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Some considerations on the origin of nitrogen

Francesca Matteucci *European Southern Observatory, Karl-Schwarzschild-Str. 2, D-8046 Garching bei München, Federal Republic of Germany*

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Summary. The evolution of nitrogen relative to carbon, iron and oxygen in the solar neighbourhood has been computed under the assumption that nitrogen is both a primary and a secondary nucleosynthesis product. In particular, it has been assumed that secondary nitrogen is produced by stars of all masses whereas primary nitrogen is produced by intermediate-mass stars ($4 \lesssim M/M_\odot \lesssim 8$) only, according to the current nucleosynthesis results. However, in order to reproduce the existing data for dwarf stars, nitrogen produced in massive stars ($M > 8\,M_\odot$) must be predominantly of primary origin. In this framework, the secondary production of nitrogen cannot be excluded but it must be confined to stars of low and intermediate mass.

Finally, nitrogen evolution in the solar neighbourhood has been compared with that in extragalactic H II regions (dwarf irregular galaxies), which are likely to experience a bursting mode of star formation instead of a continuous one. It is reasoned that it is not correct to compare the N/O versus O/H distribution for galactic and extragalactic H II regions with that for dwarf stars in the solar neighbourhood. In fact, the models suggest that the behaviour of N/O with O/H, during galactic evolution, is different from the N/O versus O/H distribution obtained by plotting the present time values of these quantities for different galaxies.

1 Introduction

The question whether nitrogen originates predominantly from primary or secondary nucleosynthesis in stars has received much discussion in the literature over the last few years.

In the case of a primary nucleosynthesis, nitrogen is expected to originate from H-burning on fresh carbon generated by the parent star, whereas in the case of a secondary nucleosynthesis nitrogen should originate from H-burning on carbon and oxygen originally present in the parent star. From a theoretical point of view, the secondary production of nitrogen should be common to stars of all masses, whereas the primary production should arise only from intermediate-mass stars ($4 \leqslant M/M_\odot \leqslant 8$) undergoing dredge-up episodes during the asymptotic giant branch evolution. In particular, when the third dredge-up is operating in conjunction with the burning at the base of the convective envelope (hot-bottom burning), primary nitrogen can originate (Renzini & Voli 1981). The amount of primary nitrogen depends mostly on the adopted value of the mixing length in the stellar models.

There is no clear indication that a mechanism for primary production of nitrogen is operating in massive stars ($M>8\,M_\odot$), although it cannot be excluded (Maeder 1983). The only indication for a primary production of nitrogen in massive stars comes from the nucleosynthetic results of Woosley & Weaver (1982a) concerning a $500\,M_\odot$ star with zero metallicity content.

Simple models of galactic chemical evolution assuming instantaneous recycling of matter from stars, predict that N/O should be constant for primary nitrogen and proportional to carbon and oxygen for secondary nitrogen. However, this interpretation is certainly an oversimplication because it does not take into account the very important effects of stellar lifetimes. In fact, independently of the primary/secondary nature of a chemical element, an element like iron, which is primary but mostly produced by low- and intermediate-mass stars, behaves like a secondary element with respect to oxygen, which is produced only in massive stars (see data of Clegg, Lambert & Tomkin 1981).

From an observational point of view, Tomkin & Lambert (1984) have recently measured the [N/O] ratio in a sample of 11 solar-neighbourhood dwarfs as a function of [O/H] (see insert in Fig. 1). Their best fit to the data suggests a constant value of $[\mathrm{N/O}]\simeq-0.6$ for [O/H] in the range -1.5 to -0.5, but the data points in this range are very few, and $[\mathrm{N/O}]=[\mathrm{O/H}]$ for $\mathrm{O/H}>-0.5$. In addition, they find that [N/C] is almost solar in halo and disc stars. Their interpretation, based on the predictions of the simple galactic evolution model, is that nitrogen is a primary element. More recently, Laird (1985) determined the abundance of nitrogen and carbon relative to iron for a larger sample of solar-neighbourhood stars (116 field dwarfs, 10 field giants and 3 Hyades dwarfs). He also found that [C/Fe] is solar over the range $-2.45\leqslant[\mathrm{Fe/H}]\leqslant+0.50$ and that the same is true for nitrogen in the range $-1.8\leqslant[\mathrm{Fe/H}\leqslant+0.5$. All these results suggest, apart from the secondary/primary distinction, that C, N and Fe should be produced by the same stars. Therefore, stars in a given mass range must produce C, N *and* Fe or none of them.

Data on nitrogen and oxygen for galactic and extragalactic H II regions, shown in Fig. 1, are more difficult to interpret because they represent a non-homogeneous sample of objects.

