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The Evolution of Radial Abundance Gradients: The two infall episode model

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Chemical Evolution at Low and High Redshift

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Abstract. The chemical evolution of our Galaxy, elliptical and dwarf irregular galaxies at low and high redshift is discussed, with the aim of studying the temporal evolution of chemical abundances and abundance ratios. Such evolution is then used as a clue to understand the nature of high red-shift objects such as QSO and Damped Lyα systems (DLA). In particular, we discuss how the comparison between the observed abundances, both in QSO and in DLA, with predictions from models of galactic chemical evolution can be used to infer their nature. We favor the idea of QSO being the result of accretion on a central massive black hole in the center of giant elliptical galaxies occurring at times larger than 1 Gyr from the beginning of star formation. Concerning DLA we conclude that some of them are probably starburst galaxies, such as the local blue compact galaxies, experiencing their first or one of their first bursts of star formation.

1. Introduction

Galactic chemical evolution models are a very useful tool to date galaxies and Galactic component as shown by Matteucci and François (1989, 1992). In particular, abundance ratios such as O/Fe or N/O can be used as cosmic clocks; the reason for this resides in the fact that O and Fe are restored into the interstellar medium (ISM), by the same stellar generation, with a temporal delay due to the fact that the bulk of O originates from short living stars (type II SNe) whereas the bulk of iron originates from long living objects (type Ia SNe). A similar situation exists for O and N; nitrogen, in fact, is mainly produced in long living stars (low and intermediate mass stars) and is also a secondary element, namely produced proportionally to the initial stellar metallicity. The identification of the typical timescales for the production of different elements is therefore extremely important to date galaxies but not only for that. Galaxies of different morphological type are believed to evolve at different rates, in the sense that their history of star formation and the rate at which they accumulate matter are different. This produces quite different abundance patterns either at high or at low redshift. See for example how elliptical galaxies and bulges show a marked overabundance of α-elements relative to iron with a very high metallicity content, as opposed to halos where the same overabundance coexists with a very low metal content. These different behaviours can be explained by a combination of the different timescales for the formation of different elements, common

to galaxies of all types, with different star formation histories (Matteucci and Brocato, 1990; Matteucci, 1994). Therefore abundances and abundance ratios can be used as a diagnostic to infer the nature of high redshift objects about which we do not have other information.

The aim of this paper is to discuss different models of chemical evolution for our Galaxy, ellipticals and dwarf irregulars and compare their predictions with the information on abundances available for QSO themselves and for QSO absorbers (DLA). Recently, more and more data are available on DLA suggesting in some cases quite unusual abundance ratios. This is a unique occasion to study the evolution of galaxies at very early stages and test our theories on nucleosynthesis and galaxy evolution.

All of our models assume the same nucleosynthesis prescriptions which we will remind briefly now:

- **α-elements and iron**- the yields from massive stars are from Woosley (1987). Recent yields from Timmes et al. (1995) are now available for different metallicities but the predicted yield of iron seems to be too high.
- **nitrogen**- the Renzini and Voli (1981) yields for low and intermediate mass stars under different assumptions about the mixing-length parameter, α, which indicates different amounts of primary and secondary N. Primary N from massive stars is assumed for some of the models, otherwise is secondary. Weaver and Woosley (1995) have calculated some models for low metallicity massive stars producing primary N but it depends crucially on the treatment of convection.
- **supernovae of type Ia**-the nucleosynthesis prescriptions are from Nomoto et al. (1986). Recent calculations from Thielemann et al. (1993) do not differ substantially from the previous ones.

