Abundances of H II regions and the chemical evolution of galaxies

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We discuss the observational constraints to the chemical evolution of the interstellar medium, ISM, provided by the abundances of H II regions. We present a review of the results derived from these constraints for the solar vicinity and for metal-poor galaxies. It is found that, contrary to previous results, black holes do not play an important role in the chemical evolution of galaxies. Chemical evolution considerations indicate that substellar objects ($M \leq 0.08 M_{\odot}$) have a mass density smaller than 0.02 $M_{\odot}\ pc^{-3}$ (2σ) in the solar neighborhood. One or more of the following ingredients are needed to explain the Z versus μ diagram of metal-poor galaxies: a) a heavy element yield increasing with Z due to a variation of the low-mass end of the IMF, b) outflow of Z-rich material, c) outflow of well-mixed material, and d) dark matter that does not participate in the chemical evolution process.

1. Introduction

H II regions are excellent probes of the chemical composition of the ISM of the Galaxy and of other galaxies. From the study of bright H II regions it is possible to derive accurate abundances of H, He, C, N, O, Ne, S, and Ar for galaxies that are located at many megaparsecs from us. Two important sources of error in the abundance determinations of bright H II regions are the temperature structure and the fraction of heavy elements that is embedded in dust.

The observed H II region abundances can be compared with those predicted by models. To produce a chemical evolution model for a given galaxy the following ingredients are needed: a) a set for stellar evolution models for all masses, b) an initial mass function, IMF, c) a star formation history, and d) a mass flow history.

In § 2 we will make a discussion of chemical evolution models, presenting some of the most popular, in § 3 we will compare chemical evolution models with observational constraints for the solar vicinity, and in § 4 we will make a review of some of the ideas that have been proposed to explain the chemical evolution of irregular and blue compact galaxies.

2. Chemical evolution models

2.1. *Net yield*

The heavy element yield is defined by

$$y(Z) = M(Z)/M_{*}, \tag{2.1}$$

where $M(Z)$ is the mass that a generation of stars ejects as newly formed heavy elements to the interstellar medium and M_{*} is the mass of the same generation that remains locked into stellar remnants and long lived stars, where we include the low-mass end of the IMF which might comprise objects that do not become stars. Similarly the oxygen yield is defined by

$$y(\mathrm{O}) = M(\mathrm{O})/M_{*}. \tag{2.2}$$

The yields in equations (2.1) and (2.2), hereafter net yields, have been also defined as true yields or real yields (e.g. Peimbert 1985, Pagel 1987 and references therein).

To derive the net yield it is necessary to adopt: a) an IMF, b) a set of stellar evolution models including the whole mass range expected.

The net yields can be compared with "observed yields". The observed yields can be computed by means of: a) the determination of the abundances by mass in a star or in an H II region, b) a model of galactic chemical evolution that should include the initial gaseous abundances by mass and the history of gas flows in and out of the representative volume under consideration, and c) the mass that participates in the chemical evolution process, M_b, and the mass that does not participate in the chemical evolution process, M_{nb}; M_b includes: the interstellar mass gas, M_g, the stellar mass, and the low-mass end of the IMF; M_{nb} includes the non-baryonic mass and the baryonic mass that does not participate in the chemical evolution process like primordial black holes. M_b and M_{nb} should be evaluated in a representative volume where the stars formed or the H II region is located.

2.2. *Basic equations*

The basic equations of a chemical evolution model in which the instantaneous recycling approximation, IRA, is assumed are the following (Tinsley 1980, Maeder 1992):

$$\frac{dM_b}{dt} = f_I - f_O, \tag{2.3}$$

where f_I and f_O are the inflow and outflow rates. Similarly M_g changes according to:

$$\frac{dM_g}{dt} = -(1-R)\Psi + f_I - f_O, \tag{2.4}$$

where R is the mass fraction returned to the interstellar medium by a generation of stars, and Ψ is the star formation rate. On the other hand, the heavy elements mass fraction, Z, evolves via:

$$M_g\frac{dZ}{dt} = y(Z)(1-R)\Psi + (Z_I - Z)f_I, \tag{2.5}$$

where $y(Z)$ denotes the "observed" yield and Z_I is the Z value of the accreting material. Equation (2.4) can be rewritten in terms of the gas mass fraction, $\mu = M_g/M_b$, as:

$$M_b\frac{d\mu}{dt} = -(1-R)\Psi + (f_I - f_O)(1-\mu). \tag{2.6}$$

Time can be eliminated by combining equations (2.5) and (2.6) as follows:

$$\frac{dZ}{d\ln\mu} = \frac{y(Z)(1-R)\Psi + (Z_I - Z)f_I}{-(1-R)\Psi + (f_I - f_O)(1-\mu)}. \tag{2.7}$$

For most of the heavy elements the IRA is very good because they are produced by stars more massive than 8 $M_\odot$. This is the case for O, Ne, Ar, and S, elements that are easily observed in bright H II regions. For C, N, Fe, and He, deviations from IRA have to be taken into account.

2.3. *Closed-box model*

When there are no gas flows in or out of the system, $f_I = f_O = 0$, the solution to equation (2.7) is given by

$$y(Z) = \frac{Z}{\ln \mu^{-1}}. \tag{2.8}$$

Notice that frequently equation (2.8) has been used with the the total mass of the system, M_T, instead of M_b, a correct procedure only if M_{nb} is negligible. The closed-box model has also been called the simple model. The yield given by equation (2.8) under the assumption that $M_{nb} = 0$ is called the effective yield (e.g. Peimbert 1985, Pagel 1987 and references therein). The yield of a given heavy element, y_i, is obtained by substituting Z for the mass concentration of element i, X_i in equations (2.5), (2.7), and (2.8).

2.4. *Infall*

Under the assumption that the inflow rate is given by $f_I = \alpha(1-R)\psi$, where α is a free parameter and integrating equation (2.7) for the case where infall and stellar mass loss are balanced by star formation ($Z_I = 0, f_O = 0$, and $\alpha = 1$) we obtain (Larson 1972, Tinsley 1980)

$$y(Z) = \frac{Z}{1 - \exp(1 - \mu^{-1})}; \tag{2.9}$$

while for other values of α the yield is given by (Matteucci & Chiosi 1983, Peimbert, Sarmiento & Colín 1994)

$$y(Z) = \frac{Z\alpha}{1 - [\alpha - (\alpha - 1)\mu^{-1}]^{-\alpha/(1-\alpha)}}. \tag{2.10}$$

Equation (2.10) is valid if $\alpha < 1$, otherwise it only applies for $\mu > \mu_{min}$, where $\mu_{min} = (\alpha - 1)/\alpha$; when $\mu \to \mu_{min}$, $M_b \to \infty$.