Overall, some correlation seems to exist with a 45° line forming a lower envelope for a good fraction of the data, but a big scatter is also present. However, it could be dangerous to interpret these data as an evolutionary track, since they refer to different objects which are likely to have evolved in very different ways. In fact, by selecting relatively homogeneous objects out of this sample, like for example blue compact galaxies or H II regions in the Milky Way, no correlation can be found between oxygen and nitrogen. On the other hand, some correlation seems to exist between nitrogen and oxygen in H II regions of M101.

Some authors who have attempted to interpret the N/O versus O/H pattern, in galactic and extragalactic H II regions, on an overall basis, have reached different conclusions.

For example, Alloin *et al.* (1979), studying extragalactic H II regions and irregular galaxies, by means of a galactic-evolution model with continuous star formation, reached the conclusion that nitrogen should be partly a primary element. On the other hand, Serrano & Peimbert (1983) concluded that nitrogen should be mostly secondary and that infall of extragalactic matter and a variable heavy element yield are required to reproduce the observed N/O distribution in galactic and extragalactic H II regions.

Tomkin & Lambert (1984) claimed that their stellar data mimic quite well the distribution of galactic and extragalactic H II regions, with the implication that nitrogen is a primary element.

Recently, Matteucci & Tosi (1985) have shown that the flat distribution of N/O in extragalactic H II regions (dwarf irregular galaxies) can be well reproduced by means of a model assuming bursts of star formation, galactic winds powered by supernovae, and that nitrogen is both a

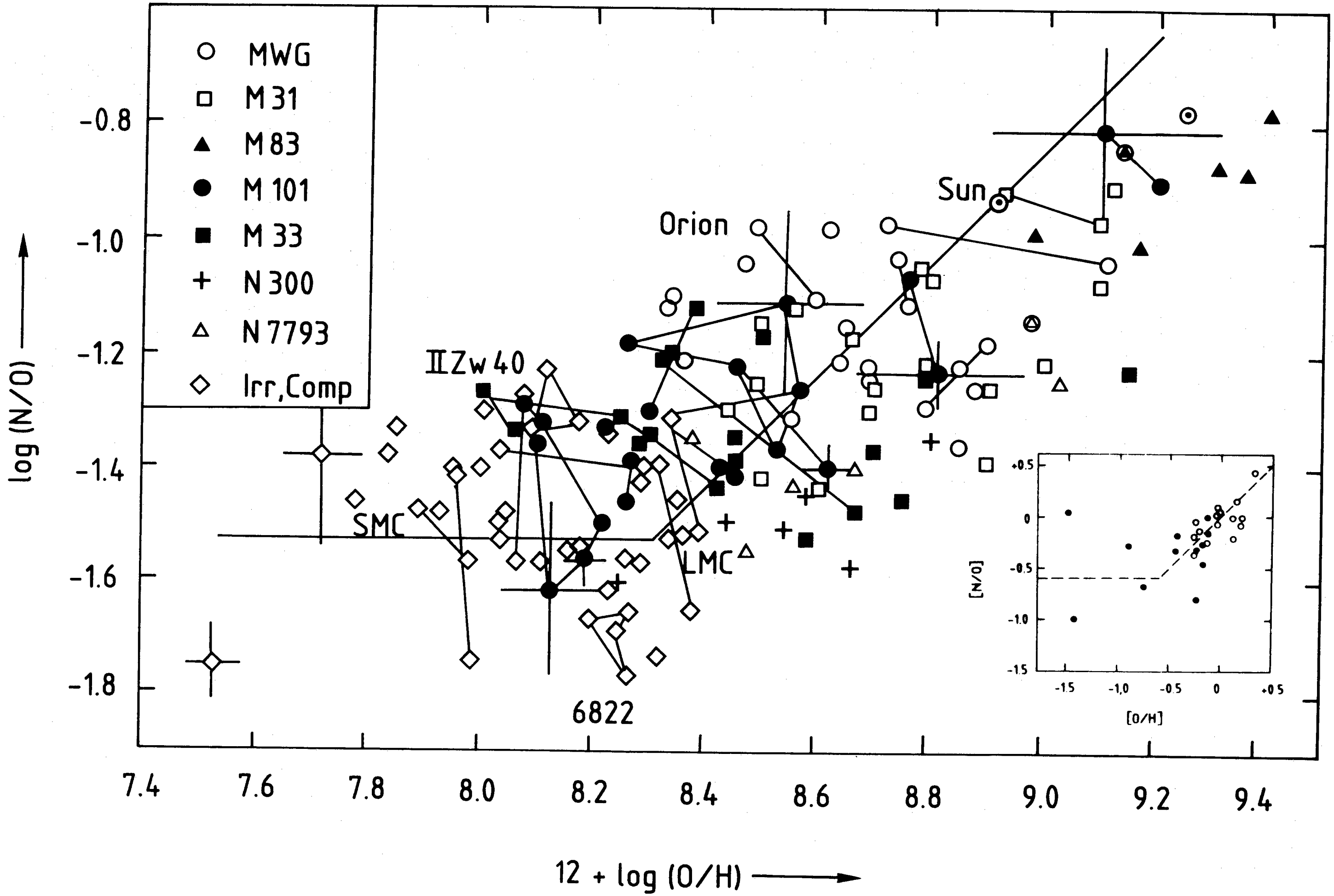

Figure 1. From Pagel (1985). Relation between N/O and O/H in H II regions. The strong horizontal and diagonal lines represent the corresponding relation for dwarf stars after Tomkin & Lambert (1984). Weak solid lines join alternative results for the same irregular galaxy or (in spirals) for the same H II regions. In the right bottom corner is reported the original fig. 3 of Tomkin & Lambert (1984).

