

The origin of nitrogen and the chemical evolution of spiral galaxies

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Summary. Numerical models of chemical evolution reproducing the observed oxygen abundances through the discs of the Galaxy and eight nearby spirals have been computed to predict their corresponding nitrogen abundances under different assumptions on the stellar nucleosynthesis involved in the computation of the yields.

It is found that a primary fraction of nitrogen between 30 and 60 % (corresponding to a mixing length $1.0 \leq \alpha_{RV} \leq 1.5$) is required in order to reproduce simultaneously the observed oxygen and nitrogen abundances. The best agreement between model results and observational data is attained for α_{RV} closer to 1.5 and an upper limit for intermediate mass stars of $M_{up} \simeq 5-6 M_{\odot}$ instead of the standard $8 M_{\odot}$. This combination of stellar evolution parameters is also required to reproduce the $^{12}C/^{13}C$ isotopic ratio observed in galactic molecular clouds and the N/C vs. C/H distribution derived from stellar observations in the solar neighbourhood.

Key words: chemical evolution – chemical abundances – spiral galaxies – nucleosynthesis

1. Introduction

The primary or secondary nature of nitrogen remains a controversial issue. Quiescent CNO processing (secondary processing in which the preexisting carbon and oxygen in the star are converted into nitrogen) is believed to be the main nucleosynthesis mechanism for the production of nitrogen. However, there are cases in which this mechanism alone is not enough to explain the observed N abundances¹ (e.g. NGC 6822, Dufour and Talent, 1980).

The interpretation of the observational data available at present is quite confusing: Pagel and Edmunds (1981) conclude that some primary contribution of nitrogen, i.e. nitrogen produced independently of any preexisting ^{12}C and O in the star, in varying amounts, is needed in order to explain the N/O vs. O/H diagram resulting from H II region observations. Tomkin and Lambert

(1984) from high resolution observations of F and G dwarfs claim that N is all of primary origin, while Laird (1985) from intermediate dispersion spectra of 116 field stars suggests that nitrogen is mostly but not exclusively primary. On the other hand, Peimbert and Sarmiento (1984) argue that, if N is assumed to come from intermediate mass stars (IMS) and to be ejected by planetary nebulae and novae, then it is mainly secondary.

Data on nitrogen abundances exist for many H II regions both in the Galaxy and in external galaxies and chemical evolution models can be used to test different nucleosynthesis theories. This approach has been followed by several authors, but the situation is far from being clear. Alloin et al. (1979) required some primary contribution of nitrogen combined with variations in the slope of the initial mass function (IMF) in order to explain the N/O vs. O/H relation observed in galaxies if simple chemical evolution models, i.e. models with no infall of matter, were used. On the other hand, Serrano and Peimbert (1983) argue that purely secondary nitrogen, when combined with chemical evolution models allowing for gas infall and including time-delay effects, can reproduce this relation if the primary yield increases with the metallicity as suggested by Peimbert and Serrano (1982).

Extrapolation of observed abundance gradients, combined with simple ideas about galactic chemical evolution, suggests that the conversion of gas into stars followed by explosive nucleosynthesis in supernovae should have gone further in the nuclear regions of galaxies. In the absence of inflow of unprocessed material, secondary CNO processing would naturally lead to N/O abundance ratios exceeding that of the Sun. Thus, the nitrogen overabundances suggested by Peimbert (1968) for M51 and M81 and for other galaxies by Alloin et al. (1979) could be taken as evidence for secondary nitrogen production. However, it is now known that both M51 and M81, and also most early type galaxies with emission lines, are LINERS (Heckmann, 1980) with strong [N II] lines. In the case of M81, Peimbert and Torres-Peimbert (1981) claimed shock excitation to be the dominant ionization mechanism and deduced a considerable overabundance of nitrogen by fitting shock models. However, recent work by different authors has shown that photoionization by a hard spectrum similar to that responsible for the ionization in Seyfert galaxies is more likely to be acting in LINERS (Diaz et al., 1985, and references therein). In this case, the derived N/O ratios are between solar and three times solar and do not constitute evidence for a strongly dominant secondary processing of nitrogen.

In a series of previous papers (Tosi, 1982; Diaz and Tosi, 1984; Tosi and Diaz 1985, hereinafter Papers I, II, and III, respectively),

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1 Hereinafter N stands for ^{14}N and O for ^{16}O , the most common isotopes of the two atomic species

