

The chemical evolution of spiral galaxies: M51, NGC 2403, NGC 6946 and IC 342

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Summary. The chemical evolution of a number of nearby spiral galaxies is investigated by using numerical models constrained by the gas and total mass distributions presently observed in these galaxies. The oxygen abundance is computed by means of the most recent results of the stellar nucleosynthesis. The results of the models are then compared with the oxygen distributions derived from the analysis of their H II regions. A reasonably good agreement between computed and observed abundances is attained.

The effect on the models of adopting different molecular hydrogen distributions resulting from the use of different CO–H₂ conversion factors is discussed for all the spiral galaxies for which both neutral and molecular hydrogen distributions are available. It is found that CO distributions corrected for the metallicity gradient observed through the discs of the galaxies provide model results in better agreement with observations.

1 Introduction

H II regions provide the best way, and in most cases the only way, of determining the chemical abundances in the interstellar medium of external galaxies. In fact, it is relatively easy to detect, even at great distances, the emission lines due to the most abundant elements and in the case of some of them, e.g. oxygen and nitrogen, their intensities can be translated into abundances in a relatively straightforward manner (e.g. Pagel 1983). It then seems natural to study the chemical evolution of galaxies through models which allow the direct prediction of the distributions of these elements and its confrontation with the observed ones. This kind of approach has previously been used in the study of the chemical evolution of our own galaxy (Tosi 1982; hereinafter Paper I) and a few nearby spirals (Díaz & Tosi 1984; hereinafter Paper II) with the aim of determining the principal parameters which govern the evolution of galaxies of different characteristics.

We have now enlarged this sample by incorporating some new galaxies for which all the necessary data entering the models have recently become available and for which H II region abundances have been derived. Three of these galaxies are large luminous spirals: M51, NGC 6946 and IC 342. The fourth galaxy is a low-luminosity late-type spiral, NGC 2403, similar in appearance to M33.

Various approaches have been followed by different authors to explain the abundance gradients observed in spiral galaxies: Tinsley & Larson (1978) argue in favour of gas infall as residual of the gravitational collapse of the protogalactic cloud, Mayor & Vigroux (1981) and Lacey & Fall (1985) consider radial flows in the discs, Peimbert & Serrano (1982) and Gusten & Mezger (1982) invoke yields varying with metallicity and bimodal star formation, respectively.

Our models assume an infall rate which is constant and uniform after the disc formation, as due to gas in the intergalactic medium trapped in the gravitational field of the galaxy. The rate of star formation (SFR) is assumed to be exponentially decreasing with time and its value at any galactocentric distance is derived from the present distributions of gas and total mass observed in each disc by means of equation (3) of Paper II. For this reason, in galaxies showing strong radial variations of the gas fraction, the SFR, and therefore the star formation to infall rate ratio, radially decreases. This implies that the metallicity gradients derived from our models are strictly related to the gas/total mass distributions, thus depending on the methods employed in the derivation of such distributions.

Although the traditional methods to derive the total mass (through the use of rotation curves) and the neutral hydrogen mass (from observations of the 21-cm line) seem to be quite well established, it has recently been suggested that the density of molecular hydrogen as derived from CO observations by standard techniques (e.g. Sanders, Solomon & Scoville 1984; hereinafter SSS) might be overestimated (Bhat *et al.* 1984). We have then investigated how and to what an extent the use of different assumptions for the CO-H₂ conversion can affect the results of the models.

Also, we show the effect on the resulting oxygen abundances of adopting different stellar nucleosynthesis models for massive stars (Arnett 1978; Chiosi & Caimmi 1979; Maeder 1981, 1983).

Section 2 of this work describes the observational data used for the galaxies of this study and some improvements to the theoretical models described in paper II. The results are presented in Section 3 and subsequently discussed in Section 4.

2 Observational data and theoretical models

2.1 H II REGION DATA

For each of the galaxies in this study the abundance gradient has been derived from published H II region data (Searle 1971; Smith 1975; McCall 1982).

The oxygen abundance for each H II region has been calculated from the reddening-free line intensity ratios of the forbidden oxygen lines, [O II] $\lambda\lambda$ 3727, 29 Å and [O III] $\lambda\lambda$ 4959, 5007 Å. Only for two H II regions in NGC 2403 and one in NGC 6946 the temperature sensitive line of [O III] λ 4363 Å has been detected. In the rest of the cases the calibration of oxygen abundance against the ratio $([O II] + [O III])/H\beta$ given by Edmunds & Pagel (1984) has been used.

Table 1 lists the values of the logarithmic abundance gradient, derived for each galaxy by fitting a straight line to the H II region abundances, and the corresponding correlation coefficient of the fit. Also given in the table are the adopted distance and effective radius (the radius containing half of the light in the disc) for each galaxy, their morphological type and the references for the data.

Table 1.

Galaxy	Morphological type	Adopted distance (Mpc)	Effective radius (kpc)	$\Delta(\log O/H)/\Delta R$ (kpc ⁻¹)	c.c.	Ref.
M51	SABcp I	9.60	7.26	-0.081 ± 0.027	-0.804	1, 2, 3
NGC 2403	SABcd III	2.62	2.08	-0.083 ± 0.032	-0.789	2, 3
NGC 6946	SABcd I	5.92	6.23	-0.077 ± 0.047	-0.639	3
IC 342	SABcd I-II	2.72	5.53	-0.103 ± 0.026	-0.941	3

References for the table:

1. Searle 1971.
2. Smith 1975.
3. McCall 1982.

2.2 INPUT DATA ENTERING THE MODELS

The input data entering the models, i.e. the total mass and gas surface density distributions, have been derived as described in Paper II.

The rotation curves used for the derivation of the total mass have been taken from Shostak (1973) for NGC 2403; Rogstad, Shostak & Rots (1972) for NGC 6946; Newton (1980) for IC 342; and Goad, de Veny & Goad (1979) for M51.