2.5. *Outflow of well-mixed material*

Under the assumption that the outflow rate is given by $f_O = \lambda(1-R)\psi$, where λ is a free parameter and integrating equation (2.7) for $f_I = 0$ we obtain (Matteucci & Chiosi 1983)

$$y(Z) = \frac{Z(\lambda + 1)}{\ln[(\lambda + 1)\mu^{-1} - \lambda]}. \tag{2.11}$$

In general when inflow and this type of outflow are occurring and a linear variation of the yield with Z is permitted, the solution to equation (2.7) is given by (Peimbert et al. 1994)

$$y(Z) = Z\left\{a + \frac{\alpha - a}{1 - [(\alpha - \lambda) + \mu^{-1}(1 - (\alpha - \lambda))]^{\frac{-\alpha + a}{1-(\alpha-\lambda)}}}\right\} - \alpha Z_I, \tag{2.12}$$

where we have assumed that $y(Z) = y_0 + aZ$. Equation (2.12) is valid if $(\alpha - \lambda) < 1$, otherwise it only applies for $\mu > \mu_{min} = [(\alpha - \lambda) - 1]/(\alpha - \lambda)$.

In deriving equations (2.11) and (2.12) it has been assumed that the fresh Z material ejected by the stars to the interstellar medium is completely mixed with the gas before it is ejected to the interstellar medium, the wind associated with this outflow has been called normal or ordinary. Notice that this outflow reduces the yields of the elements but not their ratios; in particular, it does not affect the $\Delta Y/\Delta Z$ ratio (under the assumption of IRA).

2.6. *Outflow of Z-rich material*

It has been proposed that outflow of Z-rich material is present, at least in some galaxies, to explain: a) the large helium abundances derived in some irregular and blue compact galaxies, b) the large $\Delta Y/\Delta Z$ ratios derived from samples of galaxies, c) the high Fe/O ratio in the Magellanic Clouds, and d) the Z-Mass relation present in irregular galaxies (e.g. Aparicio, García-Pelayo & Moles 1988; Russell, Bessell & Dopita 1988a,b; Lequeux 1989; Moles, Aparicio, & Masegosa 1990; De Young & Gallagher 1990; Pilyugin 1993, Tosi 1994). Pilyugin has presented quantitative estimates of this effect on the $\Delta Y/\Delta Z(\mathrm{O})$ ratio.

By assuming that a fraction γ of the freshly made $Z(\mathrm{O})$ is ejected to the intergalactic medium without mixing with the interstellar gas, and that the decrease of M_g due to this outflow is negligible it follows that

$$y(\mathrm{O}) = (1-\gamma)y(\mathrm{O})_{SN} + y(\mathrm{O})_{WIND}, \tag{2.13}$$

where $y(\mathrm{O})_{SN}$ is the net yield due to SN explosions and $y(\mathrm{O})_{WIND}$ is the net yield due to the mass loss due to stellar winds before the SN explosion of the massive stars.

About half of the freshly made He is ejected by stars in the 8–120 $M_\odot$ range and about half by stars in the 1–8 $M_\odot$ range, while almost all the O is produced by stars in the 8–120 $M_\odot$ range and most of it is ejected to the interstellar medium by supernova explosions. Stars with main sequence masses in the 1–8 $M_\odot$ range end their lives as white dwarfs and eject their excess mass in normal stellar winds in the red giant phase and as superwinds in the preplanetary nebula phase, the expanding shells have typical velocities of a few tens of $km\ s^{-1}$and the material ejected is not expected to escape the parental galaxy. Alternatively, stars in the 8–120 $M_\odot$ range lose part of their mass in stellar winds and afterwards explode like supernovae, the SN ejecta have typical initial velocities of a few thousands of $km\ s^{-1}$, a fraction of the SN ejecta is expected to leave the parental galaxy. Under these considerations it follows that

$$\begin{aligned}\left[\frac{\Delta Y}{\Delta Z(\mathrm{O})}\right]_{Obs} &= \frac{y(Y_{1-8}) + (1-\gamma)y(Y_{8-120})_{SN} + y(Y_{8-120})_{WIND}}{(1-\gamma)y(\mathrm{O})_{SN} + y(\mathrm{O})_{WIND}} \\ &= \frac{y(Y)[b+(1-b)(1-\gamma)]}{y(\mathrm{O})[c+(1-c)(1-\gamma)]};\end{aligned} \tag{2.14}$$

where b is the fraction of the net He yield due to stars in the 1–8 $M_\odot$ range and by winds of stars in the 8–120 $M_\odot$ range, $(1-b)$ is the fraction of the net He yield produced by SN explosions due to stars in the 8–120 $M_\odot$ range, c is the fraction of the net O yield due to winds by stars in the 1–120 $M_\odot$ range, and $(1-c)$ is the fraction of the O yield produced by SN explosions in the 8–120 $M_\odot$ range. From the computations by Maeder (1992) for $Z = 0.001$ and the high mass loss rate case, together with the IMF by Kroupa, Tout, & Gilmore (1993) it follows that $b = 0.56$ and $c = 0.011$, while for the Salpeter (1955) IMF it follows that $b = 0.42$ and $c = 0.006$.

Under the assumption that the two types of outflow are present the $[\Delta Y/\Delta Z(\mathrm{O})]_{obs}$ will still be given by equation (2.14) but the net oxygen yield would be given by

$$y(\mathrm{O}) = \frac{Z(\mathrm{O})(\lambda+1)}{[c+(1-c)(1-\gamma)]\ln[(\lambda+1)\mu^{-1}-\lambda]}. \tag{2.15}$$

3. Solar vicinity

3.1. *Observational constraints*

There are four observational constraints that can be used to study the chemical evolution of the solar vicinity: $Z(\mathrm{O})$, $\Delta Y/\Delta Z$, $\Delta Y/\Delta Z(\mathrm{O})$, and $Z(\mathrm{O})/[Z - Z(\mathrm{O})]$. In this discussion we will use for $Z(\mathrm{O})$the stellar value, for $\Delta Y/\Delta Z$ the M17 value, for $\Delta Y/\Delta Z(\mathrm{O})$ and $Z(\mathrm{O})/[Z - Z(\mathrm{O})]$ an average of the solar value and that of H II regions of the solar neighborhood. The adopted values are: $Z(\mathrm{O}) = 0.0096 \pm 0.0009$, $\Delta Y/\Delta Z = 2.5 \pm 0.5$, $\Delta Y/\Delta Z(\mathrm{O}) = 5.2 \pm 1.4$, and $Z(\mathrm{O})/[Z - Z(\mathrm{O})] = 0.92 \pm 0.10$ (see Peimbert et al. 1994 and references therein).