primary and secondary element. This was obtained with the nucleosynthesis prescriptions of Renzini & Voli (1981) corresponding to a mixing length parameter $\alpha=1.5$ and to a value of the upper limiting mass for intermediate-mass stars, M_{up}, of between 5 and $6\,M_\odot$. The same conclusion, relative to M_{up}, has been reached by Diaz & Tosi (1985) by studying the behaviour of nitrogen in spiral galaxies. It is worth noting that a value of M_{up} of the order of 5–6 $M_\odot$ instead of 8–9 $M_\odot$ (Becker & Iben 1979) is in agreement with recent theoretical studies of the evolution of stars of solar chemical composition (Bertelli, Bressan & Chiosi 1985; Castellani *et al.* 1985; Renzini *et al.* 1985). Matteucci & Tosi also pointed out that the observed spread in N/O for a given value of O/H (see Fig. 1), if real, could be mostly due to varying amounts of primary nitrogen, supporting a previous suggestion of Pagel & Edmunds (1981). The variation in the amounts of primary nitrogen for galaxy to galaxy could be expained by small variations in the global chemical composition of the gas, since the value of M_{up} is very sensitive to this quantity.

The aim of this paper is to present some theoretical results concerning nitrogen evolution relative to C, O and Fe, obtained by means of a complete chemical-evolution model (no instantaneous recycling approximation) for the solar neighbourhood and to compare them with the model predictions already obtained for extragalactic H II regions. On the basis of this, we will discuss how different star formation modes (bursts and continuous) can affect nitrogen evolution. We will also try to interpret observational data of solar-neighbourhood stars as well as galactic and extragalactic H II regions, in order to verify and extend the previous suggestions by Matteucci & Tosi on the nature of nitrogen and on how the primary/secondary distinction can affect the model predictions. The chemical evolution model adopted for the solar neighbourhood is the same as in Matteucci & Greggio (1986) where type I SNe from white dwarfs in binary systems are taken into account. For the prescriptions for nitrogen production in low- and intermediate-mass stars we refer to Renzini & Voli's computations, and for those for nitrogen production (only secondary) in massive stars we refer to Talbot & Arnett (1973; their prescription II, case A). The nucleosynthesis prescriptions for the other elements are taken from Arnett (1978) and the relationship between the mass of the He-core and the initial mass in massive stars is that of Maeder (1981) with mass loss (case B).

2 Results

Fig. 2 shows the N/O versus O/H predicted by models with bursts of star formation and by models with continuous star formation. Each curve describes the temporal evolution of N/O within different galaxies. The models with bursts of star formation are taken from Matteucci & Tosi (1985) (1, 5 and 10 bursts respectively, as indicated in the figure), without galactic winds, and refer to the following nucleosynthesis prescriptions: $\alpha=1.5$, $M_{up}=8\,M_\odot$ and Salpeter IMF.

These models predict a sudden increase of N/O approximately after the second burst and a flat behaviour afterwards. In the model with only one burst of star formation, the N/O value is taken at the present time under the assumption that the burst is very old. In fact, if the burst were recent (age$<10^7$ yr), the predicted N/O value at the present time would be much smaller, since intermediate- and low-mass stars ($M<8\,M_\odot$) would not have had the time to restore the bulk of nitrogen.

The points representing the present time (12 Gyr) values of N/O (indicated by crosses) for the three different burst galaxies can be joined by a flat line, in agreement with the data for extragalactic H II regions, as has already been stressed by Matteucci & Tosi (1985).

Fig. 2 clearly shows that the curve joining the final N/O values for different objects can be quite different from the temporal evolution of N/O inside each galaxy.