Table 1. Adopted abundances and galactocentric distance for each H II region

Galaxy	R(kpc)	12+log(O/H)	12+log(N/H)	Ref	Galaxy	R(kpc)	12+log(O/H)	12+log(N/H)	Ref
MWG	5.84	8.91	7.93	sh	M51	2.80	9.45	8.15	mc
	6.02	8.75	7.66	sh		5.80	9.41	7.94	mc
	6.14	8.83	7.49	sh		7.80	9.39	8.13	se
	6.32	9.02	7.86	pe		11.40	8.90	7.04	sm
	6.32	8.92	7.93	pe		12.70	9.19	7.89	sm
	6.32	8.88	8.02	pe	M83	0.87	9.47	8.69	du
	6.76	8.69	7.61	pe		1.91	9.53	8.68	du
	6.89	8.62	7.64	sh		2.70	9.42	8.58	du
	6.89	8.71	7.74	pe		5.66	9.05	8.11	du
	6.94	8.95	8.02	pe		6.87	9.18	8.21	du
	7.01	8.62	7.80	pe	M101	6.70	8.81	7.58	ra
	7.38	8.83	7.61	sh		7.22	9.10	8.29	ss
	7.69	8.49	7.52	sh		9.43	8.58	7.48	mc
	8.12	8.83	7.63	sh		10.04	8.55	7.17	mc
	8.24	8.74	7.73	pe		10.19	8.67	7.38	mc
	8.49	8.88	7.61	sh		10.77	8.56	7.39	mc
	8.73	8.46	7.43	sh		10.80	8.62	7.22	ra
	8.92	8.58	7.43	pe		13.65	8.62	7.36	mc
	9.10	8.49	7.43	sh		14.22	8.54	7.43	ss
	9.60	8.77	7.61	pe		24.53	8.11	6.52	mc
	9.60	8.63	7.49	sh	25.50	8.16	6.54	ra	
	9.87	8.68	7.46	sh	NGC2403	0.82	8.64	7.32	mc
	10.02	8.35	7.14	sh		1.01	8.82	7.64	mc
10.02	8.31	7.18	pe	2.09		8.53	6.93	mc	
10.40	8.09	7.15	pe	4.99		8.04	6.68	mc	
10.52	8.68	7.46	sh	5.30		8.22	6.55	mc	
10.53	8.34	7.24	sh	7.61		8.31	6.72	mc	
10.89	8.54	7.21	sh	NGC6946		2.17	9.13	8.19	mc
10.84	8.40	7.24	sh			4.29	9.10	8.02	mc
11.20	8.32	7.55	sh			6.00	8.49	7.38	mc
11.44	8.12	7.11	sh			6.39	8.53	7.56	mc
					7.69	8.89	7.70	mc	
M31	5.30	9.01	7.79	b1	8.57	8.66	7.54	mc	
	5.40	9.12	8.04	b1	IC342	0.00	9.40	8.72	mc
	7.10	9.16	7.82	b1		4.00	9.24	8.11	mc
	10.50	8.81	7.74	b1		7.43	8.44	7.20	mc
	10.90	8.81	7.59	b1		12.06	8.28	7.05	mc
	13.60	8.48	7.33	b1					
	14.20	8.66	7.40	b1	REFERENCES				
	14.30	8.89	7.63	b1	b1: Blair et al. (1982)				
	18.90	8.86	7.47	b1	du: Dufour et al. (1980)				
	19.70	8.61	7.17	b1	ka: Kwitter and Aller (1981)				
22.70	8.53	7.11	b1	mc: McCall (1982)					
M33	0.98	8.60	7.25	ka	pe: Peimbert (1979)				
	1.28	8.57	7.39	ka	ra: Rayo et al. (1982)				
	1.57	8.32	7.11	ka	se: Searle (1971)				
	2.22	8.38	7.11	ka	sh: Shaver et al. (1983)				
	2.83	8.45	7.10	ka	ss: Shields and Searle (1978)				
	3.06	8.30	6.97	ka	sm: Smith (1975)				
	3.83	8.16	6.87	ka					
	4.73	8.28	6.97	ka					
	4.90	8.21	6.88	ka					
	5.03	8.00	6.84	ka					
5.68	8.06	6.72	ka						

N.B. The solar galactocentric distance adopted here is 8 kpc

we have computed chemical evolution models for nine spiral galaxies, including our own, which reproduce successfully the observed distributions of oxygen abundances. These numerical models differ from those computed by the authors mentioned above because they allow a direct computation of the nitrogen abundance taking into account the actual lifetimes of stars of different initial masses and avoiding any assumed dependence of nitrogen on other elements. These models can therefore provide a self consistent indication on the nitrogen origin. We have then used them to predict the nitrogen abundances in the nine spirals previously studied and their variations when different assumptions for the production of nitrogen in stars are adopted. In particular, we have taken into account the effects of adopting different mixing lengths α_{RV} in the stellar interiors and of reducing the upper limit M_{up} for intermediate mass stars as recently suggested by Bertelli et

al. (1985), Castellani et al. (1985), and Renzini et al. (1985). The results have been compared with the nitrogen abundances derived from the H II region observations.

The observational data and the theoretical models are described in Sects. 2 and 3 of this work, while the results are discussed in Sect. 4. The main conclusions are summarized in Sect. 5.