The $Z(\mathrm{O})$ value for H II regions depends on their temperature structure; it is often assumed that the mean square temperature fluctuation, t^2, is zero, and in this case the derived $Z(\mathrm{O})$ is two or three times smaller than $Z(\mathrm{O})_\odot$. Recent results indicate that $t^2 \approx 0.04$ for H II regions of the solar neighborhood (Peimbert, Torres-Peimbert & Ruiz 1992; Peimbert, Storey & Torres-Peimbert 1993a; Peimbert, Torres-Peimbert & Dufour 1993b) which increases the $Z(\mathrm{O})$ of H II regions to values very similar to $Z(\mathrm{O})_\odot$.

3.2. *IMF*

A recent determination of the IMF for the solar neighborhood is that by Kroupa, Tout, & Gilmore (1993), hereafter KTG.

The KTG IMF is given by

$$\xi = \begin{cases} 0.035\ m^{-1.3} & \text{if } 0.08 \le m < 0.5, \\ 0.019\ m^{-2.2} & \text{if } 0.5\ \le m < 1.0, \\ 0.019\ m^{-2.7} & \text{if } 1.0\ \le m < 120, \end{cases} \tag{3.16}$$

where m is the stellar mass in solar units and $\xi(m)dm$ is the number of stars in the mass interval from m to $m + dm$. The $0.08 \le m < 0.5$ exponent for the 95 percent confidence interval is in the -0.70 to -1.85 range and the center is given by -1.3. We will define three IMFs: KTGa, KTGb and KTGc that are obtained by extrapolating the KTG IMF to zero mass and adopting the center and the two extremes of the 95% confidence interval; the corresponding IMFs are given by

$$\xi_a(\mathrm{m}) = 0.051 m^{-0.7}, \tag{3.17}$$

$$\xi_b(\mathrm{m}) = 0.035 m^{-1.3}, \tag{3.18}$$

$$\xi_c(\mathrm{m}) = 0.025 m^{-1.85}, \tag{3.19}$$

for $0 \le m < 0.5$, while for $m \ge 0.5$ we have adopted equation (3.16). The KTG IMFs have the same slope for $m \ge 1$ than the Scalo (1986) IMF and the slope only differs for $m < 1$ values.

3.3. *Stellar models and chemical evolution models of the solar vicinity*

It is possible from stellar evolution models and a given IMF to compute the following net yields and net yields ratios: $y(\mathrm{O})$, $y(Y)/y(\mathrm{O})$, $y(Y)/y(Z)$, and $y(\mathrm{O})/y(Z - \mathrm{O})$. These values will depend on $M\,(\mathrm{BH})$, the mass above which the stars end their evolution as black holes without enriching the interstellar medium with heavy elements. Black holes have been postulated by many authors to explain low values of the oxygen yield derived for the Galaxy and for other galaxies.

For different IMFs $y(Y)/y(Z)$, $y(Y)/y(\mathrm{O})$, and $y(\mathrm{O})/y(Z - \mathrm{O})$ can be directly compared with the observational constraints $\Delta Y/\Delta Z$, $\Delta Y/\Delta Z(\mathrm{O})$, and $Z(\mathrm{O})/[Z - Z(\mathrm{O})]$, respectively; this comparison is independent of the infall rate if the infall is due to gas with primordial abundances. Alternatively, $y(\mathrm{O})$ depends on the specific chemical evolution model adopted for the solar vicinity. From four recent models of the solar vicinity it is found that $y(\mathrm{O}) = (0.7 \pm 0.1)\ Z(\mathrm{O})$ (Twarog 1980a,b; Pagel 1989; Meusinger & Stecklum 1992; Malinie et al. 1993).

Peimbert et al. (1994) have found that the $Z(\mathrm{O})$, $\Delta Y/\Delta Z$, and $Z(\mathrm{O})/[Z - Z(\mathrm{O})]$ values for the solar vicinity presented in § 3.1 can only be fitted by the KTGb IMF together with stellar evolution models by Maeder (1992); this fit is made without the presence of black holes. Furthermore, they also find that regardless of the value for $M\,(\mathrm{BH})$, the Salpeter IMF can not satisfy the three restrictions at the 1σ level.

In what follows we will consider $\Delta Y/\Delta Z(\mathrm{O})$ instead of $\Delta Y/\Delta Z$; $\Delta Y/\Delta Z(\mathrm{O})$ is more convenient because the models by Maeder (1992) do not consider the production of C, N, and Fe by intermediate mass stars, IMS, those in the $1 \leq M/M_\odot \leq 8$ range, moreover for these stars, deviations from IRA can occur and should be taken into account. From the $Z(\mathrm{O})$, $\Delta Y/\Delta Z(\mathrm{O})$, and $Z(\mathrm{O})/[Z - Z(\mathrm{O})]$ constraints presented in § 3.1, the KTG IMF's and the stellar evolution models by Maeder (1992), we have developed Figure 1. From this figure it is found that at the 1σ level only KTGb, for the case of no black holes, satisfies the three observational restrictions. Similarly, it is also found that for any value of $M\,(\mathrm{BH})$ the Salpeter IMF does not satisfy the three observational constraints. The production of C, N, and Fe by IMS would move to the left the permitted area in Figure 1 due to the $Z(\mathrm{O})/[Z - Z(\mathrm{O})]$ restriction, reducing even more the possibility for the production of black holes by massive stars.

Carigi (1994) has constructed an elaborated model for the solar vicinity considering the abundances of H, He, C, O, Fe, and Z without adopting the IRA. She considers the enrichment due to stars more massive than 8 $M_\odot$ based on the computations by Maeder (1992); she also considers the enrichment of C, O, and Z by single IMS based on the computations by Renzini & Voli 1981 and of He based on the computations by Maeder (1992); moreover, she considers the enrichment due to Type Ia and Ib supernovae produced by binary evolution of IMS. Carigi does not reproduce the observed abundance pattern in the solar vicinity for any value of $M\,(\mathrm{BH})$ by using the Salpeter IMF. The best agreement by Carigi with the observational constraints is obtained with the Scalo IMF and without the presence of black holes.

From the KTGb IMF it is possible to derive the mass density in substellar objects by integrating equation (3.16) and is equal to $8.5 \times 10^{-3} M_\odot\ pc^{-3}$. This value is considerably smaller than the 0.1 $M_\odot\ pc^{-3}$ estimate of unobserved mass in the solar vicinity by Bahcall (1984), Bahcall, Flynn, Gould (1992), and implies that if the missing mass amounts to 0.1 $M_\odot\ pc^{-3}$ it is not due to substellar objects and it should be of the type that does not participate in the chemical evolution process.