The solar-neighbourhood model is the same as described in Matteucci & Greggio (1986). The assumed star formation rate is proportional to the surface gas density and is taken from Talbot &

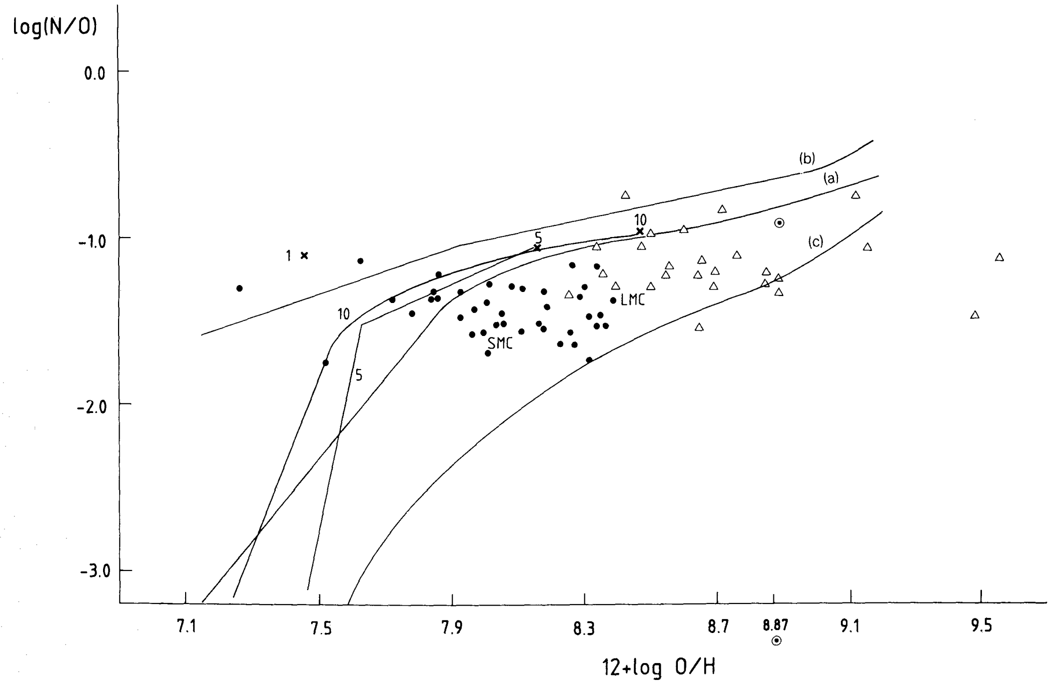

Figure 2. The N/O versus O/H relations predicted by models (a), (b) and (c) relative to the solar neighbourhood and by models with bursts of star formation (1, 5 and 10). The dots represent data for dwarf irregular galaxies, taken from Matteucci & Tosi (1985). For the model with 1 burst, only the final value is reported. The triangles represent data for H II regions in our own Galaxy taken from Shaver *et al.* (1983).

Arnett (1975) and adapted to an open model. Infall of material of primordial chemical composition is, in fact, taken into account. The nucleosynthesis prescriptions are the same as those adopted in the burst galaxy model in order to compare the predictions for the solar neighbourhood and burst galaxies. The solar-neighbourhood model [curve labelled (a)] predicts a smoother and more gentle increase of N/O with O/H until it reaches a saturation phase. The flat part of the curve is just in the metallicity range of the galactic H II regions, which in fact show a flat N/O ratio. However, in order to make a correct comparison between model predictions and data in galactic H II regions, one should plot the single evolutionary tracks for N/O corresponding to the evolution of the galactic disc at various galactocentric radii and join their final values together. The result, in analogy with what happens for extragalactic H II regions, should be an even flatter curve than the plateau predicted for the solar neighbourhood.

The behaviour of N/O versus O/H in the solar neighbourhood is understandable in terms of nucleosynthesis: at the beginning of galactic evolution (low O/H values) the ratio N/O is very low because only massive stars contribute to the galactic enrichment by producing oxygen and *secondary* nitrogen. Therefore N/O is proportional to the initial stellar metal content. As the evolution proceeds, the N/O ratio reaches a phase where it increases much more slowly. This is due to the fact that intermediate- and low-mass stars start to eject nitrogen (both primary and secondary) for the first time, and, at this point, the primary production predominates over the secondary one.

Fig. 2 also reports a prediction for N/O evolution in the solar neighbourhood obtained by tentatively assuming that massive stars produce only nitrogen of primary origin (curve labelled (b)). In particular, the nucleosynthesis prescriptions adopted in this model refer to the amount of secondary nitrogen produced by a 25 $M_{\odot}$ star of Population I (Woosley & Weaver 1982b), under the rough assumption that it is representative of the average nitrogen production in massive stars