The classical assumption of a constant M/L ratio in the derivation of the total mass seems to be well justified in the cases of M51, NGC 6946 and IC 342 for which the blue and infrared brightness profiles are similar (Elmegreen & Elmegreen 1984) but in the case of NGC 2403 the infrared brightness profile is somewhat steeper, indicating that large uncertainties could exist in the derivation of the total mass for this latter galaxy.

The H I distributions have been taken from Shostak (1975) for M51, Rogstad & Shostak (1972) for NGC 2403 and NGC 6946, and Newton (1980) for IC 342, as tabulated by McCall (1982), and scaled to our adopted distance for every galaxy.

Finally, the molecular hydrogen distributions have been obtained from the observed CO distributions for NGC 6946 and IC 342 (Young & Scoville 1982a) and M51 (Scoville & Young 1983). For these three galaxies the CO distributions have been shown to follow the exponential blue luminosity profiles. The same assumption has been used in the case of NGC 2403 for which only two detections, at the nuclear region and at 1.5 arcmin away from the nucleus, have been reported by Young & Scoville (1982b).

A chain of arguments is used to relate the CO column densities to those of H₂ (see for example Li *et al.* 1983; SSS). In Paper II a constant value of $N(\text{CO})/N(\text{H}_2) = 4 \times 10^{-5}$ (Gordon & Burton 1976; Solomon & Sanders 1979; Encrenaz *et al.* 1979) was used through the entire disc of the galaxies, except in the case of the Galaxy and M83 whose H₂ distributions, taken from Talbot (1980) had been derived taking into account the effect of the metallicity gradient in the conversion procedure. In a recent paper Bhat *et al.* (1984) argue for a CO-H₂ conversion factor lower than that assumed by SSS and by most authors by a factor of ~ 3 . Their result is based on a comparison between the expected dependence of the γ -ray emissivity on galactocentric distance and the measured γ -ray intensities for the Milky Way, and it is claimed to apply to all galaxies.

We have then considered it of interest to investigate the effect of using different H₂ distributions, as derived with different conversion factors, on our chemical evolution models. Three different H₂ distributions have been considered. The first one (which we call 'conventional' following Bhat *et al.* 1984) is derived assuming a conversion factor $N(\text{H}_2)/\int T(\text{CO}) dv = 3.6 \times 10^{20} \text{ molecules K}^{-1} \text{ km}^{-1} \text{ s}$ (SSS) constant through the galactic discs. The second one, referred to by us as 'metallicity corrected', is derived using the same conversion factor but

applying a correction for the metallicity gradient. This correction has been obtained under the assumption that, in the molecular clouds where CO is observed, all the gas phase carbon is in the form of CO and hence its abundance is proportional to C/H and therefore to the metallicity that we typify by oxygen. We consider this to be an upper limit to the effect of the metallicity gradient on the H₂ distribution. The adopted conversion factor is varying with radius and equal to

$$\left[N(\text{H}_2) / \int T(\text{CO}) dv \right]_R = 3.6 \times 10^{20} [\text{O}/\text{H}]_{R_0} / [\text{O}/\text{H}]_R$$

where R_0 is, for each galaxy, the radius equivalent to the solar galactocentric distance (Bhat *et al.* 1984).

The third distribution ('totally corrected') is derived assuming a conversion factor lower than the previous one by a factor of 2.7 as suggested by Bhat *et al.* (1984) and the same metallicity correction as above. For this third distribution

$$\left[N(\text{H}_2) / \int T(\text{CO}) dv \right]_R = 1.3 \times 10^{20} [\text{O}/\text{H}]_{R_0} / [\text{O}/\text{H}]_R.$$

2.3 THEORETICAL MODELS

The numerical models used in this study are essentially the same as those described in Papers I and II with some modifications and are summarized below.

We have assumed the initial mass function (IMF) to be the same as that derived for the solar neighbourhood (Tinsley 1980) but with a higher mass limit of $100 M_\odot$, as suggested by more recent studies (Terlevich 1982; Humphreys & McElroy 1984) and we have adopted exponentially decreasing star formation rates parametrized by their e -folding times τ . Infall of unprocessed gas is allowed to occur at a rate assumed to be constant and uniform. Recent models of star formation and infall rates in the Galaxy indicate (Tosi 1985, in preparation) that this law of infall rather than one exponentially decreasing with galactocentric distance and/or time seems to be required to fit simultaneously the age-metallicity relation derived by Twarog (1980) in the solar neighbourhood and the abundances and gradients observed in stars (e.g. Mayor 1976; Laird 1985) and H II regions (Shaver *et al.* 1983).

With respect to Paper II, we have removed any simplifying assumption or arbitrary normalization in computing the oxygen abundances. Here, they are derived by directly taking into account at each time step the contribution of dying stars. Therefore, at any time t and galactocentric distance R , the abundance of any element i is:

$$X_i(t, R) = \sum_{[m]} X_i^{[m]} [\alpha_{[m]}(t, R) - \alpha_{[m]}(t - \Delta t, R)] + X_i(t - \Delta t, R) [1 - f(t, R) \Delta t / G(t, R)] \quad (1)$$

where the second term of the right-hand side of the equation gives the abundance due to all the preceding time steps and to the infalling gas $\{f(t, R)$ is the infall rate in $M_\odot \text{ yr}^{-1}$ and $G(t, R)$ is the gas mass $\}$. The first term of the rhs represents the 'fresh' abundance coming from stars in the mass range $[m]$ and dying in the time interval $[t - \Delta t, t]$. $\alpha_{[m]}$ is the fraction of gas coming from stars in the mass range $[m]$ and

$$X_i^{[m]} = \frac{\int_{[m]} M_i^m \phi(m) dm}{\int_{[m]} M_{\text{ej}}^m \phi(m) dm} \quad (2)$$

is the corresponding element abundance (see Papers I and II for a more detailed description of all these quantities). The values of M_i^m (mass of newly synthesized element i) and M_{ej}^m (total mass ejected by stars of initial mass m) are taken from Renzini & Voli (1981) for stars of mass $m \leq 8 M_\odot$, adopting a mixing length $1/H_Q = 1$ and a mass loss parameter of $\eta = 1/3$ (see Diaz & Tosi 1985 for a discussion of this choice). In any case variations of $1/H_Q$ have no effect on the oxygen abundance since this element is in practice not produced by these stars.