2. Chemical evolution of the solar neighbourhood

The model we are discussing here is that of Matteucci and François (1992). This model does not assume instantaneous recycling approximation (I.R.A.) and it computes the temporal and spatial evolution of several chemical elements (H, D, ^{3}He, ^{4}He, ^{7}Li, C, N, O, Ne, Mg, Si, S, Ca, Cu, Zn and Fe). The initial mass function (IMF) is taken from Scalo (1986). The process of formation of the Galaxy is treated as a continuous one where the halo and the central parts form faster than the disk and the outer regions. The formation is simulated by an accretion process characterized by a typical timescale τ. In this way, the evolution of the Galaxy occurs at a rate decreasing in time, in the sense that both the star formation rate and the accretion rate decrease in time, although at different speed. Alternative models exist (Pardi et al. 1995) where the formation of the Galaxy is seen as a process where all the different Galactic components (halo, thick- and thin-disk) start forming together but evolve at different rates. In this scenario, at any time there is an overlapping of stars with the same age but different chemical abundance and kinematics. This last scenario is probably more realistic than the previous one but it is not possible yet to distinguish between the two. However, the predicted behaviours of the elemental abundances

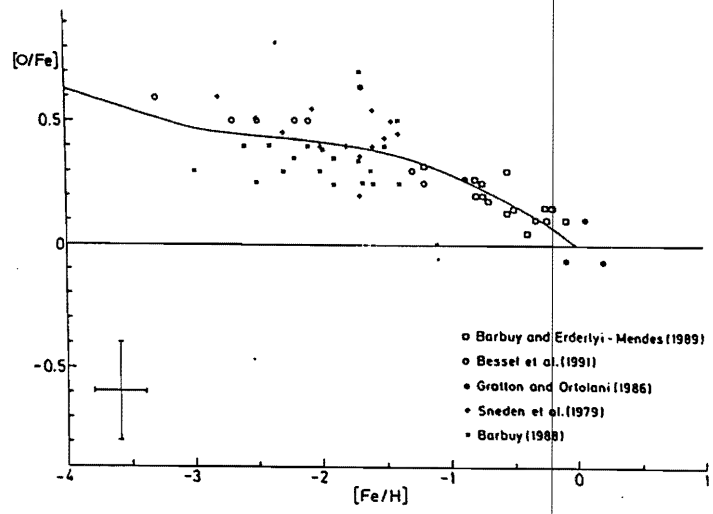

Figure 1. Predicted and observed [O/Fe] vs [Fe/H] for the solar neighbourhood. The model is by Matteucci and François (1992) from where the figure is taken (for the data see the references there).

in time are qualitatively the same, the only difference being that in the continuous evolution one has only one evolutionary curve for each element whereas in the evolution in parallel one has, for a given element, one evolutionary curve for each Galactic sub-structure and they run roughly in parallel. As an example we present in Figs. 1 and 2 the predictions from the two models concerning the [O/Fe] vs. [Fe/H] relation for solar neighbourhood stars. In Fig. 1 are the predictions of Matteucci and François (1992) compared with data. During the halo phase the [O/Fe] is predicted to be roughly constant as due to the only contribution of type II SNe whereas during the disk phase the [O/Fe] decreases as due to the bulk of iron restored by type Ia SNe. The timescale at which type Ia SNe become no more negligible and induce the change in slope of [O/Fe] is $\simeq$ 1.4 Gyr. This timescale corresponds also, in this model, to the the duration of the halo phase (halo stars have [Fe/H]≤ -1.0).

In Fig.2 are shown the predicted relations for the halo, thick- and thin-disk. The shape of the thin-disk curve is very similar to that of Fig.1. Concerning the curve for the thick disk and halo we should keep in mind that we are plotting the abundances in the gas, not those in the stars, and that star formation in the halo is practically over after 2 Gyr in this model. Thus, in principle, there could be halo stars of high metallicity, as indicated in the figure, but in practice the halo curve should be cut at [Fe/H]$\simeq$ -1.0dex since halo stars of metallicity higher than that should be rare due to the paucity of halo gas available at that stage.

The same is true for the thick disk which should be truncated in the figure at [Fe/H] $\simeq$ -0.5 dex.