2. Observational data

We have included in this study the nine galaxies analyzed in Papers II and III: the Galaxy (MWG), M31, M33, M51, M83, M101, NGC 2403, NGC 6946, and IC 342. The galactocentric distance and the nitrogen and oxygen abundances adopted for the H II regions of each galaxy are listed in Table 1, together with their

corresponding references. For the other parameters (e.g. morphological type, distance from the Galaxy, etc.) see Papers II and III.

Ionic abundances of O^+ , O^{2+} , and N^+ are derived directly from the measured intensity of the $[O\ II]\ \lambda\lambda 3727, 29$, $[O\ III]\ \lambda\lambda 4959, 5007$ and $[N\ II]\ \lambda\lambda 6548, 84$ lines relative to $H\beta$, once the electronic temperature, t_e , is known. This temperature was calculated directly following Seaton (1975) in the cases where the temperature sensitive line of $[O\ III]\ \lambda 4363$ was detected. In the rest of the cases the empirical calibration of Pagel and Edmunds (1981) was adopted for the determination of the mean electron temperature, $\langle t_e \rangle$.

Once the ionic abundances are determined, total abundances have to be computed. In the case of oxygen the two ions expected to be present in H II regions on the basis of their ionization potentials, are observed and therefore

$$\frac{N(O)}{N(H)} = \frac{N(O^+) + N(O^{2+})}{N(H^+)}$$

In the case of nitrogen, the assumption is made that the ratio N/O is equal to that of N^+/O^+ which is a good approximation in H II regions if the charge exchange reaction $O^{2+} + H^0 \rightarrow O^+ + H^+$ is not important (Stasińska, 1980). Then

$$\frac{N(N)}{N(H)} = \frac{N(N^+)}{N(O^+)} \frac{N(O)}{N(H)}$$

Typical errors in the abundances determined in this way when a mean electron temperature, $\langle t_e \rangle$, derived from an empirical calibration is used, are of the order of ± 0.2 dex for both O/H and N/O (Pagel and Edmunds, 1981).

3. Theoretical models

3.1. Chemical evolution

The models used in this study have been described in detail in Papers I, II, and III, and therefore only a brief description is given here. The disc of each galaxy is approximated by concentric rings 1 kpc wide. The gas and total mass of each ring are deduced from the observed present distributions as described in Papers II and III. Gas flows between consecutive rings are not considered. The initial mass function adopted for the models is independent of time and galactocentric distance and taken to be the same as that derived for the solar neighbourhood (Tinsley, 1980) with a higher upper mass limit of $100 M_\odot$. The two free parameters of the models are the star formation rate (SFR) and the infall of unprocessed gas (F). The SFR follows an exponential law $e^{-t/\tau}$ with the e -folding time $\tau \leq \infty$, and the infall is assumed, for simplicity, to be constant and uniform.

3.2. Stellar nucleosynthesis and yields

Oxygen (^{16}O) is synthesized mainly by massive stars ($M > 9 M_\odot$). Because of the importance of mass loss effects in the resulting stellar yields, we have adopted the nucleosynthesis results by Arnett (1978), but scaling his $M - M_\alpha$ (initial mass - helium core mass) relation according to Maeder's (1981, 1983) models with intermediate mass loss rate (his case b).

High mass stars contribute to the nitrogen (^{14}N) enrichment only through stellar winds (Woosley, private communication). This contribution has been calculated by Maeder (1981, 1983) and

is taken into account here, but turns out to be very small. In fact, the bulk of nitrogen is produced by intermediate mass stars (IMS).

For low and intermediate mass stars, we have adopted the nucleosynthesis results by Renzini and Voli (1981). Their stellar evolution models are characterized by the rate of stellar mass loss, through the parameter η , and the mixing length, α_{RV} , the characteristic travel distance of a convective cell. The contribution of N and O of a star of a given initial mass is a function only of the assumed mass loss and mixing length.

Primary nitrogen is produced only by stars experiencing the hot-bottom burning during the asymptotic giant branch phase (Renzini and Voli, 1981) and therefore is restricted to a limited mass range. The upper mass limit of this range, M_{up} , corresponds to the maximum initial mass of stars that ignite carbon in degenerate cores and therefore experience the asymptotic branch phase (i.e. IMS). The lower limit depends on the value of the mixing length adopted in the computation of stellar evolution models. This minimum mass is 6.8, 4, and $3.3 M_\odot$ for $\alpha_{RV} = 1.0, 1.5,$ and 2.0 , respectively². This implies that for higher α_{RV} there are more stars producing primary N at the expense of the fresh ^{12}C dredged-up in the envelope burning phases.

Standard models of stellar evolution predict an upper mass limit for IMS of $M_{up} \simeq 8-9 M_\odot$. However, recent suggestions (Bertelli et al., 1985; Castellani et al., 1985; Renzini et al., 1985) indicate that the inclusion of overshooting from convective cores can limit M_{up} to values as low as $5-6 M_\odot$.