For the contribution of massive stars we have adopted the nucleosynthesis results by Arnett (1978) but scaling his $m - m_\alpha$ (initial mass–helium core mass) relation in order to take mass loss into account. In Fig. 1 we show the $m - m_\alpha$ relations as given by Arnett (1978) without mass loss and by Chiosi & Caimmi (1979) with high mass loss. The dashed line in Fig. 1 represents the $m - m_\alpha$ relation derived from Maeder's (1981, 1983) models with intermediate mass loss (case b) assuming as He-core mass the mass corresponding to the evolutionary stage of complete exhaustion of the surface hydrogen (Greggio, private communication). The best agreement between theoretical and observational data is attained when Maeder's $m - m_\alpha$ is adopted for the computation of the present oxygen abundances. This conclusion is exemplified for our own Galaxy in Fig. 2, where the three dashed lines represent the oxygen distributions as derived from the same chemical evolution model ($\tau = 15$ Gyr and $F = 3.5 \times 10^{-3} M_\odot \text{ kpc}^{-2} \text{ yr}^{-1}$) but under the three assumptions for the $m - m_\alpha$ relations.

3 Results

The results of the models can be seen in Figs 3 to 6. Panel (a) of each figure shows the adopted present distributions of gas and total mass density through the disc. Panel (b) shows the resulting present star formation rates corresponding to the different models, and panel (c) shows the oxygen abundance distribution predicted by each model adopting Maeder's $m - m_\alpha$ relation together with the oxygen abundances derived from H II region analysis.

Only for NGC 6946 (Fig. 3) the three gas distributions corresponding to the three H_2 derivations (see Section 2.2) are shown. The qualitative differences between the three distributions for the other galaxies are similar. The effects on the models of adopting one given distribution can be seen by comparing in Fig. 3(c) the three lines corresponding to the 'simple'

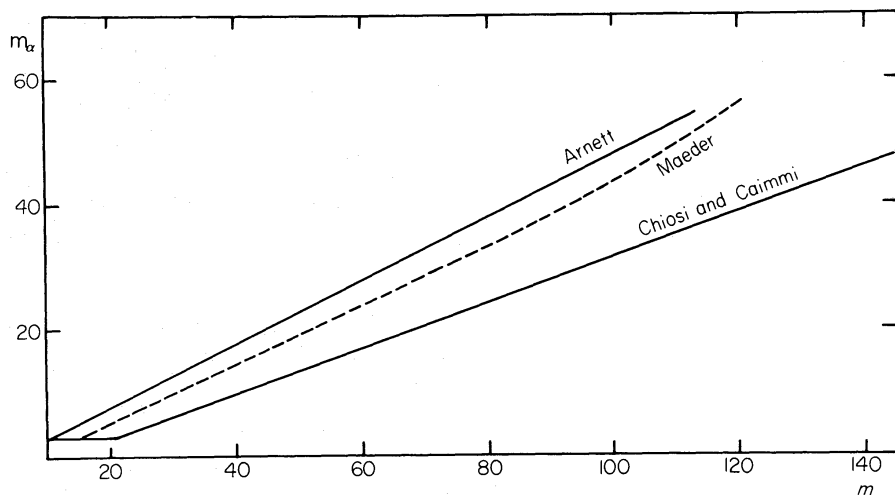


Figure 1. The relation $m - m_\alpha$ between initial and helium core masses in massive stars. The solid lines show this relation as computed by Arnett (1978) for constant mass evolution and by Chiosi & Caimmi (1979) with a high mass loss rate. The dashed line has been derived from Maeder's (1981, 1983) models with intermediate mass loss rate and represent the $m - m_\alpha$ here adopted.

