTPR). These results indicate that equation (3) is not correct and that a different $i_{\mathrm{cf}}(\mathrm{Ne}^{++})$ has to be used. These results also imply that some $Ne^{+}$ coexists with $O^{++}$. We consider that the higher the fraction of O in the $O^{++}$ stage the better is the approximation presented by equation (3). We have computed the Ne/O abundance from equation (3) for the Orion nebula by considering only the three regions with the highest degree of ionization in Figure 1, the resulting value is 0.16 dex higher than the value derived by Peimbert & Torres-Peimbert (1977).

For M8 the Ne/O value derived from equation (3) is 0.31 dex smaller than the $Ne^{+}/H^{+}$ value derived from infrared data and an average of the $Ne^{+}/H^{+}$ value and that given from equation (3) is presented in Table 1. By placing the M8 observations in Figure 1 and by analogy with the Orion nebula an $i_{\mathrm{cf}}(\mathrm{Ne}^{++})$ value about 0.2 dex higher than that given by equation (3) is derived in good agreement with the Ne/O value for M8 presented in Table 1.

The ionization structure models by Mathis & Rosa (1991) and Stasinska (1990) agree with equation (3) and are not able to explain the results presented in Figure 1 of this paper nor those in Figure 9 of PTPR. The effects of dust in the radiation field or different stellar atmospheres need to be considered to try to explain those figures.

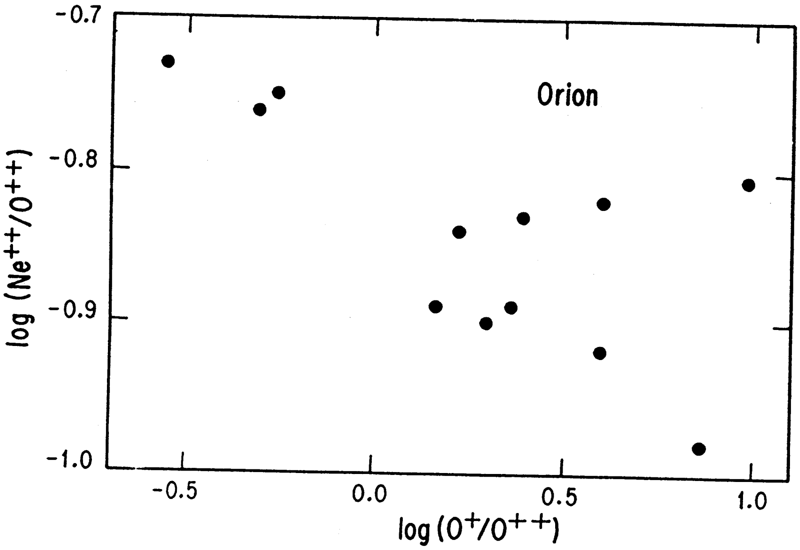


Fig. 1.— $N(Ne^{++})/N(O^{++})$ as a function of ionization degree for the Orion nebula. Data from Peimbert & Torres-Peimbert (1977) for $t^2 = 0.035$.

### 2.5. N, S, Cl, Ar

The abundances of N, S, Cl and Ar relative to H are based on the ratio of collisionally excited lines to a recombination line, therefore these abundances are sensitive to the adopted $t^2$ value.

The ionization structure models by Mathis & Rosa (1991) that apply to M17 predict substantial amounts of $S^{+3}$ and $Ar^{+3}$ that were not detected by PTPR. This might be due to dust transfer problems, to geometrical effects, or to stellar atmospheres with weaker fluxes beyond the ionization potentials of $S^{+2}$ and $Ar^{+2}$ than those used by Mathis & Rosa.

### 2.6. Si, Fe, Ni

The Si, Fe, and Ni abundances are also derived from forbidden lines and are strongly sensitive to $t^2$, this is even more so for Si since its abundance has been derived from the $Si^{++}$ lines at 1883 and 1892Å. These elements are about one order of magnitude underabundant in the Orion nebula because large fractions of them are embedded in dust grains (Osterbrock et al. 1992; Rubin et al. 1993). The underabundance of Fe relative to O is highest in M8, intermediate in Orion and smallest in M17, the Fe/O variation might be due to dust destruction (Peimbert et al. 1993b).