4. Results and discussion

Figures 1–3 show for each of the studied galaxies the nitrogen abundance distributions resulting from the models which in Paper III best reproduced the observed radial distribution of oxygen. Only for the Galaxy (Fig. 1) the results corresponding to all the four values of α_{RV} (i.e. 0, 1.0, 1.5, and 2.0) are shown. For the rest of the galaxies only the models computed with $\alpha_{RV} = 1.0$ and $\alpha_{RV} = 1.5$ are plotted, but the results for the other values can easily be envisaged with reference to Fig. 1: for all these spirals, models with $\alpha_{RV} = 0$ and $\alpha_{RV} = 2$ give nitrogen abundances well outside the observational range.

All the models shown in Figs. 1–3 have been computed using the standard upper mass limit of $8 M_\odot$ for carbon ignition in a degenerate core. Values of $\alpha_{RV} = 0, 1.0, 1.5,$ and 2.0 imply a present fraction of secondary nitrogen of 1.0, 0.7, 0.3, and 0.2 respectively.

As can be seen from the figures, the slope of the nitrogen gradient can be very well reproduced for each galaxy by the same models which also fit its oxygen abundance gradient. According to these models the observed nitrogen abundances correspond to a value of α_{RV} between 1.0 and 1.5. The galaxies with the lowest metallicity (M33 and NGC 2403) look in better agreement with an α_{RV} of 1.0, while those with higher metallicity (M83 and M51) seem to be closer to a value of α_{RV} of 1.5.

Figures 4–6 show the $\log(N/O)$ vs. $\log(O/H)$ diagram for each of the galaxies. This sort of diagrams are the best tools to study the origin of nitrogen, since they are much more sensitive to the adopted nucleosynthesis than to the chemical evolution models if a constant and uniform IMF is assumed.

² The Renzini and Voli models have also been computed for a mixing length $\alpha_{RV} = 0$ for which case the hot-bottom burning has been omitted, and therefore no primary production of nitrogen exists

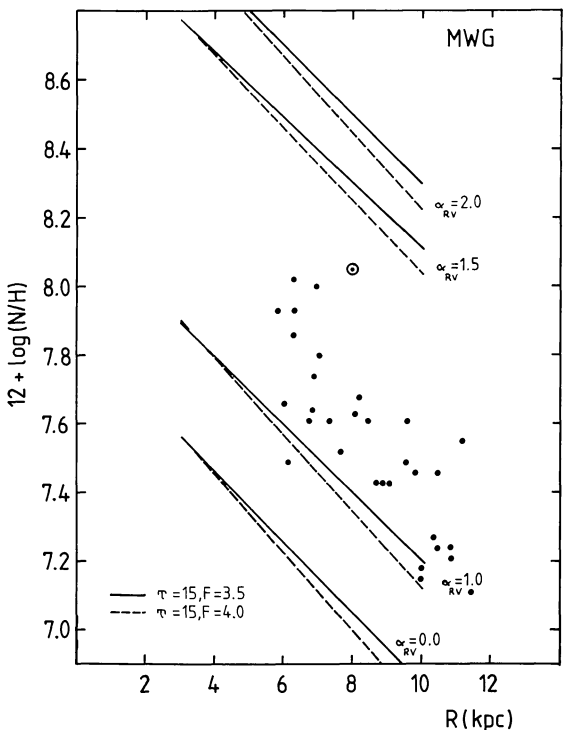


Fig. 1. Present radial variation of the nitrogen abundance for the Milky Way as derived from the indicated models. The four different sets of curves correspond to different values of the mixing length α_{RV} , as labelled (see text for details). The dots represent the observed abundances listed in Table 1. The solar abundance is indicated by the usual sun symbol.