After all, the predictions of the two models are similar and therefore is difficult to distinguish between the two different scenarios. In Fig. 3 we show the predictions of the Matteucci and François (1992) model concerning the variation of the abundances of several elements as a function of time and redshift. The time-redshift relation used is based on a Hubble constant of 50 $Kmsec^{-1}Mpc^{-1}$ and a deceleration parameter $q_o = 0.5$ (see Matteucci and Padovani, 1993 for more details) and we will adopt this cosmology through the whole paper.

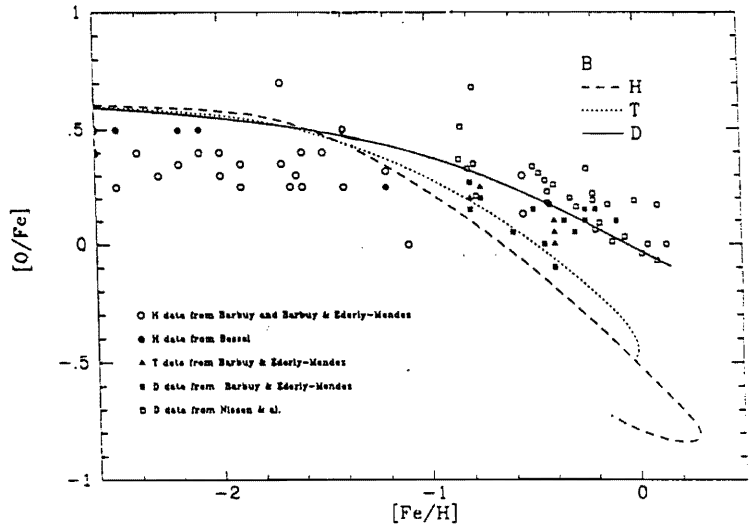

Figure 2. Predicted and observed [O/Fe] vs [Fe/H] for the solar neighbourhood. The model is by Pardi et al. (1995) from where the figure is taken. The symbol H stands for halo, T for thick-disk and D for thin-disk.

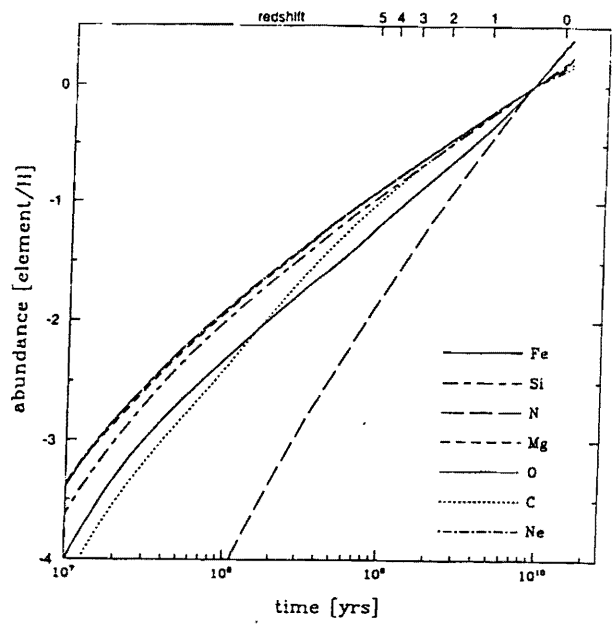

Figure 3. Predicted evolution of the abundances of several heavy elements in the solar neighbourhood as a function of time and redshift. The figure is taken from Matteucci and Padovani (1993).