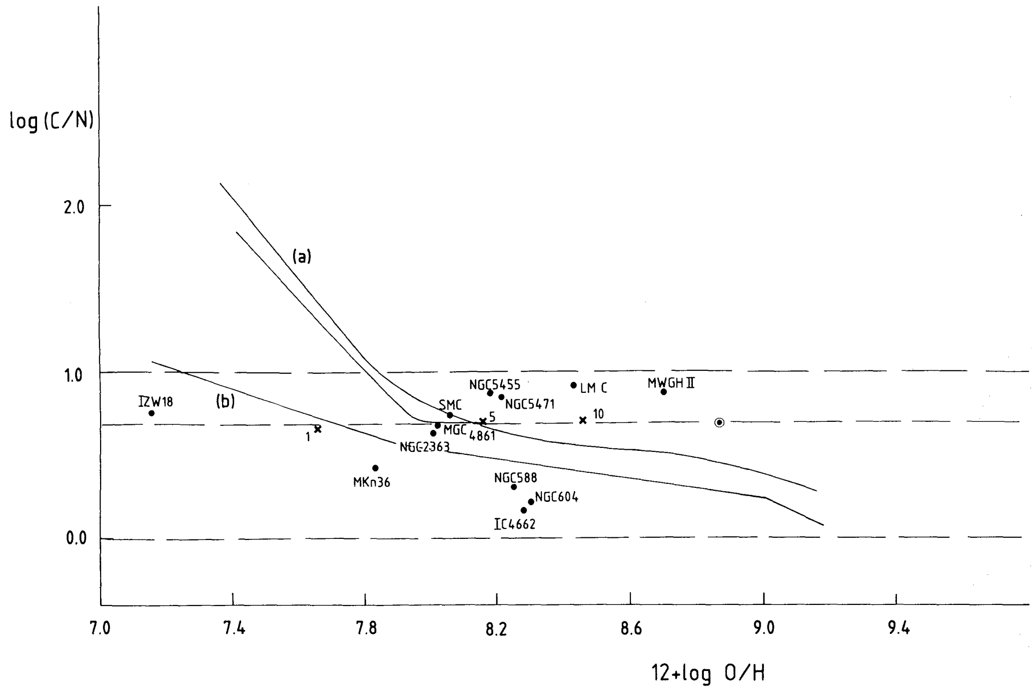

Figure 3. The C/N versus log O/H relations predicted by models (a) and (b) for the solar neighbourhood and by models with bursts of star formation (1, 5 and 10). For models with 1 and 10 bursts only the final value of log C/N is reported. the data points are taken from Dufour *et al.* (1984).

and treated as a primary nucleosynthesis product. In this case, the value of N/O is higher at early epochs than that predicted by model (a) and the overall trend looks much flatter. This is due to the fact that now primary nitrogen predominates over the secondary one during the whole galactic lifetime. Although in this discussion we are not interested in the absolute abundance values, it is worth noting that the absolute value of N/O predicted for the Sun by models (a) and (b) is greater than the one observed. This is due to the assumed nucleosynthesis prescriptions. On the other hand, with a value of M_{up} as low as 5 $M_\odot$ [curve labelled (c)], less primary nitrogen is produced, since M_{up} is the limiting mass beyond which stars do not undergo the third dredge-up. The net result is a lower solar value of N/O as well as a more continuous increase of N/O with O/H, with a less marked change in the slope. However, the N/O value for the Sun is now too low, but this is due to the fact that Matteucci & Greggio's (1986) model predicts a solar oxygen abundance higher than the one observed.

Fig. 3 shows the values of C/N versus O/H as predicted by the solar-neighbourhood models (a) and (b) and by the models with 1, 5 and 10 bursts of star formation (indicated by crosses) compared with data from Dufour, Schiffer & Shields (1984) for extragalactic H II regions and the Milky Way. The observational data suggest that C/N is constant and almost solar for all the observed galaxies. Again, the difference between the predicted temporal evolution of C/N and the curve joining the final values of C/N, predicted for galaxies with a different number of bursts, is evident. The predicted variation of C/N versus O/H in the solar neighbourhood by model (a) shows a steep decrease of C/N for O/H between 7.0 and ~8.0 and a flatter behaviour afterwards. This is partly due to the secondary nature of nitrogen and partly to the fact that Arnett's (1978) carbon yield from massive stars is probably overestimated. New nucleosynthesis models of massive stars, computed with a revised rate for the $^{12}C(\alpha,\gamma)^{16}O$ reaction seem, in fact, to predict much less carbon and much more oxygen than Arnett's models (Woosley & Weaver 1986). In addition, with a lower carbon yield from massive stars, the agreement with Laird's (1985) data on