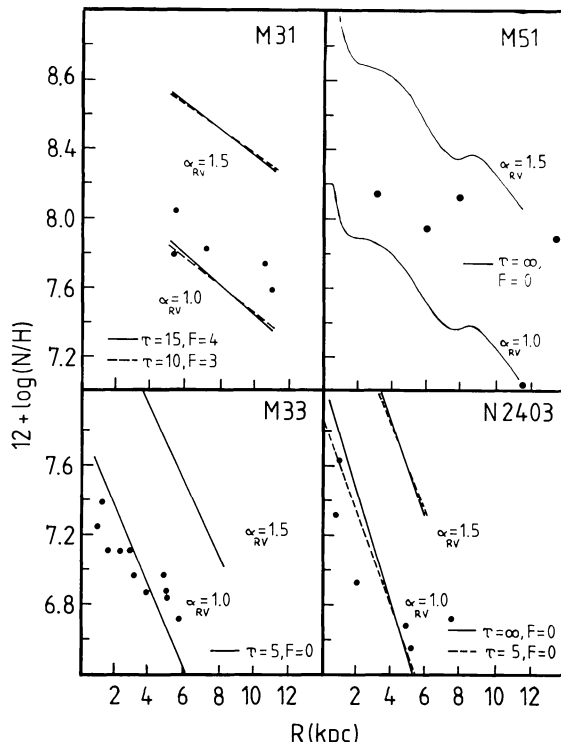


Fig. 3. Same as Fig. 2, but for the galaxies: M31, M51, M33, and NGC 2403

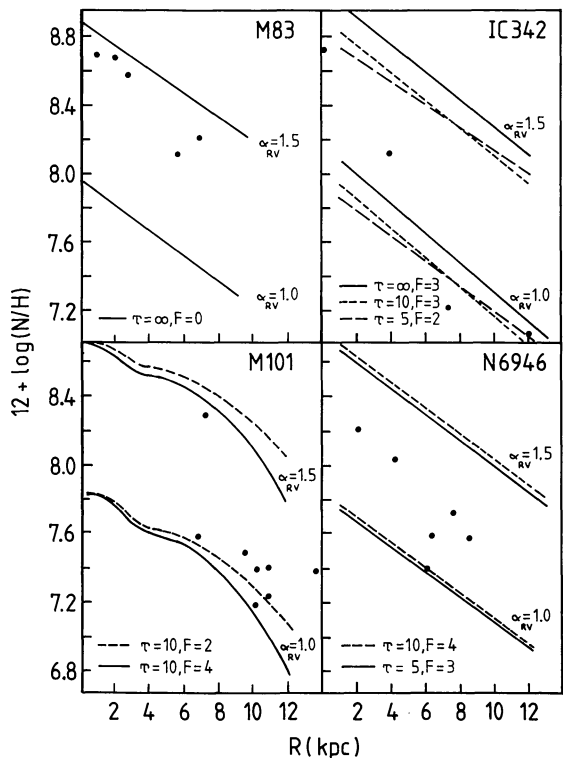


Fig. 2. Present radial variation of the nitrogen abundance for the galaxies: M83, IC 342, M101, and NGC 6946. Only two sets of models, corresponding to values of $\alpha_{RV} = 1.0$ and 1.5 are shown. The parameters of the models are indicated and the dots represent the observed data listed in Table 1

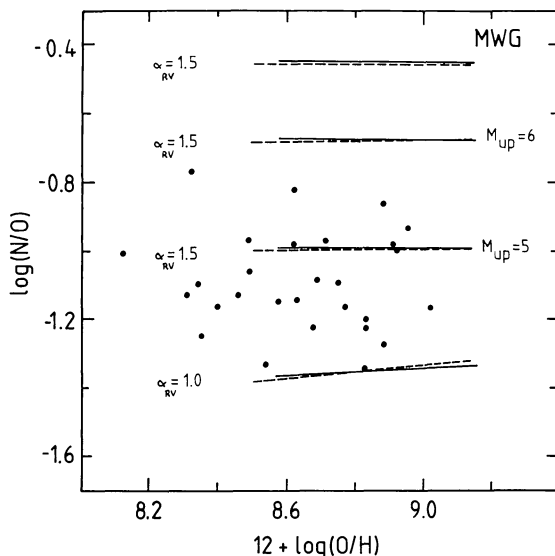


Fig. 4. Present N/O vs. O/H diagram for the Milky Way, as derived from the indicated models. Symbols are the same as in Fig. 1. Three sets of models computed with the same value of $\alpha_{RV} = 1.5$ are shown, corresponding to three different values of M_{up} (see text) as labelled. The two unlabelled sets correspond to the standard value of $M_{up} = 8 M_{\odot}$

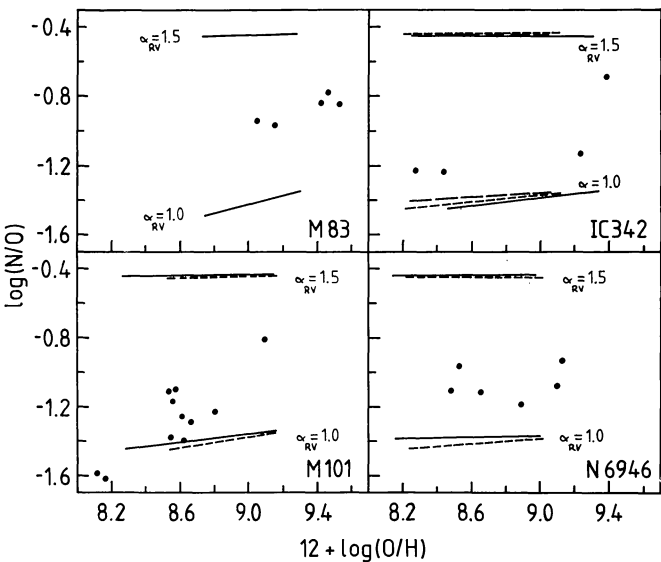


Fig. 5. Present N/O vs. O/H diagram for the galaxies: M83, IC 342, M101, and NGC 6946. Symbols are the same as in Fig. 2