## 3. TEMPERATURE STRUCTURE

As we saw before, the C II and O II recombination lines together with the C III and O III collisionally excited lines yield $t^2$ values around $0.04 \pm 0.015$ for M8, M17 and Orion. In addition to these large $t^2$ values the comparison of the Balmer continuum temperatures with the forbidden line temperatures also yield $t^2$ values around $0.04 \pm 0.02$ (Peimbert 1967; Sánchez & Peimbert 1991; PTPR). The values imply large temperature variations; these variations, if real, need to be explained by detailed models of the nebulae.

### 3.1. Photoionization Models

Ionization structure models with uniform chemical composition predict $t^2$ values around 0.01, considerably smaller than the observed values (e.g., Garnett 1992; Gruenwald & Viegas 1992). Therefore an additional source of temperature variations is needed to explain the observations.

### 3.2. Dust

As originally suggested by Maciel & Pottasch (1982) and Oliveira & Maciel (1986), photoelectric heating of the gas by grain photoionization is an important mechanism in H II regions. Baldwin et al. (1991) in their model for the Orion nebula considered photoelectric heating and cooling of the gas by grain ionization and grain collisions respectively and found that both effects are significant. From the model by Baldwin et al. (1991), which assumes that the gas and grains are well mixed, Peimbert et al. (1993a) find that $t^2 = 0.004$, a value considerably smaller than that needed to explain the observations.

Non-uniform dust distributions might produce larger $t^2$ values and they should be explored. O'Dell & Hubbard (1965), based on a spherical model found evidence for a hole in the dust to gas ratio in the center of the Orion nebula; this result should be tested using different geometries for the nebula.

### 3.3. Shock Waves

Peimbert, Sarmiento & Fierro (1991) have presented arguments in favor of large $t^2$ values inside H II regions due to shock waves produced by supernovae and by stellar winds from WR and O stars. The presence of shock waves would produce large $t^2$ values. The effect has to be quantified for each nebula; the detection of gas motions with supersonic velocities would help to quantify this effect.

### 3.4. Chemical Inhomogeneities

The presence of chemical inhomogeneities inside H II regions can also produce large $t^2$ values. How well mixed is the interstellar medium in the Galaxy? Inhomogeneities in composition exist in the disk on mixing time scales of less than $10^9$ years. Four clusters with ages in the $3 \times 10^8$ to $1 \times 10^9$ years range show a spread in their Fe/H ratio of 0.2 dex (Boesgaard 1989). Within a given cluster the differences in the Fe/H ratios are smaller than 0.1 dex with the exception of Praesepe where the differences might amount to 0.15 dex (Nissen 1988).

There are two comments that can be made to the previous discussion: a) by sampling stars one is looking at inhomogeneities in the stellar mass range, at smaller masses the inhomogeneities could be larger, b) Fe might be better mixed than O because Fe mainly originates in SN of type Ia while O originates in SN of types II and Ib (e.g., Nomoto et al. 1992).

¿From the work of Cunha & Lambert (1992) and Cunha (1993) it is found that the spread of the O/H ratio in their Ic age group reaches 0.5 dex. Inhomogeneities of O/H in the 0.3 dex to 0.5 dex range in a given nebula can produce $t^2$ values in the 0.03 to 0.04 range.

TABLE 3
ORION ASSOCIATION: OXYGEN ABUNDANCES OF THE STELLAR SUBGROUPS AND OF THE NEBULA[a]

| Object | O (average) | O (range) | References[b] |
|---|---|---|---|
| Subgroups Ia + Ib | 8.60 | 8.54 - 8.66 | 1 |
| Subgroup Ic | 8.68 | 8.46 - 8.96 | 1 |
| Subgroup Id | 8.77 | 8.69 - 8.83 | 1 |
| Nebula ($t^2 = 0.00$) | 8.51 | ... | 2 |
| Nebula ($t^2 = 0.04$) | 8.76 | ... | 2 |

[a] Given in $12 + \log N(\mathrm{O})/N(\mathrm{H})$
[b] (1) Cunha & Lambert 1992; (2) Table 1.