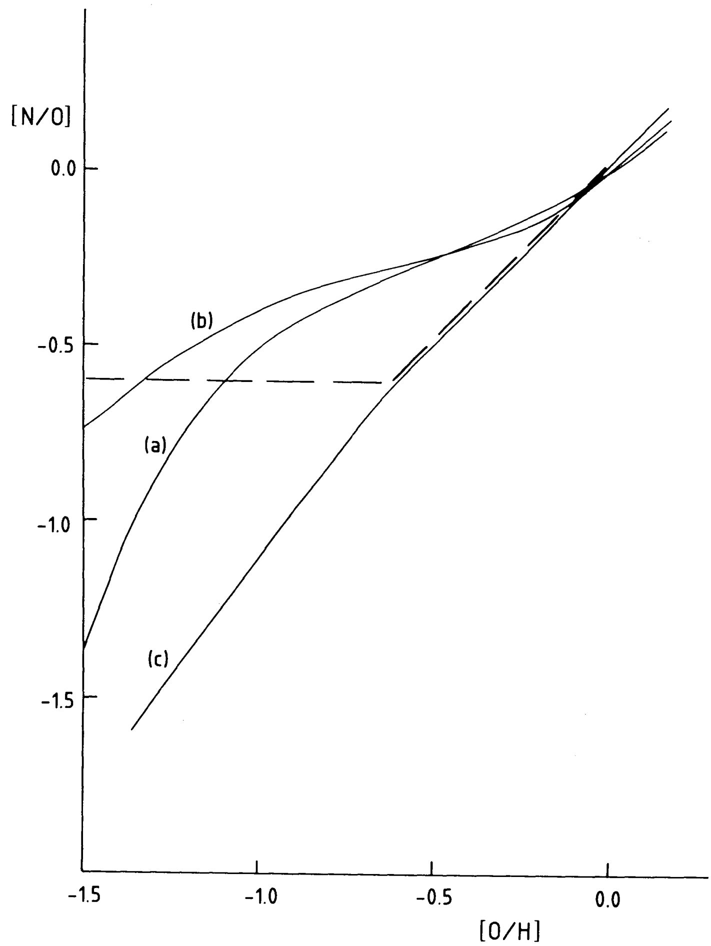

Figure 4. The [N/O] versus [O/H] relation predicted by models (a), (b) and (c) for the solar neighbourhood. The dashed line represents the best fit to dwarf stars in the Galaxy from Tomkin & Lambert (1984).

dwarf stars will also be improved, as stressed in Matteucci & Greggio (1986). In this case, intermediate-mass star would be responsible for the bulk carbon production and the C/N curve would be flatter than that shown in Fig. 3. Model (b), computed by assuming that massive stars produce only primary nitrogen, again predicts a much flatter curve than model (a).

In Fig. 4 we report the [N/O] versus [O/H] relations predicted for the solar neighbourhood by models (a), (b) and (c) and compared with Tomkin & Lambert's (1984) best fit. At variance with the observational fit, models (a) and (c) do not predict any constant behaviour for [N/O] below $[O/H] \simeq -0.5$. This is mainly due to the assumed secondary nature of nitrogen in massive stars, as already discussed for Fig. 2.

On the other hand, Tomkin & Lambert's best fit for $[O/H] < -0.5$ is based on very few data, which could not completely exclude behaviour like that predicted by these models. In order to obtain a flatter N/O ratio at very low metallicities, one has to assume that massive star produce only primary nitrogen (model (b)), as already discussed for Fig. 2. On the other hand, model (c), with less primary nitrogen from intermediate-mass stars, better reproduces the behaviour of [N/O] for $[O/H] > -0.5$, due to the greater amount of secondary nitrogen. Probably a model with the correct amount of nitrogen of primary origin coming from massive stars (there are no nucleosynthesis predictions at the moment) and with a nucleosynthesis prescription like that of model (c) for intermediate-mass stars [e.g. a model between (b) and (c)], would better approach the observational data.

Finally, we want to discuss the difference between the behaviour of nitrogen and iron. Both

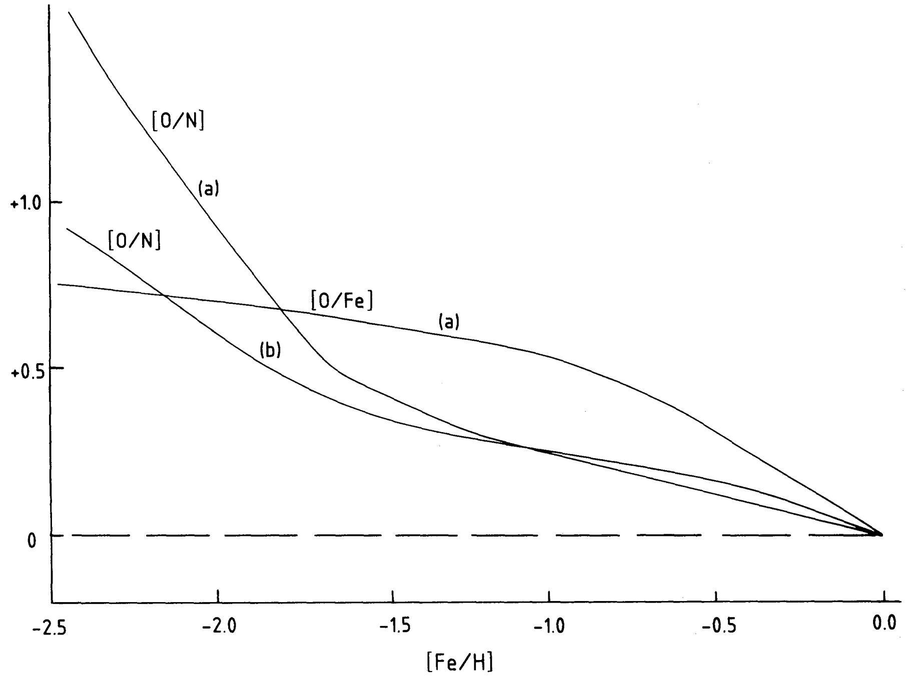

Figure 5. The [O/N] and [O/Fe] ratios as functions of [Fe/H], as predicted by models (a) and (b) for the solar neighbourhood.