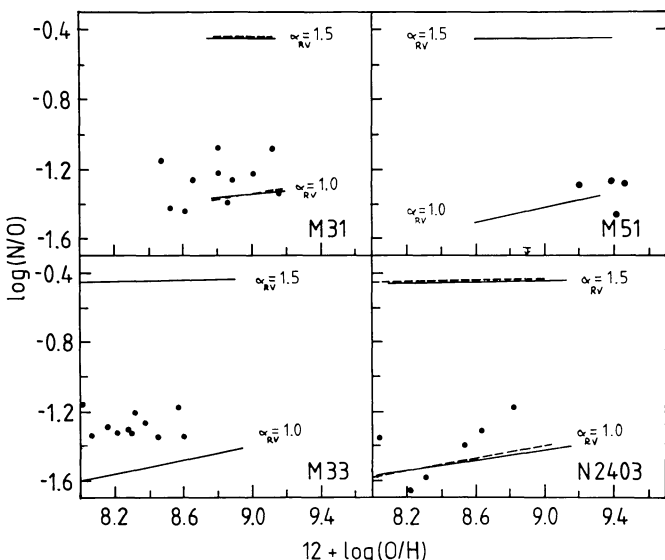


Fig. 6. Present N/O vs. O/H diagram for the galaxies: M31, M51, M33, and NGC 2403. Symbols are as in Fig. 3

Recently, Terlevich (1982), Güsten and Mezger (1983), and Larson (1985) have argued against this simplifying assumption. The former suggests an IMF where the fraction of massive stars strongly decreases for increasing ambient metallicity, while the others invoke *bimodal star formations* where the fraction of massive stars is higher in regions of higher SFR. All these IMFs would somehow alter the N/O distributions resulting from our models, since they let vary the relative contribution of high (oxygen producers) and intermediate (nitrogen producers) mass stars. However, all of them seem to be inconsistent with at least one observational constraint. Terlevich's IMF implicitly excludes any oxygen gradient since the higher metallicity of the inner regions is compensated by their lower fraction of oxygen contributors, and the predicted amount of oxygen is lower than observed in galactic and extragalactic H II regions (see also Matteucci and Tosi, 1985).

Vice versa, Güsten and Mezger (1983) predict oxygen abundances a factor of two higher than observed, and Larson's models reproduce the solar abundance only if stars above $16 M_{\odot}$ do not explode as supernovae and therefore do not eject oxygen. Furthermore, the observational evidence at least of the present galactic IMF (Humphreys and McElroy, 1984) suggests a uniform spatial distribution similar to that adopted here.

Assuming our IMF to be valid, it is apparent from Figs. 4–6 that for a given α_{RV} different evolution models give results very similar to each other. All models with $\alpha_{RV} \geq 1.5$ produce a flat straight line due to the high percentage of primary nitrogen which makes it almost independent of oxygen. For $\alpha_{RV} \leq 1.0$ (i.e. a fraction of secondary nitrogen higher than 0.7) the spatial relation between N and O is evidenced by the presence of a small slope in the log(N/O) vs. log(O/H) distribution. Apart from the case of M101, the slopes obtained for a value of α_{RV} of 1.0 appear to be consistent with the observed ones. Moreover, for most of the galaxies, the observed N/O values are on the average closer to those computed with $\alpha_{RV} = 1.0$ than to those with $\alpha_{RV} = 1.5$.

In order to check this indication, we have computed for the Galaxy (the only galaxy for which the observational counterpart exists) the ^{12}C and ^{13}C abundances. ^{13}C has a nucleosynthesis story similar to that of N. It is mostly produced by IMS and its primary production also depends on the hot-bottom burning, and therefore on the value of α_{RV} . ^{12}C is a primary element produced by both IMS and high mass stars. Therefore, we should expect to find the best agreement between the N/O and $^{12}\text{C}/^{13}\text{C}$ observed ratios and the model results for the same value of α_{RV} . For the model with $\tau = 15$ Gyr and $F = 4 \cdot 10^{-3} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$, the value of $\alpha_{RV} = 1.0$ yields at the solar galactocentric distance a ratio of $^{12}\text{C}/^{13}\text{C}$ by mass of 170. The same model computed with a value of $\alpha_{RV} = 1.5$ yields a ratio $(^{12}\text{C}/^{13}\text{C})_{8\text{kpc}} = 45$. The corresponding observed value, as derived by Henkel et al. (1982) and Henkel et al. (1985) from molecular cloud radio observations, is $(^{12}\text{C}/^{13}\text{C})_{8\text{kpc}} \approx 65 \pm 10$ by mass. Therefore, here a better agreement is found for models with α_{RV} closer to 1.5 rather than to 1.0. Although the uncertainties on both observational data and theoretical models are large, this discrepancy is disturbing. However, if M_{up} can be as low as $5\text{--}6 M_{\odot}$, as stressed by Bertelli et al. (1985), Castellani et al. (1985), and Renzini et al. (1985), this discrepancy is removed. In fact, a lower mass limit for degenerate carbon ignition implies that the mass range where the primary production of both ^{13}C and N, can take place is sensibly smaller than that assumed in the previous computations. Thus a decrease of M_{up} implies an increase of $^{12}\text{C}/^{13}\text{C}$ and a decrease of N/O.