## 4. DISCUSSION

### 4.1. Evolution of the Orion Association

Cunha & Lambert (1992) have divided the B stars of the Orion association into four subgroups according to age: Ia, Ib, Ic and Id. They have found that the O/H abundance increases from Ia to Id, the younger the subgroup the higher the O/H ratio (see Table 3). They argue that this result supports the SN self-enrichment hypothesis of Olive & Schramm (1982). Additional support for this result has been presented by Cunha (1993) that finds a very large spread in the O/H ratio and a small one in the C/H ratio implying that the self-enrichment is due to SN in the 30 to 40 $M_\odot$ range (e.g., Weaver & Woosley 1993).

The Orion nebula O/H value for $t^2 = 0.04$ supports the result of Cunha & Lambert (1992) and Cunha (1993) in favor of self-enrichment; alternatively the O/H result for $t^2 = 0.00$ does not follow the trend of a higher O/H value for the youngest component of the association (see Table 3).

### 4.2. Comparison of Stellar and Nebular Abundances

In Table 4 we present the abundances for the Sun, B stars of the solar vicinity, and B stars of subgroup Id of the Orion association. For the B stars, the errors are given in the original papers or were estimated by comparing the values derived for the same stars in different papers. The errors in the He/H values are about two to three times higher for stars than for H II regions. The CNO solar abundances relative to H are about 0.2 dex higher than those of subgroup Id. The Orion nebula has CNO abundances intermediate between those of the Sun and subgroup Id, and in good agreement with both. The new result derived in this paper for the Ne/H value of the Orion nebula is in excellent agreement with the solar value and with that of B stars. Similarly the S/H ratios for the Orion nebula, the B stars and the Sun are in excellent agreement.

TABLE 4
ABUNDANCES OF THE SOLAR VICINITY STARS[a]

| Element | Sun | B stars | B stars Orion Id |
|---|---|---|---|
| He | 10.99 ± 0.035 | 11.00 ± 0.04 | ... |
| C | 8.56 ± 0.04 | 8.20 ± 0.08 | 8.35 ± 0.08 |
| N | 8.00 ± 0.04 | 7.81 ± 0.08 | 7.81 ± 0.08 |
| O | 8.93 ± 0.035 | 8.68 ± 0.08 | 8.77 ± 0.08 |
| Ne | 8.09 ± 0.10 | 7.97 ± 0.10 | ... |
| Si | 7.55 ± 0.05 | 7.58 ± 0.10 | ... |
| S | 7.21 ± 0.06 | 7.21 ± 0.10 | ... |
| Cl | 5.50 ± 0.30 | ... | ... |
| Ar | 6.56 ± 0.10 | ... | ... |
| Fe | 7.51 ± 0.03 | 7.72 ± 0.20 | ... |
| Ni | 6.25 ± 0.04 | ... | ... |
| References[b] | 1,2,3,4,5 | 6 | 7 |

[a]Given in $12 + \log N(\mathrm{X})/N(\mathrm{H})$.
[b](1) Grevesse & Anders 1989; (2) Grevesse et al. 1990; (3) Biémont et al. 1991; (4) Holweger et al. 1991; (5) Hannaford et al. 1992; (6) Gies & Lambert 1992; (7) Cunha 1993.

To compare M8 and M17 with the Orion nebula and with the stellar values it has to be considered that the galactocentric distances of M8 and M17 are 1.9 kpc and 2.5 kpc smaller, respectively, than that of the Orion nebula, and in the presence of Galactic abundance gradients higher heavy element abundances are expected for M8 and M17 relative to those of the Orion nebula. The distance baselines are small and therefore it is not possible to derive accurate abundance gradients. Nevertheless the averages of the C, N, O, Ne, and S abundances for M8 and M17 are 0.04 dex and 0.11 dex higher than for the Orion nebula.

### 4.3. Evolution of C/O versus O/H

In Figure 2 we present C/O versus O/H values for the Galactic H II regions, the Sun and the extragalactic H II regions. The solid arrows for the Galactic H II regions indicate the displacement if the O/H values are increased by 0.08 dex under the assumption that a fraction of the O atoms is embedded in dust grains (Meyer 1985).