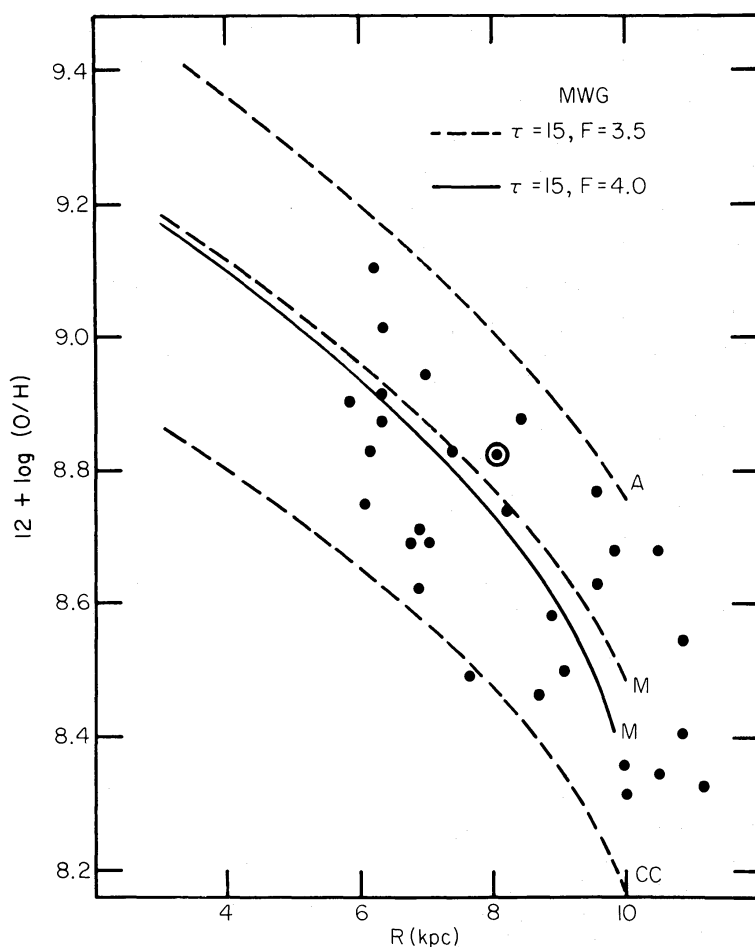


Figure 2. The Galaxy: radial variation of the oxygen abundances as derived from the indicated models computed adopting the $m-m_\alpha$ relation given by Arnett (1978) (labelled A), Chiosi & Caimmi (1979) (labelled CC) and Maeder (1981, 1983) (labelled M). The infall rate, F , is in units of $10^{-3} M_\odot \text{ kpc}^{-2} \text{ yr}^{-1}$ and the SFR e -folding time, τ , in units of 10^9 yr . The dots represent the observed H II region abundances from Shaver *et al.* (1983). The solar oxygen abundances is indicated by the usual Sun symbol.

model (i.e. the model with a constant SFR and no infall). The use of an H_2 distribution corrected for metallicity effects leads to a steepening of the gradient, thus providing results in better agreement with the observations. In fact, if the ‘conventional’ H_2 distribution were adopted, it would not be possible to reproduce the metallicity gradient observed in this galaxy with any combination of infall and SFR. The use of the ‘totally corrected’ gas distribution produces an approximately constant shift in the curve by $\sim 0.05 \text{ dex}$ well within the errors of the observed abundances ($\pm 0.2 \text{ dex}$; see Paper II).

For the rest of the galaxies (Figs 4 to 6) only models computed with the ‘metallicity corrected’ H_2 distribution are shown in order not to complicate the figures, but the effects of using the other distributions can easily be envisaged with reference to Fig. 3.

Models with rapidly decreasing SFR ($\tau=5-10 \text{ Gyr}$) and with the highest possible infall ($F=(3-4) \times 10^{-3} M_\odot \text{ kpc}^{-2} \text{ yr}^{-1}$) give oxygen abundances in good agreement with those observed in the H II regions of NGC 6946 (Fig. 3c).

A very similar situation is found for IC 342 (Fig. 4) where models with exponentially decreasing SFRs ($\tau=5-10 \text{ Gyr}$) and infall rate between 2 and $3 \times 10^{-3} M_\odot \text{ kpc}^{-2} \text{ yr}^{-1}$ reproduce the observed gradient reasonably well. Models with constant or slowly decreasing SFRs would