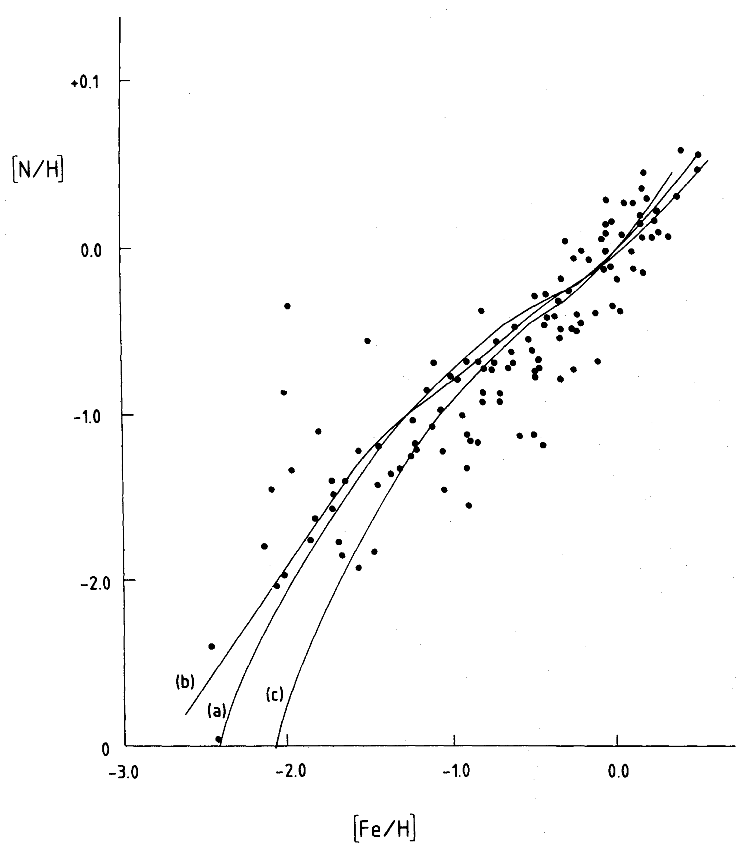

Figure 6. [N/H] versus [Fe/H] as predicted by models (a), (b) and (c). Data points from Laird (1985).

these elements seem to be produced mostly by stars of low and intermediate mass and, to a lesser extent, by massive stars. Iron, in fact, can be produced either by Type II SNe, coming from stars with $M>8\,M_{\odot}$, or by Type I SNe which are likely to originate from white dwarfs in binary systems (see Matteucci & Greggio 1986, and references therein). If nitrogen were of primary origin, we would expect nitrogen and iron to behave in the same way with respect to oxygen. In particular, [O/Fe] seems to be overabundant with respect to iron and constant in stars with $[\mathrm{Fe/H}]<-1.0$, and it decreases towards the solar value in more metal-rich stars (Clegg, Lambert & Tomkin 1981). This is understandable assuming that iron comes from both massive and intermediate-mass stars, whereas oxygen comes only from massive stars, with iron and oxygen being 'bona fide' primary elements (Tinsley 1979; Matteucci & Tornambè 1985; Matteucci & Greggio 1986). Fig. 5 shows the evolution of [O/N] and [O/Fe] as functions of [Fe/H] in models (a) and (b) ([O/Fe] is the same in both models). The difference between the behaviour of nitrogen and iron with respect to oxygen is mainly due to the fact that nitrogen is assumed to be partly a secondary element even in model (b), whereas iron is entirely primary. Therefore, full resemblance of the [O/Fe] and [O/N] behaviour, with respect to [Fe/H], would be possible only if nitrogen were considered to be totally primary. Note that model (a) predicts an [O/Fe) behaviour in very good agreement with the observations (see Matteucci & Greggio 1986).

In Fig. 6 we show the [N/H] versus [Fe/H] as predicted for the solar neighbourhood by models (a), (b) and (c), and compared with the data of Laird (1985). Both models (a) and (c) substantially deviate from the observational best fit in the range of very low [Fe/H] values. On the other hand, if nitrogen produced by massive stars is primary [model (b)], the agreement with the observations at very low metallicities seems to improve. However, due to the paucity of data in this range of metallicity, it is difficult to draw any firm conclusion. If further data, taken at low [Fe/H], confirm that nitrogen and iron behave strictly in the same way, we should revise the standard nucleosynthesis prescriptions and assume, that some mixing, at least, is occurring in massive star and that primary nitrogen is indeed produced.