The C/O and O/H values for I Zw 18 do not follow the trend of the other O/H poor objects. There are at least two possible explanations in the literature for this anomaly (Dufour et al. 1988 and references therein) that the extremely low O/H value is due to: a) escape of O-rich supernova ejecta from the galaxy (while the C produced by intermediate mass stars does not escape), or b) accretion of primordial gas without heavy elements. To reach the relation defined by the other objects in Fig. 2 possibility a) would imply a $12+\log \mathrm{O/H} \sim 7.7$ value (see the arrow with dashed lines) while possibility b) would imply a $12+\log \mathrm{O/H} \sim 8.6$ value. From the mass versus heavy element content relation (Lequeux et al. 1979; Skillman et al. 1988) and the mass of $6 \times 10^8 M_\odot$ derived by Lequeux & Viallefond (1980) we would expect a $12+\log \mathrm{O/H}$ value of about 7.7 for I Zw 18 in favor of possibility a) above.

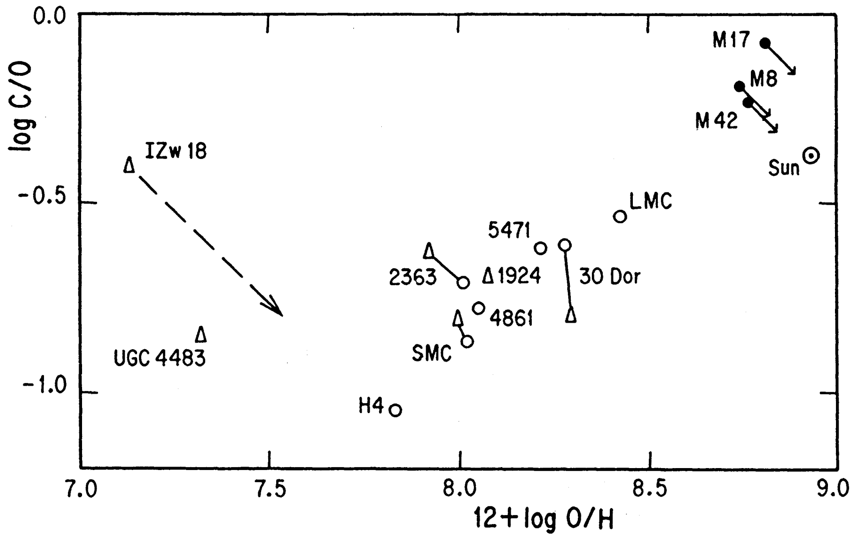


Fig. 2.— C/O versus O/H diagram based on observations of H II regions in the Galaxy and in irregular and blue compact galaxies, the Sun is also included. The filled circles come from Table 1; the open circles come from Dufour et al. (1984); the triangles come from: Bergvall (1985) for Tololo 1924, Mathis, Chu & Peterson (1985) for 30 Dor and the SMC, Peimbert, Peña & Torres-Peimbert (1986) for NGC 2363, Skillman (1991) for UGC 4483, Skillman (1991), Dufour, Garnett & Shields (1988), Davidson, Kinman & Friedman (1989) and Dufour & Hester (1990) for I Zw 18; Haro 4 is also known as Markarian 36 and the solar values come from Table 4.

The C/O difference between the Sun and the Galactic H II regions (M8, M17 and M42), if real, could be due to: a) a delay in the C enrichment of the interstellar medium by intermediate mass stars, or b) to the formation of the Sun in an O-rich region contaminated by recent SN explosions.

From Figure 2 it is seen that for low O/H objects $\mathrm{C/O} \rightarrow -0.8$ dex while for objects with $12+\log \mathrm{O/H} \gtrsim 8.0$ the C/O ratio increases with O/H. A possible interpretation for this behavior is that for O/H poor objects the

C enrichment of the ISM is due to massive stars, while for O/H rich objects part of the enrichment is due to massive stars, and part to intermediate mass stars, IMS (e.g., Dufour et al. 1984, Mallik & Mallik 1985, Peimbert 1985 and references therein). Support for the importance of IMS in the C enrichment of the solar vicinity comes from the C and O yields for massive stars computed by Weaver & Woosley (1993). Support for the delay in the C enrichment idea comes from the C/O abundance ratios in absorbing gas clouds at high redshift derived by Reimers et al. (1992), they find that the C/O ratio is a factor of 3 to 5 times smaller in clouds with redshifts in the 1.7 to 2.6 z range, in excellent agreement with the C/O value for O/H poor objects in Figure 2. The C delay idea also implies that the average stellar age increases with O/H ratio in the objects presented in Figure 2, with the exception of I Zw 18 that was discussed before.