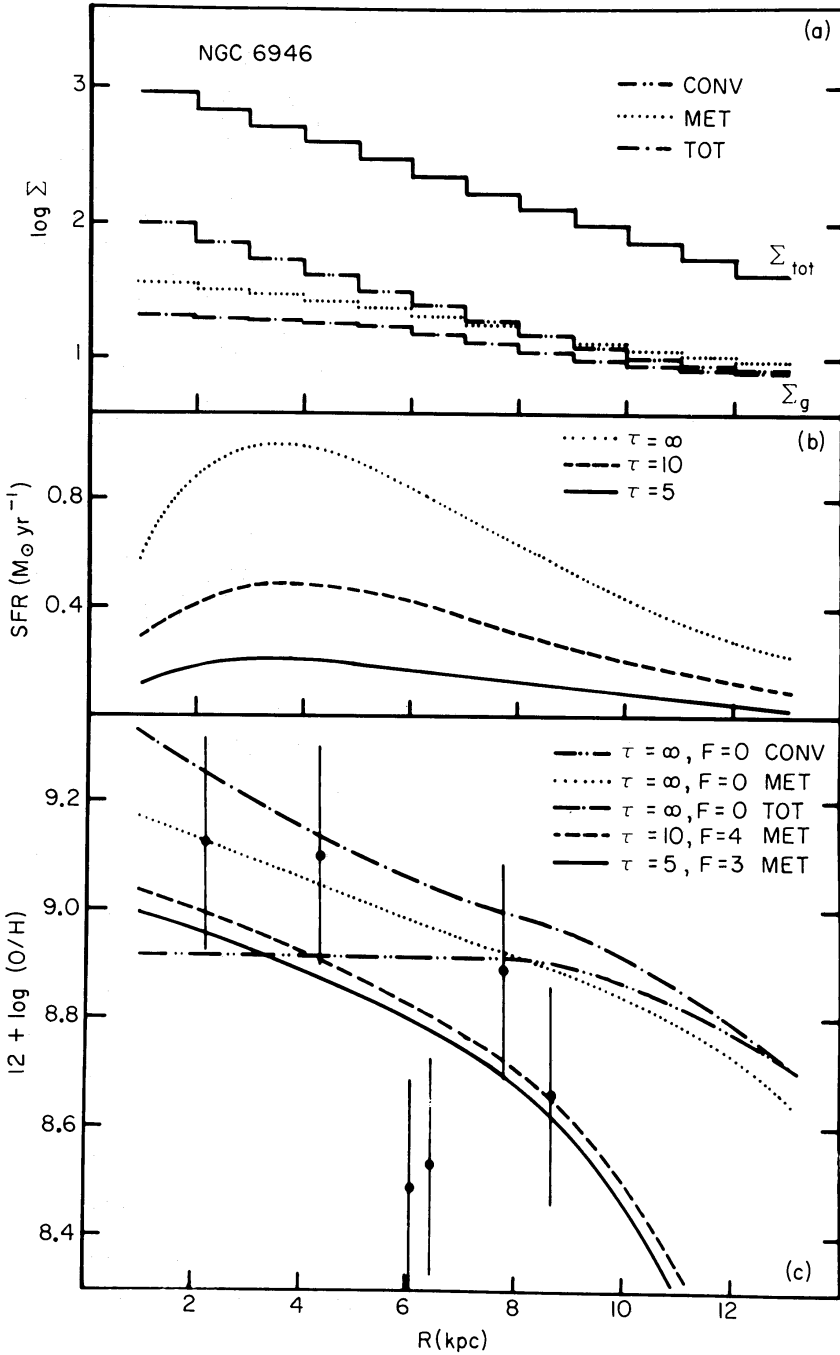


Figure 3. For NGC 6946: (a) Gas, Σ_g , and total mass, Σ_{tot} , density distributions with galactocentric distance, R . (b) Present star formation rates as resulting from the indicated models. (c) Radial variation of the oxygen abundance as derived from the indicated models and adopting Maeder's $m-m_{\odot}$ relation. The dots represent the observed abundances referenced in the text. The infall rate, F , and the SFR e -folding time, τ , are in the same units as in Fig. 2. The curves labelled CONV, MET and TOT correspond respectively to gas distributions derived with a 'conventional', 'metallicity corrected' or 'totally corrected' H_2 distributions, as defined in Section 2.3).

require infall rates in violation of the unremovable constraint of positive initial mass (see section 3 of Paper II).

Also in the low-luminosity galaxy NGC 2403 (Fig. 5) the SFR e -folding time seems to be short ($\tau = 5$ Gyr) but here the infall rate cannot be higher than $1 \times 10^{-3} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$. Models with no

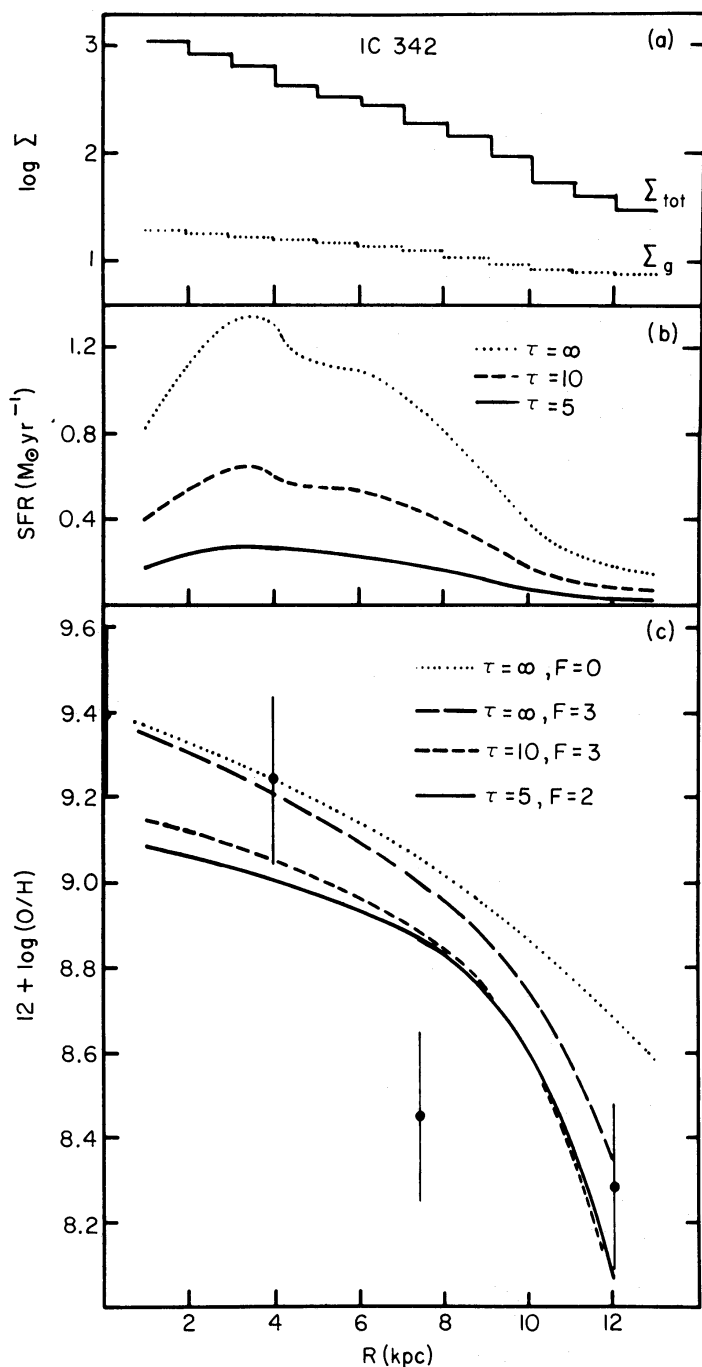


Figure 4. Same as Fig. 3 but for IC342. Only curves corresponding to the MET H_2 distribution are shown.

infall at all seem to be in better agreement with the observations, although their resulting oxygen abundances are slightly overabundant in the central regions of this galaxy. Again, we should recall that for this galaxy the uncertainties in the derivation of the total mass and gas densities are larger than for the rest of the galaxies (see Section 2.2), and that small variations in these distributions can lead to strong variations in the SFRs and therefore in the predicted abundances.