3. The evolution of elliptical galaxies

The chemical evolution model for elliptical galaxies is described in Matteucci (1994) and Matteucci and Gibson (1995). It belongs to the class of supernova driven wind models (Arimoto and Yoshii, 1987; Matteucci and Tornambè 1987) but with the inclusion of diffuse halos of dark matter ten times more massive than the luminous content. The galactic wind is supposed to occur when the thermal energy of gas heated by supernovae and other stellar events equates the potential energy of the gas. The star formation is assumed to be very efficient (10-40 times more efficient than in the solar neighbourhood) and to stop immediately after the development of the galactic wind. After the wind, in fact, the gas restored by dying stars is heated by the explosions of type Ia supernovae and star formation is not likely to occur. The mass to luminosity ratio in each galaxy is calculated according to the choice of the IMF. Three types of IMF are considered:

- IMF with x=1.35 (Salpeter 1955) over the whole mass range
- IMF with x=0.95 (Arimoto and Yoshii 1987) over the whole mass range
- IMF with three slopes (Kroupa et al. 1993)
- IMF with x=2.0 over the whole mass range

3.1. Results for elliptical galaxies

The best model reproducing the main properties of low redshift elliptical galaxies suggests that elliptical galaxies should have an IMF much flatter ($x \simeq 1$) than the solar neighbourhood in order to explain the high [Mg/Fe] ratio observed in the core of giant ellipticals (Worthey et al. 1992; Weiss et al. 1995) as well as the high [α/Fe] ratio (+0.1-+0.7) measured by ASCA in the ICM (Mushotzky 1994) and the observed iron mass to light ratio in clusters of galaxies (IMLR=(0.007–0.014)$h^{-1/2}$) (Matteucci and Gibson, 1995). However, for a reasonable IMF (Salpeter or flatter) a high [Mg/Fe] or [O/Fe], of the order of +0.3–+0.7 in giant ellipticals, as required by population synthesis studies (Weiss et al., 1995), is obtained **only** if the dominant stellar population formed in a timescale $\leq 3 \cdot 10^8$ years (see Fig. 4). This fact argues against the formation of ellipticals by merging of disk systems (van den Bergh, 1995).

Figure 4 shows the predicted [O/Fe] vs [Fe/H] in the gas of elliptical galaxies of different initial luminous mass and different IMF. The occurrence of the galactic wind is marked on each curve. According to the time of occurence of the galactic wind one predicts different amount of stars formed with high [O/Fe] . Therefore, the predominance of stellar populations with high [O/Fe] or [Mg/Fe] is crucially dependent on the time of occurrence of the wind which, in turn, depends on the assumed galactic potential, IMF, star formation rate and efficiency of energy transfer from the stars to the ISM.

As a consequence of the high required [O/Fe] and [Mg/Fe] we must conclude that SNII nucleosynthesis dominates the energetic and chemical evolution of elliptical galaxies at variance with what happens in our Galaxy, where SNII dominates in the early evolutionary phases (halo and bulge) and SNIa dominates

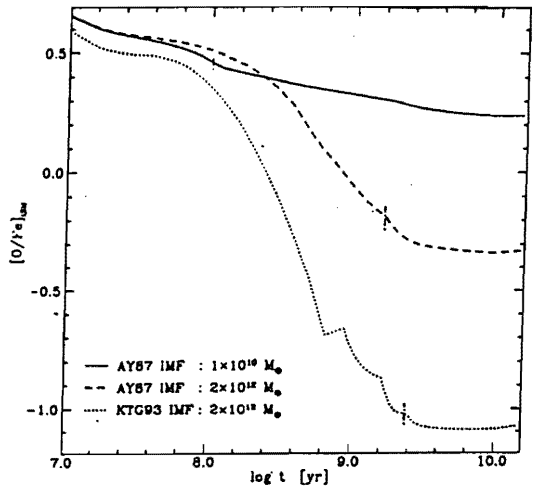

Figure 4. Predicted behaviour of the [O/Fe] in the ISM of elliptical galaxies of different mass and IMF. The figure is taken from Matteucci and Gibson (1995). AY87 stands for Arimoto and Yoshii (1987) and KTG93 stands for Kroupa et al. (1993).The masses refer to the initial luminous mass of the galaxy.

in the late stages (thick- and thin- disk). In Fig.5 we show the different contributions from type II and Ia SNe to the enrichment in Fe of the ISM of elliptical galaxies of different initial luminous mass and IMF. Again the occurrence of the galactic wind is marked.