Another explanation for Figure 2 is that the ratio of the C to O yields increases with $Z$ (see Tables 7 and 8 in Maeder 1992), this result might help to explain the low C/O ratios in the SMC that has an old stellar population. The trend in Figure 2 could be due to a combination of both effects: the C/O increase in the ratio of the yields with $Z$ and the delay in the C enrichment. Detailed models of Galactic chemical evolution are needed to evaluate the relative importance of these two effects.

### 4.4. Evolution of $Y$ versus $Z$

In Table 5 we show the $Y$ and $Z$ values for the Galactic H II regions; to take into account the possible amount of O trapped in dust grains 0.08 dex has been added to the nebular O/H ratio (Meyer 1985). To estimate the $Z$ value it was assumed that CNO made 71% by mass of the total $Z$ value (Grevesse & Anders 1989). The $\Delta Y/\Delta Z$ values were computed under the assumption that the pregalactic He abundance by mass, $Y_p$, was equal to 0.23 (e.g., Torres-Peimbert et al. 1989; Pagel et al. 1992), and that the pregalactic $Z$ value was equal to zero.

TABLE 5
HELIUM AND HEAVY ELEMENT ABUNDANCES BY MASS

| Object | $Y$ | $Z$ | $\Delta Y/\Delta Z$ | References[a] |
|---|---|---|---|---|
| Orion ($t^2 = 0.00$) | 0.292 | 0.0108 | 5.74 | 1,2 |
| Orion ($t^2 = 0.04$) | 0.281 ± 0.011 | 0.0160 ± 0.0024 | 3.19 ± 0.85 | 1,2 |
| M8 ($t^2 = 0.00$) | 0.292 | 0.0112 | 5.08 | 1,2 |
| M8 ($t^2 = 0.046$) | 0.281 ± 0.011 | 0.0156 ± 0.0032 | 3.27 ± 1.00 | 1,2 |
| M17 ($t^2 = 0.00$) | 0.292 | 0.0122 | 4.59 | 1,2 |
| M17 ($t^2 = 0.04$) | 0.280 ± 0.006 | 0.0200 ± 0.0030 | 2.50 ± 0.5 | 1,2 |
| Sun | 0.275 ± 0.016 | 0.0195 ± 0.0018 | 2.31 ± 0.85 | 3 |
| B stars | 0.283 ± 0.018 | 0.0104 ± 0.0021 | 5.10 ± 2.2 | 3,4 |
| B stars (Orion Ia + Ib + Ic) | 0.251 ± 0.017 | 0.0103 ± 0.0021 | 2.04 ± 1.8 | 3,4,5,6 |

[a](1) Table 1; (2) See text; (3) Table 4; (4) Gies & Lambert 1992; (5) Cunha & Lambert 1992; (6) Cunha 1993.

The $\Delta Y/\Delta Z$ value derived from the B stars of the Orion association is based on the 5 objects with H, He, C,N and O abundance determinations. The difference in $\Delta Y/\Delta Z$ between the B stars of the solar vicinity and the B stars of the Orion association is within the estimated errors.

The best $\Delta Y/\Delta Z$ determination is the one for M17 and amounts to $2.5 \pm 0.5$. This result is higher than those predicted from reasonable initial mass functions and stellar evolution computations that are in the 0.5 to 1.0 range (e.g., Maeder 1992 and references therein). To obtain $\Delta Y/\Delta Z$ values in the 2 to 3 range it has to be assumed that there is a stellar mass above which no heavy element enrichment of the interstellar medium occurs due to the production of black holes (e.g., Mallik & Mallik 1985; Schild & Maeder 1985; Maeder 1992). This limiting value for black hole production is in the 20 to $25M_\odot$ range; for higher values of the limiting mass $\Delta Y/\Delta Z$ becomes smaller than 2 while for lower values of the limiting mass $\Delta Y/\Delta Z$ becomes larger than 3 (Mallik & Mallik 1985; Maeder 1992).