In the case of M51 (Fig. 6) no model could be found to reproduce the high oxygen abundances observed, although the gradient that seems to be present is reproduced by the models. We should none the less remember that the presence of a close companion could modify not only the

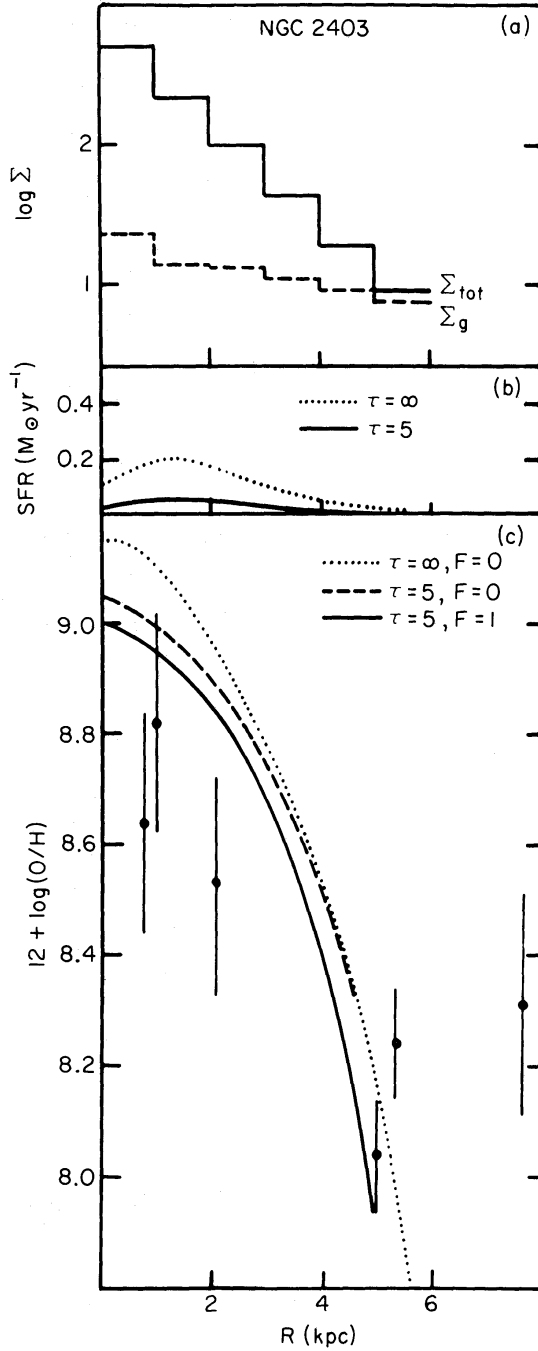


Figure 5. Same as Fig. 4 but for NGC 2403.

rotation curve and, as a consequence, the model parameters adopted here, but also the global evolution of this galaxy.

4 Discussion and conclusions

As an extension of a previous study on the chemical evolution of spiral galaxies (Paper II), the radial distribution of oxygen through the discs of four spiral galaxies has been analysed with the use of numerical models constrained by the presently observed distributions of gas and total mass

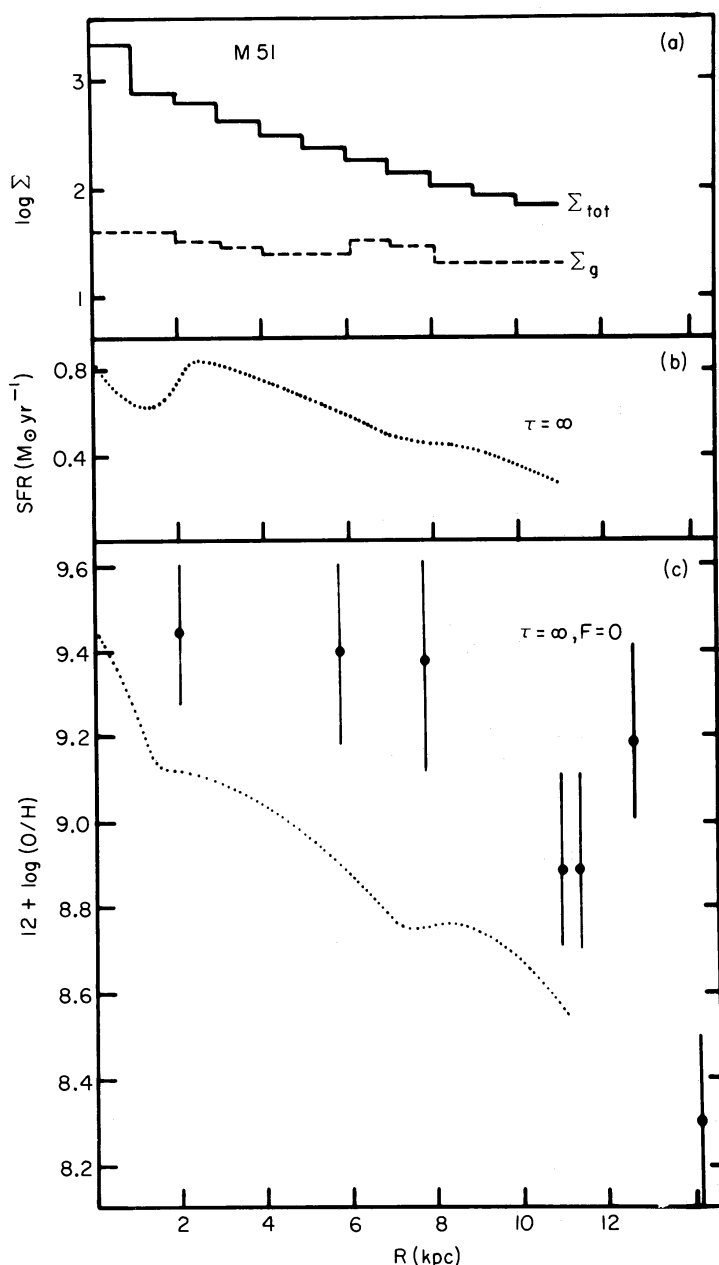


Figure 6. Same as Fig. 4 but for M51.

and characterized by different combinations of only two parameters: star formation and infall rates. Confirming our previous results, these two parameters are shown to be sufficient to adequately describe the abundance distributions in the galactic discs. It is worthwhile to emphasize here that both a reduction of the star formation e -folding time τ and an increase of the infall rate f have the effect of reducing the computed abundances. Since for all these galaxies the ratio SFR/f is a decreasing function of the galactocentric distance, variations of τ and f affect more the abundances in the inner and outer regions, respectively.