3.4. *Conclusions*

Carigi (1994) and Peimbert et al. (1994) find, from independent considerations, that the production of black holes by massive stars is not needed to explain the chemical evolution of the solar vicinity. This result contradicts previous results by other authors (e.g. Twarog & Wheeler 1982, 1987; Mallik & Mallik 1985; Maeder 1992, 1993) who find that objects more massive than 20–28 $M_\odot$ end their lives as black holes without enriching the interstellar medium with heavy elements. Carigi (1994) finds that while the Scalo IMF is in agreement with the observational constraints, the Salpeter IMF is not; similarly, Peimbert et al. (1994) find that while the KTG IMF is in agreement with the observational constraints, the Salpeter IMF is not.

Peimbert et al. (1994) find, from chemical evolution considerations, that the mass of substellar objects in the solar vicinity is smaller than 0.02 $M_\odot\ pc^{-3}$ (2σ). This result

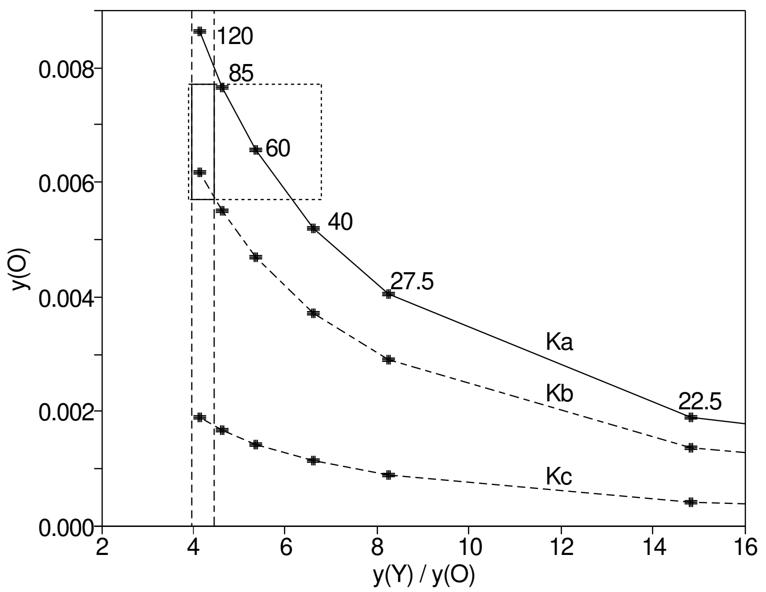

FIGURE 1. Oxygen yield, $y(\mathrm{O})$, versus helium to oxygen yield ratio, $y(Y)/y(\mathrm{O})$, based on the KTG IMF and the computations by Maeder (1992). The numbers inside the figure denote M(BH) values. The square is the permitted region for the $Z(\mathrm{O})/[Z\text{-}Z(\mathrm{O})]$ value. The small rectangle bounded by solid lines is the only permitted region that satisfies the three observational constraints.

rules out the possibility that the dark mass derived from dynamical considerations by Bahcall (1984) and Bahcall et al. (1992) could be due to substellar objects.

4. Metal-poor galaxies

4.1. *Observational constraints*

A recent discussion of the problems involved with chemical evolution of metal-poor galaxies has been presented by Lequeux (1993). One of the most important constraints for the study of the chemical evolution of metal-poor galaxies is provided by the Z-μ diagram. In Figure 3 we present a $Z(\mathrm{O})$-μ diagram from the M_g and M_T data by Staveley-Smith, Davies & Kinman (1992), where $Z(\mathrm{O})$ was derived from the (O/H)-L_B relationship presented by Skillman, Kennicutt & Hodge (1989).

Lequeux et al. (1979) presented the Z-μ diagram for a group of irregular and blue compact galaxies. They found that $y(Z) = 0.004$ together with a closed-box model could explain the observations. Notice that this value of the yield is a factor 3.5 times smaller than that derived from the KTG IMF and the stellar evolution models by Maeder (1992) (see below).

Peimbert & Serrano (1982) tried to explain the distribution of irregular galaxies, blue compact galaxies, the Galaxy, and M83 suggesting that the yield increases with metallicity as $y(Z) = 0.002 + 0.6Z$, all the objects but one considered by them fall in the region limited by the closed-box model and an infall model with $\alpha = 1$. They gave arguments in favor of a change of the low-mass end of the IMF to explain the increase of y with Z.

Matteucci & Chiosi (1983) and Chiosi & Matteucci (1984) suggested that in addition to infall, outflow models of well-mixed material could also explain the position of irregular and blue compact galaxies in the Z-μ diagram.

Kumai & Tosa (1992) suggested that the Z-μ diagram could be explained with a closed-box model and a varying fraction of M_{nb}/M_b.

Another important observational constrain is the $\Delta Y/\Delta Z$. As mentioned in § 2 this ratio is affected by outflow of metal-rich material and is not affected by the gas flow behaviour of other models.

The presence of black holes could also be important in explaining the $Z(\mathrm{O})$-μ diagram because they reduce the $y(Z)$ value. Therefore we will also consider the $Z(\mathrm{O})/[Z - Z(\mathrm{O})]$ ratio which is very sensitive to $M\,(\mathrm{BH})$. In what follows we will discuss the different suggestions that have been proposed to explain the $Z(\mathrm{O})$-μ diagram. We will consider the $Z(\mathrm{O})$-μ diagram instead of Z-μ diagram because: a) for most objects we only have a $Z(\mathrm{O})$ value, b) there are some elements, like C and Fe, for which the IRA is not as good as for O. The two main characteristics that need explanation are: a) the large range of μ values for a given $Z(\mathrm{O})$ value and b) the low $\langle Z(\mathrm{O})\rangle$ associated to the $\langle\mu\rangle$ value.