As shown by Renzini (1984, Figs. 1 and 2), for $\alpha_{RV} = 1.0$ both ^{13}C and N are synthesized from ^{12}C in stars with initial mass $(6\text{--}7) M_{\odot} \leq M \leq M_{\text{up}}$. A reduction of M_{up} to $6 M_{\odot}$ is therefore incompatible with such a value of the mixing length, since there would not be any ^{13}C and N contribution from IMS (and then no ^{13}C at all!) and too much ^{12}C . For $\alpha_{RV} = 1.5$, the bulk of ^{13}C (mostly primary) is produced in the mass range around $5 M_{\odot}$, while the nitrogen contribution increases with stellar initial mass increasing from $4 M_{\odot}$ to M_{up} . For this mixing length, a reduction of M_{up} to $6 M_{\odot}$ then implies a sensible drop of the N/O ratio and a slight increase (e.g. from 45 to 48) of the $^{12}\text{C}/^{13}\text{C}$ ratio, due only to the reduced depletion of ^{12}C . If M_{up} drops to $5 M_{\odot}$, N/O steadily keeps decreasing, but the production of ^{13}C at the expense of ^{12}C is strongly reduced and the $^{12}\text{C}/^{13}\text{C}$ ratio suddenly rises to high values.

The effect of reducing M_{up} on the N/O vs. O/H distribution in the Galaxy can be seen in Fig. 4, where we show the results of the models computed with $\alpha_{RV} = 1.5$ and three different values of M_{up} :

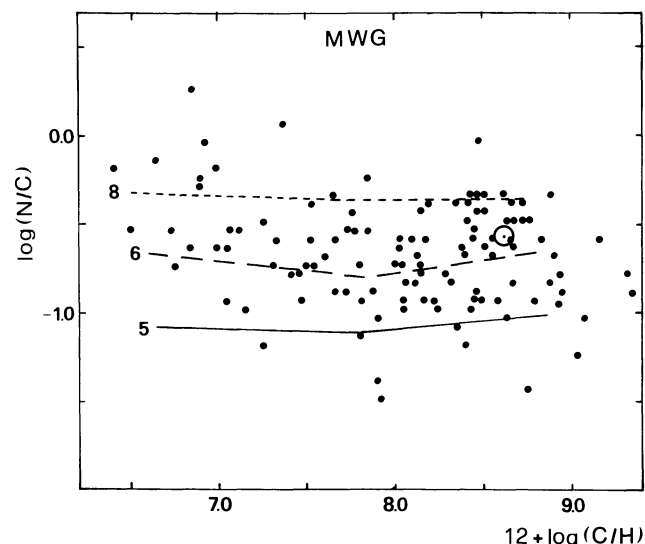


Fig. 7. Time behaviour of the N/C vs. C/H distribution in the solar neighbourhood as derived from stellar observations (Laird, 1985) and from the model with $\tau = 15$ Gyr, $F = 4 \cdot 10^{-3} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$, $\alpha_{RV} = 1.5$ and the three labelled values of $M_{up} = 5, 6, \text{ and } 8 M_{\odot}$.

5, 6, and $8 M_{\odot}$. The effect mainly consists in a reduction of the total nitrogen abundance with decreasing M_{up} for a given value of α_{RV} . The corresponding computed values of $(^{12}\text{C}/^{13}\text{C})_{8\text{kpc}}$ are 48 for $M_{up} = 6 M_{\odot}$ and 99 for $M_{up} = 5 M_{\odot}$. The values predicted by these models for the sun are $(^{12}\text{C}/^{13}\text{C})_{\odot} = 51$ and 107, respectively, to be compared with the observed solar value of 82.2. This implies that for values of M_{up} between 5 and $6 M_{\odot}$ both the $^{12}\text{C}/^{13}\text{C}$ and N/O ratios resulting from the best models for the Galaxy would be roughly consistent with the observations for a value of α_{RV} close to 1.5. It should be noticed however that the observed time variation of the $^{12}\text{C}/^{13}\text{C}$ ratio in the solar vicinity is larger than predicted by the models. Such a large variation can be reproduced only by increasing the time delay between the ejection of the bulk of ^{12}C and that of ^{13}C , for instance by allowing ^{13}C to be produced mostly by stars smaller (i.e. with longer life) than assumed by Renzini and Voli (1981).