3 Conclusions

We have presented here models of chemical evolution for the solar neighbourhood and extragalactic H II regions (dwarf irregular galaxies), and discussed nitrogen evolution relative to carbon, oxygen and iron. Our main conclusions concerning nitrogen evolution in the solar neighbourhood can be summarized as follows:

(i) Standard nucleosynthesis prescriptions for nitrogen production in stars of all masses (Renzini & Voli 1981; Talbot & Arnett 1973) do not reproduce the observed [N/O] at low metallicities. In particular, our models, which assume that massive stars ($M>8\,M_{\odot}$) produce only secondary nitrogen predict a steep increase of [N/O] at low metallicities, at variance with the interpretation of observations which are claimed to show [N/O] to be approximately constant among halo stars. However, the data points relating to low [O/H] are very few and no firm conclusion can be drawn from them.

Better agreement would be obtained by assuming that massive stars produce only nitrogen of primary origin. In any case, [N/O] is predicted to increase in time, even if nitrogen were only primary (in intermediate- and low-mass stars as well), due to the fact that the bulk of the nitrogen is produced by stars living longer than those producing the bulk of the oxygen.

It is worth noting that these results are relatively model independent since assumptions on the infall of primordial matter or the temporal dependence of the rate of star formation do not affect the evolution of the ratio between elements, which instead depends mostly on the assumed nucleosynthesis prescriptions. In fact, different rates of infall of primordial material do not affect the ratio between two heavy elements, since the effect of the infall on them is just to lower their abundances by the same factor. Different assumptions on the star formation rate, like a constant rather than a time-dependent one, again affect the evolution of the abundance of each element in the same way. On the other hand, the effect of the infall and the star formation rate is evident in the temporal behaviour of the absolute abundances, like in the age-metallicity relationship (Twarog 1980; Matteucci & Greggio 1986). Therefore, plots of elemental ratios as a function of time or of another element, are useful tests for the nucleosynthesis theories.

(ii) Following the current nucleosynthesis prescriptions we assumed that iron and nitrogen are mainly produced by low- and intermediate-mass stars, but iron is only a primary nucleosynthesis product whereas nitrogen is both a primary and secondary element.

Model predictions suggest that [N/H]<[Fe/H] for very low [Fe/H] values. The observations seem to suggest [N/H]=[Fe/H] over the whole range of [Fe/H]. Unfortunately, however, the observational data on [N/H] at very low [Fe/H](<−1.8) are so few that no firm conclusion can be drawn. Again, if massive stars were producing primary nitrogen, the agreement with observation would improve.

The situation of nitrogen with respect to carbon is the same as the situation of nitrogen with respect to iron.

If future observational data at low [Fe/H], low [C/H] and low [O/H] confirm that nitrogen, carbon and iron behave strictly in the same way, we should conclude that, at least, there must exist a mechanism (mixing) for the production of primary nitrogen also in massive stars.

Our main conclusions on galactic and extragalactic H II regions can be summarized as follows:

(i) The temporal evolution of nitrogen is likely to be different in galaxies with different evolutionary histories (e.g. solar neighbourhood and dwarf irregular galaxies). As a consequence, it is formally incorrect to interpret the data points referring to different objects as a continuous evolutionary path. In addition, the predicted temporal evolution of N/O and C/N within a single extragalactic H II region is different from the line joining the present time N/O and C/N values predicted for different extragalactic H II regions (models with different number of bursts).

(ii) The bursting rather than continuous star formation mode in extragalactic H II regions is responsible for a sudden increase of N/O and for a subsequent flat behaviour. A model with continuous star formation and current nucleosynthesis prescriptions, suitable for the solar neighbourhood, predicts a much smoother increase of N/O in time and, for values of O/H in the range found for extragalactic H II regions, it would predict a steeper behaviour than the one observed. This argument, as Matteucci & Tosi (1985) suggested, can be applied to the evolution of the solar neighbourhood, in the sense that if the constancy of N/O in halo stars is true, star formation in the halo could have proceeded in bursts whereas the disc should have undergone a continuous star formation. This could represent an alternative explanation to the requirement of primary production of nitrogen in massive stars, although very metal-poor stars would show, even in this case, very low N/O values.

In conclusion, the evolution of nitrogen seems to be still not completely clear and more observations of stars of very low metallicities are necessary, as well as some revisions of the current ideas about nitrogen nucleosynthesis. In spite of this, the present analysis can help to clarify some points concerning the behaviour of nitrogen under different assumptions about its nature and its dependence on the assumed chemical evolution model. We have suggested that it is likely that nitrogen is both a primary and secondary nucleosynthesis product. From a comparison between model results and observational data we infer that primary nitrogen should originate in high- and intermediate-mass stars, whereas secondary nitrogen should be confined to lower mass stars. As a consequence, the primary production should predominate at low and intermediate metallicities, whereas the secondary one should appear only during the latest evolutionary phases both in the solar neighbourhood and in galaxies experiencing more than five bursts of star formation.

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