4.2. *Stellar models and black holes*

For our discussion we will make use of the Maeder (1992) stellar evolution computations for $Z = 0.001$ and $Z = 0.02$ with the high mass loss rate. From these models the Z production considered is due to stars with $M > 8M_\odot$ for which the IRA is excellent, moreover the $Z(\mathrm{O})/Z$ ratio is a strong function of the stellar mass. In Figure 2 we present the $y(\mathrm{O})/y(Z-\mathrm{O})$ ratio based on Maeder's computations and the KTG and Salpeter IMFs, notice that this ratio is independent of the behaviour of the IMF for $M < 8M_\odot$; this ratio is compared with the observed $Z(\mathrm{O})/[Z - Z(\mathrm{O})]$ value determined for the best observed metal poor H II region, NGC 2363; from this H II region it is obtained that $Z(\mathrm{O})/[Z - Z(\mathrm{O})] = 1.48 \pm 0.15$ (Peimbert, Peña, Torres-Peimbert 1986). This observational restriction is presented in Figure 2. From this figure it follows that there is an excellent agreement between the KTG IMF and Maeder's model without the need to invoke black holes. Alternatively, with the Salpeter IMF, $M\,(\mathrm{BH}) = (83 \pm 15)\ M_\odot$; by considering the production of C, Fe, and N by stars with $M < 8M_\odot$, the $y(\mathrm{O})/y(Z-\mathrm{O})$ ratio becomes even smaller, strengthening the result that black holes do not play a role in the chemical evolution of metal-poor galaxies.

4.3. *Closed-box model*

From the computations by Maeder (1992) and the KTG IMF we find that $y(Z) = 0.014$ and $y(\mathrm{O}) = 0.0083$ for $Z = 0.001$. In Figure 3a-3b we present the closed-box solution for $y(\mathrm{O}) = 0.0085$. It is clear that a closed-box solution, under the assumption that $M_{nb} \ll M_b$, can not explain the observed distribution of points presented in Figure 3. Similar results are obtained if other samples of galaxies are used, for example those by Lequeux et al. (1979) and by Matteucci & Chiosi (1983).

4.4. *Problems with $Z(\mathrm{O})$ and μ*

The determination of $Z(\mathrm{O})$ based on the nebular lines of O is in good shape (Peimbert, Sarmiento, & Fierro 1991, McGaugh 1991). For determinations based on λ 4363 a value of t^2 is needed, however from the work by Garnett (1992) and Peimbert et al. (1991) we expect the effect to be small for metal-poor H II regions. We estimate that the errors in the O/H ratio due to the temperature structure of H II regions are smaller than 0.2 dex.

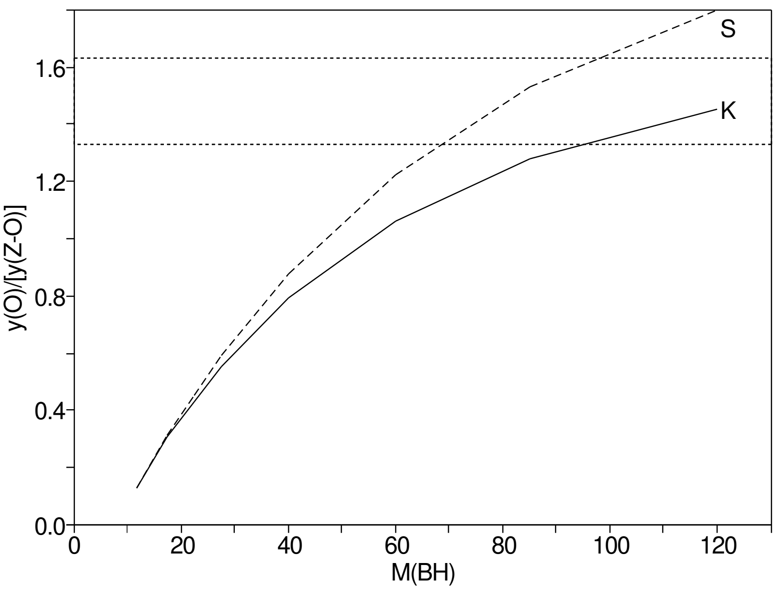

FIGURE 2. $y(\mathrm{O})/y(Z-\mathrm{O})$ versus $M\,(\mathrm{BH})$ (in solar mass units) diagram for the IMFs by KTG and Salpeter based on the computations by Maeder (1992). The yields ratio depends only on the IMF for $m \geq 1$, consequently there are no differences among cases a, b, and c. The permitted band corresponds to the $Z(\mathrm{O})/[Z\text{-}Z(\mathrm{O})]$ observed value of 1.48 ± 0.15.

Self-enrichment of giant H II regions due to stellar winds and SN explosions introduces the question of how representative is the O/H ratio for a given galaxy. The N and He abundances might be affected by the presence of Wolf Rayet stars (Pagel et al. 1992), but the O/H ratios derived from different H II regions in the SMC and the LMC (e.g. Dufour 1984 and references therein) and for different H II regions in I Zw 18 (Skillman & Kennicutt 1993), indicate that the self-enrichment in O is not very important. Furthermore, the presence of O self-enrichment makes it more difficult to explain the $Z(\mathrm{O})$-μ diagram, since we need to increase $y(\mathrm{O})$ not to lower it.

The problems associated with the determination of M_T could be larger. A line profile obtained with a single radio dish can not be converted into a reliable total mass estimate because the inclination and radius derived from optical images can be misleading (Skillman 1992); moreover, the assumption that the velocity field is due to rotation might not be correct in some cases (e.g. Skillman & Kennicutt 1993), nor the assumption that rotation is completely absent in others. Reliable mass estimates must be based on interferometric observations and only a few objects have reliable total mass determinations.

4.5. *Variations in the IMF*

To explain the $Z(\mathrm{O})$-μ diagram for low $Z(\mathrm{O})$ values, smaller values of $y(\mathrm{O})$ are needed. This can be done by reducing the fraction of stars in the high-mass end of the IMF ($M > 8M_\odot$) or by increasing the fraction of objects in the low-mass end of the IMF ($M \leq 1 - 2M_\odot$), including substellar objects.

Massey et al. (1989a,b), and Parker et al. (1992) find that most of the OB associations in the Magellanic Clouds have IMFs with slopes in the $-1.6 \leq \Gamma \leq -1.9$ range. Parker & Garmany (1993) find $\Gamma = -1.5 \pm 0.2$ for the 30 Doradus region. These results are in agreement with the KTG slope of -1.7 and do not present evidence for substantial changes in the high-mass end of the IMF with metallicity.

Moreover, from the study of many extragalactic H II regions in irregular and blue compact galaxies of different Z(O) content, McGaugh (1991) finds that a fixed IMF adequately explains the observed trends in the spectra, so no variation in the high-mass end of the IMF is inferred. Notice that a Salpeter slope for the high-mass end of the IMF predicts a higher heavy element yield making it more difficult to explain the Z(O)-μ diagram.

There is some evidence in favor of an increase in the fraction of low-mass objects with decreasing Z (e.g. Peimbert & Serrano 1982). Furthermore, Elmegreen (1994) has suggested that smaller mass galaxies could have a lower low-mass end of their IMF due to their smaller velocity dispersion.