Various molecular hydrogen distributions have been considered in the derivation of the gas surface density. It is found that H_2 distributions which are corrected for the metallicity gradient observed in each galaxy provide model results in better agreement with observations.

The effect of a radial gradient in carbon and/or oxygen abundance is to increase the $N(\text{CO})/N(\text{H}_2)$ ratio, and therefore decrease $N(\text{H}_2)$, in the inner parts of the galaxies with respect

to the outer parts (Blitz & Shu 1980). SSS claim this effect to be unimportant in the case of the Galaxy based on the small value of the galactic carbon abundance gradient and the non-existence of a $^{12}\text{C}/^{13}\text{C}$ gradient as reported by Wannier (1980). However, Tosi (Paper I) finds a gradient in $^{12}\text{C}/^{13}\text{C}$ if only single molecular ratios from Wannier's data are used in the computation, thus avoiding the arbitrary assumption that companion isotopic ratios have a constant value taken to be the terrestrial one. This result has been found also by Henkel, Wilson & Bieging (1982) and Henkel, Gusten & Gardner (1985) from new molecular cloud observations. On the other hand, even with the value of the C/H gradient quoted by SSS, a difference in the H_2 density by a factor of ~ 2 is found between the galactic centre and the solar ring if a dependence of the CO intensity with the square root of the abundance is assumed. Therefore, we think that the inclusion of metallicity gradient effects in the CO- H_2 conversion factor may be of importance in the derivation of the H_2 distribution in galaxies, including our own. Unfortunately our models do not constitute a test for the different conversion factor suggested by Bhat *et al.* (1984) since a reduction in the amount of H_2 by a constant factor of 2.7 reflects in a shift of the model abundances toward higher values, as might be expected, but by an amount well within the observational errors.

We have also investigated the effect of removing the solar abundance normalization adopted in Paper II in computing the present oxygen abundances. The basic result is a reduction of the computed abundances which can be visualized for the Galaxy by comparing our Fig. 2 with fig. 1 of Paper II. For this reason, the $m-m_\alpha$ relation from Chiosi & Caimmi (1979) now gives abundances lower than observed in all galaxies. On the other hand, for all galaxies and for all possible evolution models, the oxygen abundances derived without taking mass loss into account (Arnett 1978) are too high, while a very good agreement between model results and observations (see also Diaz & Tosi 1985 for other elements) is attained for most spirals when the $m-m_\alpha$ derived from Maeder's models (1981, 1983) is adopted.

This detailed computation of the oxygen yields, together with the metallicity correction in the derivation of the H_2 distributions, constitutes a more realistic approach in modelling the chemical evolution of spiral galaxies and provides a general improvement in the agreement between predicted and observed abundances.

Star formation rates are found to be higher for the more massive galaxies M51, NGC 6946 and IC 342 than for the small galaxy NGC 2403. Since the SFR is derived from the gas and total mass densities (equation 3, Paper II), this result is not surprising. Star formation appears to have decreased rapidly with time for the three later type spirals in this study. Although M51 might have also evolved with a decreasing rate of star formation, no conclusive information can be obtained from the models for this galaxy. The fact that these galaxies have evolved with rapidly decreasing SFRs does not necessarily mean that the present SFR is lower than in galaxies with constant SFRs, but it rather indicates that it was much higher in the past. As already found for most of the galaxies in Paper II, the radial behaviour of the present SFR is quite similar for all the galaxies decreasing with galactocentric distance and showing a peak at ~ 4 kpc for NGC 6946, IC 342 and M51 and at ~ 2 kpc for NGC 2403. Although DeGioia-Eastwood *et al.* (1984) find monotonically decreasing SFR and efficiency for NGC 6946, the combination of both quantities shows a maximum in the integrated SFR between 3 and 4 kpc.

Infall rates are found to be moderate for the four galaxies in this study. Actually the upper limit for infall, as resulting from the present gas and mass distributions is of the order of $(3-4) \times 10^{-3} M_\odot \text{ kpc}^{-2} \text{ yr}^{-1}$ for NGC 6946 and IC 342. Higher infall rates would be allowed for M51, but they do not seem to be required. Although the question of the existence of infall in galaxies is highly controversial, some authors have recently presented new observational evidence for inflow of neutral hydrogen toward the Galaxy (Mirabel 1982; Mirabel & Morras 1984) and some spirals and irregulars (van der Hulst, Golish & Haschick 1983 and references