As a further and independent check of our result on α_{RV} and M_{up} , we have plotted in Fig. 7 the N/C vs. C/H distribution as derived from the above mentioned models and from Laird's (1985) observations of 116 nearby stars. The adopted solar values are indicated by the usual sun symbol. In this case, the abscissa (C/H) is an implicit monotonic function of time in a given region, contrary to Figs. 4 to 6 where H II regions and models show the abundance ratios at the present epoch and represent their spatial behaviour. Despite the large spread in the observed distribution, the only model predicting abundances within the observational range has $M_{up} = 6 M_{\odot}$ and $\alpha_{RV} = 1.5$. Whatever M_{up} , $\alpha_{RV} = 1.0$ implies too much carbon and too low nitrogen (cf. Renzini, 1984), giving at most $\log(N/C) \simeq -1.4$ and is therefore to be rejected.

Since α_{RV} is a stellar parameter which should not be dependent on the circumstellar ambient, it seems reasonable to extrapolate the result obtained for our galaxy to the other spirals and assume that also there the value of α_{RV} is always close to 1.5. If this is the case, the suggested dependence of M_{up} on metallicity (see e.g. Castellani et al., 1985) might be responsible for the different N/O ratios observed from one galaxy to another. In fact, if we put together all the H II region abundances (see e.g. Pagel and Edmunds, 1981,

Fig. 3), the superposition of the various flat distributions within each single galaxy leads to an apparent general increase of N/O with O/H. A variation of M_{up} with metallicity would also reduce the range of mixing length required to explain the different nitrogen abundances observed in different galaxies.

5. Summary and conclusions

We have presented numerical models for the chemical evolution of nine nearby spirals able of reproducing the main observed features of these galaxies. These results are obtained introducing only two free (and independent) parameters, SFR and infall rate, which also turn out to be consistent with the available observational data.

As stressed in Papers I–III of this series, the gas and total mass distributions observed in the disc of each spiral are taken as input data for deriving the initial SFR values and therefore are automatically reproduced by the models.

The nitrogen and oxygen abundances derived from H II region observations in these nine galaxies are well fitted by those computed by the models under the most recent nucleosynthetic prescriptions, and the abundance gradients resulting from these computations are in very good agreement with the observed ones. Since nitrogen and oxygen are produced by stars of completely different mass ranges, these good agreements also imply that the assumption of an IMF constant everywhere (i.e. independent of time, galactocentric distance, or metallicity) and equal to that of the solar neighbourhood is reasonably correct. Strong deviations from this assumption would reflect in strong variations in the computed abundances and gradients and would not be consistent with the observed data.

In the case of the Milky Way, where detailed data are available not only for O–B stars and H II regions, but also for older objects, our models turn out to reproduce (Paper I) also the age-metallicity relation derived by Twarog (1980) for the solar neighbourhood and the metallicity gradients for stars older than ~ 2 Gyr (e.g. Mayor, 1976).

The main conclusions of the present paper concern the controversial origin of nitrogen and can be summarized as follows:

(i) A primary fraction of nitrogen, synthesized during the envelope burning of intermediate mass stars (Renzini and Voli, 1981) and ranging between 30% and 60%, explains the observed nitrogen abundances and abundance ratios in all the analyzed nearby spirals.

(ii) A reduction of the upper mass limit of intermediate mass stars to $M_{up} \simeq 5\text{--}6 M_{\odot}$ combined with a mixing length α_{RV} of the order of 1.5 leads to abundances in better agreement with the observed trends of N/O vs. O/H and N/C vs. C/H, and with the present $^{12}\text{C}/^{13}\text{C}$ isotopic ratio derived in the solar neighbourhood.

More detailed results on this latter point cannot be inferred from our analysis since the effects on the nucleosynthesis processes of including overshooting from convective cores in the stellar evolution models are presumably well beyond a simple reduction of the range of masses where hot-bottom burning can take place. For example, the inclusion of a strong overshooting in massive star models can alter our computed oxygen abundances by increasing the helium core and thus changing the $M\text{--}M_{\alpha}$ relation (Greggio and Tosi, 1986).

On the other hand, exactly the same conclusions on M_{up} , α_{RV} , and the primary fraction of nitrogen have been reached by Matteucci and Tosi (1985) by reproducing the nitrogen and oxygen abundances observed in dwarf irregular galaxies. It should be

emphasized that this agreement is attained with chemical evolution models completely different from those described here, since dwarf irregulars evolve with bursting star formation, sometimes just one single burst, and loss of gas through galactic winds, while spiral galaxies evolve with continuous, sometimes constant, star formation and infall of gas. This supports the idea that the same nucleosynthesis processes are responsible of the abundances observed in galaxies of the various morphological types, even if these abundances can appear very different from each other because of the very different evolutions of the parent galaxies.

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