In Figure 3c-3d we present a series of models with different outflow rates and with $y(\mathrm{O}) = 0.0012 + 0.67Z$, or $y(Z) = 0.002 + 1.1Z$. This type of yield reduces the need for strong effects due to other mechanisms to explain the Z(O)-μ diagram.

4.6. $\Delta Y/\Delta Z(\mathrm{O})$

The best $\Delta Y/\Delta Z(\mathrm{O})$ ratio for irregular and blue compact galaxies is that by Pagel et al. (1992) and is equal to 10.3 ± 3.5, this value was derived without considering the fraction of O tied down in dust grains nor the presence of temperature variations inside the observed H II regions.

From the results by Skillman et al. (1994) it is found that about 15 % of O is tied down in dust grains, therefore the $\Delta Y/\Delta Z(\mathrm{O})$ by Pagel et al. (1992) should be lowered to 8.8. By considering a modest amount of correction due to t^2 the value should be lowered to about 6.7. This value is a factor of 2.4 higher than that computed from the KTG IMF and the stellar evolution models by Maeder (1992) and probably implies the presence of Z-rich outflows. This value is also a factor of 3.3 higher than that computed from the Salpeter IMF.

Unfortunately not all the objects in the sample by Pagel et al. (1992) have M_T and M_g determinations. On the other hand, not all the objects in the sample by Matteucci & Chiosi (1983) and by Stavely-Smith et al. (1992) have Y and Z determinations. Colín et al. (1994) have used a subsample of the sample by Pagel et al. (1992) with 10 objects and find the $\Delta Y/\Delta Z(\mathrm{O}) = 10.3 \pm 1.8$ without considering the amount of O tied down in dust grains, nor the effect of t^2 in the O determinations. The $\langle Z(\mathrm{O})\rangle$ and $\langle \log \mu \rangle$ values for the Colin et al. (1994) sample are 0.0016 and -0.52, respectively.

4.7. *Inflow*

Inflow of material with pregalactic abundances, $Y = Y_p$ and $Z = 0$, does not change $\Delta Y/\Delta Z(\mathrm{O})$, though it is important in reducing Z for values in the $0 < \alpha \leq 1.0$ range. For larger values of α there is a minimun μ value, see Figures 3a-3b and equation (2.10), and this process is not able to cover the regions of low Z(O) and low μ values. The solutions presented by Matteucci & Chiosi (1983) that cover all the Z-μ diagram for $\alpha > 1.0$ are incorrect because equation (2.10) does not apply for $\mu \leq (\alpha - 1)/\alpha$.

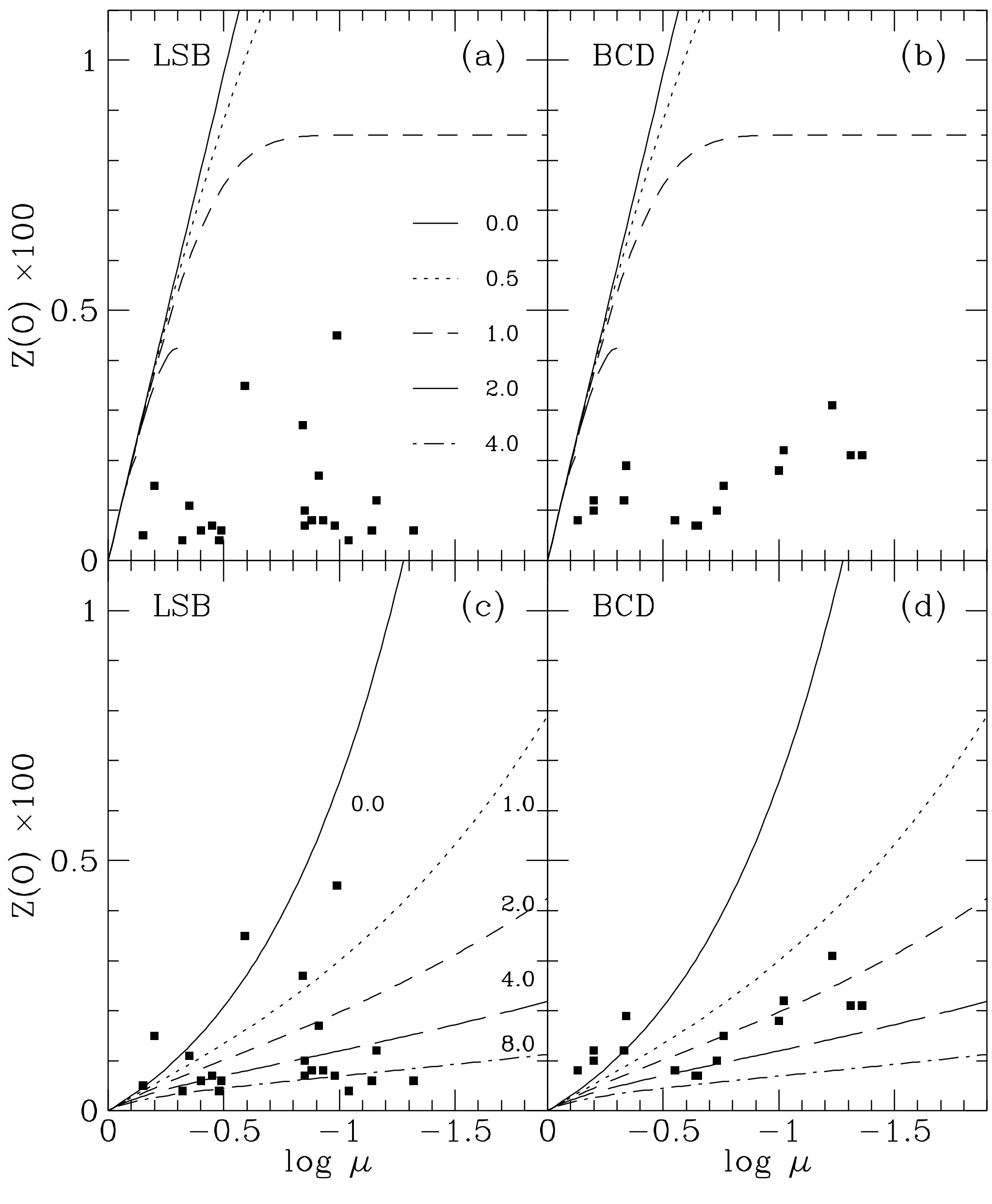

FIGURE 3. $Z(\mathrm{O})$-μ diagram for the sample by Staveley-Smith et al. (1992); where BCD and LSB denote blue compact and low surface brightness galaxies, repectively. Figures (a-b) present a closed-box model for $y(\mathrm{O}) = 0.0085$ and infall models for different values of the infall parameter α (see eq. 2.10). Figures (c-d) present well-mixed outflow models for a yield increasing with metallicity given by $y(\mathrm{O}) = 0.0012 + 0.67\ Z(\mathrm{O})$ and for different values of the outflow parameter λ (see eq. 2.12); the 0.0 curve corresponds to the closed-box model.