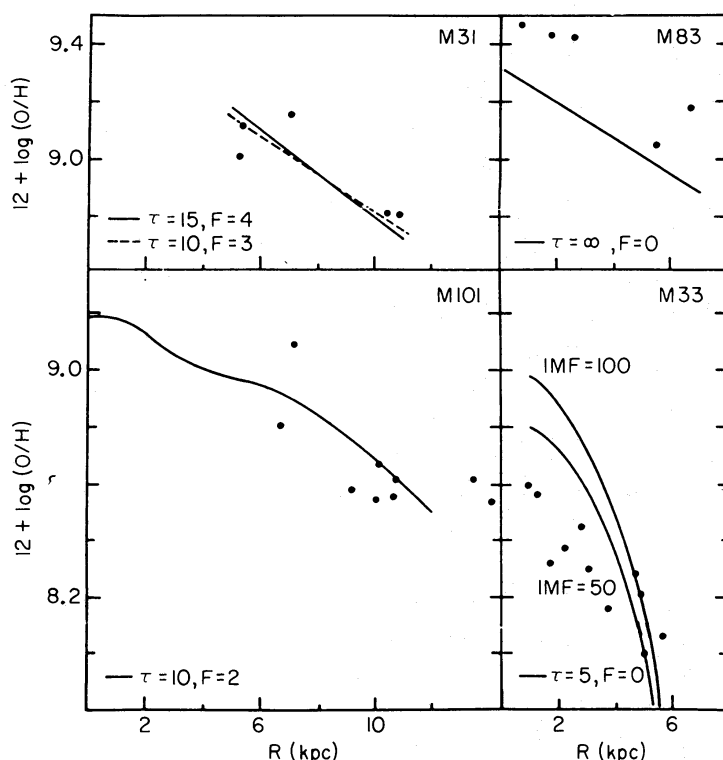


Figure 7. Radial variation of the oxygen abundance in M31, M33, M83, and M101 as derived from the indicated models and using the gas distribution computed with the MET H_2 distribution and the new procedure for abundance computation (see text). Units of the SFR e -folding time and infall rate are the same as in Fig. 3.

therein) and the infall rates required by the models do not seem to be unrealistically high. For the Galaxy, in fact, the infalling gas mass as derived from High and Very High Velocity Clouds is $1\text{--}2 M_\odot \text{yr}^{-1}$ (see also van Woerden, Schwartz & Hulbosch 1985), consistent with the value of $1.8 M_\odot \text{yr}^{-1}$ corresponding to our $F = 4 \times 10^{-3} M_\odot \text{kpc}^{-2} \text{yr}^{-1}$.

In order to check whether the results for τ , SFR, and infall rate found for these four galaxies apply also to the galaxies analysed in Paper II, we have recomputed for them the chemical evolution models adopting the new H_2 distributions and the new abundance computation procedure. The results for each galaxy are shown in Fig. 7. For M31 and M101 the indicated models give results in very good agreement with the observations, while for M33 the computed abundances result too high in the central regions as already found for its ‘twin’ spiral NGC 2403. As shown in Fig. 7, in these small, low-luminosity galaxies an upper mass limit of 50 instead of $100 M_\odot$ gives a better fit to the observed H II region abundances, but we should bear in mind that for both M33 and NGC 2403 the uncertainties on the mass and gas distributions are larger than for the other galaxies and this might be the reason of the apparent discrepancy in the central regions.

Correspondingly, for the very metal rich galaxy M83, even a model with constant SFR and no infall does not provide enough oxygen abundances to fit well the observed data (but again Arnett’s yields would be overabundant). In this case, even an increase of the IMF upper limit, e.g. to $150 M_\odot$, would not improve much the situation, since very massive stars have so little weight in the IMF. Furthermore, nitrogen turns out to be even more overabundant than oxygen (Díaz & Tosi 1985), although it is mainly produced by intermediate mass stars. In this particular case, the adoption of the Bhat *et al.* (1984) CO– H_2 conversion factor would actually improve the model results, since it reduces the present gas density and therefore increases the average SFR.

Table 2.

Galaxy	Morphological type	Model τ	F	$\Delta(\log \text{O}/\text{H})/\Delta R$ (kpc^{-1})
MWG	SABbc II	∞	0	-0.057 ± 0.006
		*15	3.5	-0.094 ± 0.005
		*15	4	-0.104 ± 0.006
M31	SAb I-II	∞	0	-0.077 ± 0.006
		*15	4	-0.077 ± 0.001
		*10	3	-0.067 ± 0.002
M33	SAcd II-III	∞	0	-0.222 ± 0.079
		* 5	0	-0.210 ± 0.077
M51	SAbcp I	* ∞	0	-0.067 ± 0.005
M83	SABcd I-II	* ∞	0	-0.064 ± 0.002
M101	SABcd I	∞	0	-0.064 ± 0.003
		*10	2	-0.054 ± 0.003
NGC 2403	SABcd III	∞	0	-0.274 ± 0.048
		* 5	0	-0.247 ± 0.051
		5	1	-0.196 ± 0.029
NGC 6946	SABcd I	∞	0	-0.040 ± 0.001
		*10	4	-0.072 ± 0.007
		* 5	3	-0.075 ± 0.009
IC 342	SABcd I-II	∞	0	-0.063 ± 0.004
		∞	3	-0.078 ± 0.007
		*10	3	-0.082 ± 0.011
		5	2	-0.072 ± 0.010

On the other hand, Talbot (1980) mentions that the luminosity profile of M83 shows a prominent spheroidal bulge component, while its mass appears to be small when applying the adopted fitting procedure of the rotation curve of Monnet & Simien (1977). If the bulge mass component has actually been underestimated, this would be reflected in an underestimate of the SFR, and may explain our resulting low oxygen abundances, at least in the inner regions of the galaxy.

We have summarized in Table 2 the results of the principal models for all the galaxies studied so far. The table gives for each model the value of the SFR e -folding time, τ , in units of 10^9 yr; the value of the infall rate, F , in units of $10^{-3} M_{\odot} \text{kpc}^{-2} \text{yr}^{-1}$; the value of the oxygen gradient derived by fitting a straight line through the model computed abundances which can then be compared with the observed ones listed in Table 1 of this paper and table 1 of Paper II. An asterisk indicates the model(s) in better agreement with the observations for each galaxy.

From this table we can infer that small late-type spirals evolve with rapidly decreasing star formation rates ($\tau \approx 5$ Gyr) and no infall, while in large late-type spirals the SFR is also decreasing ($\tau \approx 5$ –10 Gyr) but the infall rate is larger than about $2 \times 10^{-3} M_{\odot} \text{kpc}^{-2} \text{yr}^{-1}$. For earlier type galaxies the star formation is more constant ($\tau \approx 10$ Gyr).

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