The heavy element yield, $p$, is defined as the ratio of the mass that a generation of stars ejects as newly formed heavy elements to the mass of that generation that remains locked into stellar remnants and long lived stars, where the low mass end of the IMF which might comprise objects that do not become stars should be included. The net yield results by Maeder (1992) are upper limits to the $p$ values because he did not consider the mass locked into objects with initial masses smaller than $1M_\odot$. By adopting an IMF by mass, $\Phi(M)$, proportional to $M^{-0.6}$ in the 0.1 to $1M_\odot$ range the net yield results by Maeder need to be reduced by a factor of about 5 to derive the $p$ values. From the IMF used by Serrano & Peimbert (1981), which is given by $\Phi(M) = 0.56M^{-2}$ for $M > 1.8M_\odot$ and $\Phi(M) = 0.25M^{-0.6}$ for $M < 1.8M_\odot$ and a total mass range from 0.007 to $110M_\odot$, the net yield results by Maeder need to be reduced also by a factor of about five to derive the $p$ values. The $p$ value for the solar vicinity has been determined by different methods and it is in the 0.006 to 0.010 range (e.g., Pagel & Patchett 1975; Pagel 1981; Peimbert & Serrano 1982; Pagel 1987), these $p$ values might be affected by gas flows (e.g., Peimbert 1985; Edmunds 1989 and references therein). Black hole production by stars with masses higher than about 20 to $30M_\odot$ is in agreement with the observed $p$ values, smaller masses or larger masses for black hole production will produce smaller or larger $p$ values than observed (Mallik & Mallik 1985). The black hole idea permits fitting two observational constraints provided by the $\Delta Y/\Delta Z$ and $p$ values of the solar neighborhood.

In Figure 3 we show the $Y$ versus $Z$ diagram where the Galactic H II regions, the Sun, and some extragalactic H II regions are presented. In addition to the value for Orion from Table 5, we also present the abundances derived for Orion by Baldwin et al. (1991): $Y = 0.257$ and $Z = 0.011$, which give a $\Delta Y/\Delta Z$ value of 2.45 in excellent agreement with the value for M17; I consider this agreement fortuitous because the assumption of no neutral helium produces a smaller $Y$ value, and the adoption of $t^2 = 0.004$ (almost zero) produces a smaller $Z$ value than those presented for Orion in Table 5.

The models by Maeder (1992) indicate that $\Delta Y/\Delta Z$ decreases with $Z$ in agreement with the results by Pagel et al. (1992) that derive $\Delta Y/\Delta Z$ values in the 4 to 5 range for O/H poor objects and the $\Delta Y/\Delta Z$ values in the 2 to 3 range presented in Table 5 for the solar neighborhood.

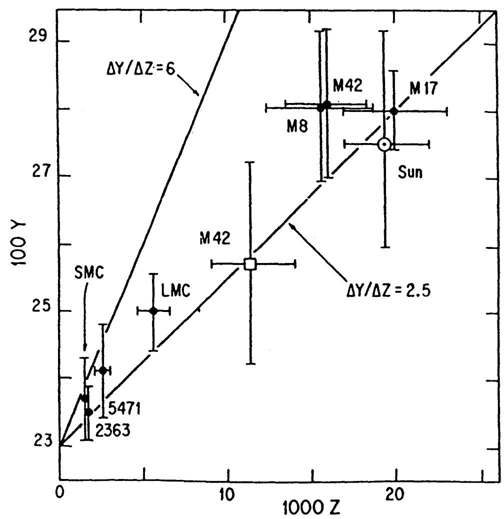


Fig. 3.— Helium, $Y$, versus heavy elements abundance, $Z$, by mass. See text and Table 5. The values for the SMC, the LMC, NGC 5471 and NGC 2363 for $t^2 = 0.00$ are also presented (Peimbert & Torres-Peimbert 1974, 1976; Dufour 1984; Dufour, Schiffer & Shields 1984; Peimbert, Peña & Torres-Peimbert 1986; Torres-Peimbert et al. 1989). The $t^2$ values for the last four objects might be different from zero, but in general we expect smaller $t^2$ values for smaller $Z$ values. The square for M42 comes from Baldwin et al. (1991).

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Manuel Peimbert: Instituto de Astronomía, UNAM, Apartado Postal 70-264, 04510 México, D.F., México.