4.8. *Outflow of well-mixed material*

It is possible to cover the Z-μ diagram, to the right of the solution for the closed-box model, by varying λ. There are two problems with this solution: a) it does not explain the large $\Delta Y/\Delta Z$(O) observed values, and b) for some galaxies, with low Z(O) and low μ, values of λ of about 50 are needed, these values would imply the presence of haloes with about fifty times more mass in gas than the amount of mass in the form of stars in the main body of the galaxy, we consider this possibility unlikely. This type of outflow does make the prediction that galaxies should be surrounded by massive gas haloes, a prediction that could be tested.

In Figures 3c-3d we present models with a yield increasing with metallicity and various values of λ.

4.9. *Outflow of Z-rich material*

To explain an increase in the $\Delta Y/\Delta Z$(O) ratio due to the outflow of Z(O) rich material we can make use of equation (2.14) and the stellar evolution models by Maeder (1992). For an increase of a factor of 2 in the $\Delta Y/\Delta Z$(O) ratio, for an object with $Z = 0.001$, a value of $\gamma = 0.71$ is needed for the Salpeter IMF and a value of $\gamma = 0.65$ for the KTG IMF, this would raise the yields derived from Z-μ diagram by a factor $1/(1-\gamma)$ which is of the order of three, reducing the importance of the other suggested mechanisms to explain the Z-μ diagram. Moreover, the objects with small μ and small Z might yield even higher $\Delta Y/\Delta Z$(O) ratios and this process by itself could explain all the points in the Z-μ diagram.

In particular for the sample of Colín et al. (1994): $\langle Z \rangle = 0.0027$, $\langle Z(\mathrm{O}) \rangle = 0.0016$ and $\langle \log \mu \rangle = -0.52$, which together with equation (2.8) give $y(\mathrm{O})_{ef} = 0.0013$, and $y(Z)_{ef} = 0.00225$. Based on the computations by Maeder (1992) interpolated for $Z = 0.0027$ and adopting the KTG IMF we obtain $b = 0.58$ and $c = 0.033$; under the assumption that $\Delta Y/\Delta Z$(O) has been increased by a factor of 2.4 due to Z-rich outflow we obtain that $\gamma = 0.74$, which together with equation (2.15 for $\lambda = 0$) give $y(\mathrm{O}) = 0.0056$ and $y(Z) = 0.0092$, still a factor of 1.5 smaller than the predicted yields from Maeder and the KTG IMF that amount to 0.0083 and 0.014, respectively. This result reduces considerably the importance of other mechanisms under consideration, nevertheless the errors in the $\Delta Y/\Delta Z$(O) determination are large and better determinations are needed to evaluate the importance of this effect.

4.10. *Dark matter that does not participate in the chemical evolution process*

Kumai & Tosa (1992) have suggested that the Z-μ diagram can be explained with a closed-box model with a constant yield combined with $M_{nb} \neq 0$, where each object would have a different M_{nb}/M_b ratio. Based on the sample by Matteucci & Chiosi (1983), Kumai & Tosa find a good correlation between the dark matter fraction, f_D, derived by two independent methods. The methods to determine f_D are based on: a) fitting the Z-μ diagram with a constant yield, and b) determining the difference between the dynamical mass and the sum of the gaseous mass plus the stellar mass derived from an adopted M_*/L ratio. Of the effects that affect the Z-μ diagram discussed before there is one that is particularly relevant to this suggestion: errors in the determination of M_T could be responsible for part of the correlation derived by Kumai & Tosa (1992) because they will affect in the same manner the f_D values derived by the two methods.

Nevertheless, from the sample of Matteucci & Chiosi (1983) there is no correlation between M_{nb}/M_b (or f_D) and the mass of the galaxy. We would expect f_D to increase for less massive objects (e.g. White & Frenk 1991; Persic & Salucci 1988; Persic, Salucci & Ashman 1993). Persic et al. find for a sample of 56 galaxies, most of them spiral, that the fractional visible mass at the optical radius, R_{opt}, decreases for less luminous galaxies.

From the sample by Staveley-Smith et al. (1992), Colín et al. (1994) find that there is an inverse correlation of M_{nb}/M_b with M_T for the subsample made up of the low surface brightness galaxies of the sample, but there is no correlation between M_{nb}/M_b and M_T for the subsample of blue compact galaxies. This result might imply that M_{nb} plays a role in the explanation of the Z-μ diagram for the low surface brightness galaxies but not for the blue compact ones.

4.11. *Conclusions*

The closed-box model with the KTG or the Salpeter IMF and the stellar evolution models by Maeder (1992), under the assumption that $M_{nb} = 0$, can not explain all the points in the Z(O)-μ diagram.

The distribution of points in the Z(O)-μ diagram is *not* mainly due to: a) errors in the Z(O) determinations, b) the presence of black holes, c) inflow, and d) a varying IMF at the high-mass end.

Alternatively, the distribution of points in the Z(O)-μ diagram could be due to: a) errors in M_T, b) a varying IMF at the low-mass end, c) outflow of well-mixed material, d) the presence of dark matter that does not participate in the chemical evolution process, and e) outflow of Z(O) rich material. The first four possibilities can not explain the high $\Delta Y/\Delta Z$(O) observed values and one or more of them should be combined with the last to reproduce the Z(O)-μ diagram. Alternatively, if the $\Delta Y/\Delta Z$(O) observed value is considerably higher than the value discussed above, then the derived γ will become even higher and the last possibility alone might be responsible for the distribution of points in the Z(O)-μ diagram.

Determinations of Y, Z(O), M_g, and M_T of high qualtity are needed to advance in this problem, particularly of objects with low Z(O) and low μ values.

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REFERENCES

Aparicio, A., García-Pelayo, J.M. & Moles, M. 1988 *A. & A. S. S.* **74**, 375.

Bahcall, J.N. 1984 *Ap. J.* **287**, 926.

Bahcall, J.N., Flynn, C. & Gould, A. 1992 *Ap. J.* **389**, 234.

Carigi, L. 1994 *Ap. J. in press.*

Colín, P., Sarmiento, A., Carigi, L. & Peimbert, M. 1994 *in preparation.*

Chiosi, C. & Matteucci, F. 1984 In *Stellar Nucleosythesis* (ed. C. Chiosi & A. Renzini) Dordrecht:Reidel, 359.

De Young, D.S. & Gallagher, J.S. 1990 *Ap. J.* **356**, L15.

Dufour, R.J. 1984 In *Structure and Evolution of the Magellanic Clouds* (ed. S. van den Bergh & K.S. de Boer), 363.

Elmegreen, B.G. 1994 *this conference.*

GARNETT, D.R. 1992 *A. J.* **103**, 1330.

KROUPA, P., TOUT, C.A. & GILMORE, G. 1993 *M.N.R.A.S.* **262**, 545.

KUMAI, Y. & TOSA, M. 1992 *A. & A.* **257**, 511.

LARSON, R.B. 1972 *Nature Phys. Sci.* **236**, 7.

LARSON, R.B. & TINSLEY, M.B. 1978 *Ap. J.* **219**, 46

LEQUEUX, J. 1989 In *Evolution of Galaxies-Astronomical Observations* (ed. I. Appenzeller, H.J. Habing & P. Lena) Berlin:Springer, 147.

LEQUEUX, J. 1993 In *Origin and Evolution of the Elements* (ed. N. Prantos, E. Vangioni-Flam & M. Cassé) Cambridge:Cambridge University Press, 504.

LEQUEUX, J., PEIMBERT, M., RAYO, J.M., SERRANO, A. & TORRES-PEIMBERT, S. 1979 *A. & A.* **91**, 269.

MAEDER, A. 1992 *A. & A.* **264**, 105.

MAEDER, A. 1993 *A. & A.* **268**, 833.

MALLIK, D.C.V. & MALLIK, S.V. 1985 *J. Astrophys. & Astron.* **6**, 113.

MALINIE, G., HARTMANN, D.H., CLAYTON, D.D. & MATHEWS, G.J. 1993 *Ap. J.* **413**, 633.

MASSEY, P., GARMANY, C.D., SILKEY, M. & DEGIOIA-EASTWOOD, D.K. 1989a *A. J.* **97**, 107.

MASSEY, P., PARKER, J.WM. & GARMANY, C.D. 1989b *A. J.* **98**, 1305.

MATTEUCCI, F. & CHIOSI, C. 1983 *A. & A.* **123**, 121.

MCGAUGH, S.S. 1991 *Ap. J.* **380**, 140.

MEUSINGER, H. & STECKLUM, B. 1992 *A. & A.* **256**, 415

MOLES, M., APARICIO, A. & MASEGOSA, J. 1990 *A. & A.* **228**, 310.

PAGEL, B.E.J. 1987 In *The Galaxy* (ed. G. Gilmore & B. Carswell) Dordrecht:Reidel, 341.

PAGEL, B.E.J. 1989 *Rev. Mexicana Astron. Astrofis.* **18**, 161.

PAGEL, B.E.J., SIMONSON, E.A., TERLEVICH, R.J. & EDMUNDS, M.G. 1992 *M.N.R.A.S.* **255**, 325.

PARKER, J.WM., GARMANY, C.D., MASSEY, P. & WALBORN, N.R. 1992 *A. J.* **103**, 1205.

PARKER, J.WM. & GARMANY, C.D. 1993 *A. J.* **106**, 1471.

PEIMBERT, M. 1985 In *Star Forming Dwarf Galaxies and Related Objects* (ed. D. Kunth, T.X. Thuan & J.T.T. Van) Gif/Ivette:Editions Frontiers, 403.

PEIMBERT, M. & SERRANO, A. 1982 *M.N.R.A.S.* **198**, 563.

PEIMBERT, M., PEÑA, M. & TORRES-PEIMBERT, S. 1986 *A. & A.* **158**, 266.

PEIMBERT, M., SARMIENTO, A. & FIERRO, J. 1991 *P.A.S.P.* **103**, 815.

PEIMBERT, M., TORRES-PEIMBERT, S. & RUIZ, M.T. 1992 *Rev. Mexicana Astron. Astrofis.* **24**, 155.

PEIMBERT, M., STOREY, P.J. & TORRES-PEIMBERT, S. 1993a *Ap. J.* **414**, 626.

PEIMBERT, M., TORRES-PEIMBERT, S. & DUFOUR, R.J. 1993b *Ap. J.* **418**, 760.

PEIMBERT, M., SARMIENTO, A. & COLÍN, P. 1994 *Ap. J. submitted.*

PERSIC, M. & SALUCCI, P. 1988 *M.N.R.A.S.* **234**, 131.

PERSIC, M., SALUCCI, P. & ASHAMN, K.M. 1993 *A. & A.* **279**, 343.

PILYUGIN, L.S. 1993 *A. & A.* **277**, 42.

RENZINI, A. & VOLI, M. 1981 *A. & A.* **94**, 175.

RUSSELL, S.C., BESSELL, M.S. & DOPITA, M.A. 1988a In *Galactic and Extragalactic Star Formation* (ed. R.E. Pudritz & M. Fich) Dordrecht:Kluwer, 601.

RUSSELL, S.C., BESSELL, M.S. & DOPITA, M.A. 1988b In *The Impact of Very High S/N Spectroscopy* (ed. G. Cayrel de Strobel & M. Spite) Dordrecht:Kluwer, 545.

SALPETER, E.E. 1955 *Ap. J.* **121**, 161.

SCALO, J.M. 1986 *Fund. Cosmic Phys.* **11**, 1.

Skillman, E.D. 1992 In *Elements and the Cosmos* (ed. M.G. Edmunds & R. Terlevich) Cambridge:Cambridge University Press, 246.

Skillman, E.D., Kennicutt, R.C. & Hodge, P.W. 1989, *Ap. J.* **347**, 875.

Skillman, E.D. & Kennicutt, R.C. 1993 *Ap. J.* **411**, 655.

Skillman, E.D., Garnett, D.R., Dufour, R.J., Peimbert, M., Torres-Peimbert, S., Shields, G.A., Terlevich, E. & Terlevich, R.J. 1994 *in preparation.*

Staveley-Smith, L., Davies, R.D. & Kinman, T.D. 1992 *M.N.R.A.S.* **258**, 334.

Tinsley, B. 1980 *Fund. Cosmic Phys.* **5**, 287.

Tosi, M. 1994 *preprint.*

Twarog, B.A. 1980a *Ap. J.* **242**, 242.

Twarog, B.A. 1980b *Ap. J. S.* **44**, 1.

Twarog, B.A. & Wheeler, J.C. 1982 *Ap. J.* **261**, 636.

Twarog, B.A. & Wheeler, J.C. 1987 *Ap. J.* **316**, 153.

White, S. & Frenk, C. 1991 *Ap. J.* **379**, 52.