From Fig. 5 it follows that the predicted iron abundance in the gas observed now in ellipticals is solar or larger, in agreement with stellar populations studies (Weiss et al. 1995) but in disagreement with ASCA data (Lowenstein et al., 1994).

3.2. Giant ellipticals and high redshift objects

Matteucci and Padovani (1993) suggested that giant ellipticals (2-5 $\cdot$ $10^{12} M_{\odot}$) developing cooling flows (Ciotti et al. 1991; David et al., 1991) may become QSO. Their activity could in fact be induced by stellar mass loss fuelling a central black hole after star formation has stopped and cooling flows are established. In this case, the predicted abundances in the gas restored by dying stars are the abundances observed in the central QSO and can be compared with QSO broad emission lines.

3.3. Observed chemical evolution of QSO

The observations of QSO suggest:

- a broad similarity (at the first order) of the spectra in different objects and at different red-shift: compare for example the composite quasar spectrum of Francis et al. (1991) with the spectra of high redshift QSO implying a roughly similar metallicity and therefore a small (if any) redshift dependence of quasar metallicities.

- The presence of standard emission lines like OIV 1034 Å, NV 1240 Å and CIV 1550 Å in high-z AGN and QSO (Schneider et al. 1991). This shows that metal production was well under way in these young objects.

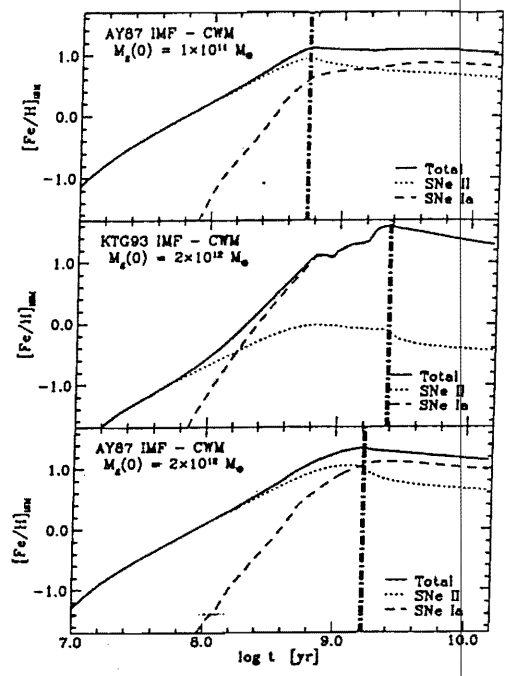

Figure 5. Predicted behaviour of [Fe/H] vs. time for elliptical galaxies of different initial mass and IMF. The contributions from type Ia and II supernovae are indicated. The figure is taken from Matteucci and Gibson (1995), $M_g(0)$ refers to the initial luminous mass.

- Broad line region line ratios suggest a factor of ten (or possibly higher) overabundances of N, Fe and Si; as regards other elements there seems to be no evidence for abundances much different from solar (see Matteucci and Padovani 1993 and references therein). However, one should keep in mind that elemental abundances derived from QSO emission lines are model dependent, since results can vary with the assumed ionizing continuum, electron density and ionization parameter.

3.4. Main results for QSO

After comparing the observed chemical properties of QSO with models, Matteucci and Padovani (1993) concluded that:

- solar abundances are reached in a few 10^8 years after star formation starts in the host galaxy (an elliptical or a bulge of a spiral) for a model with a Salpeter-like or a flatter IMF. This explains in a natural way the "standard" emission lines (CIV; NV, OVI, SiIV) displayed by high redshift QSO.

- After the first Gyr from the beginning of star formation, corresponding to a redshift $z \leq 4.5$ in the assumed cosmology, the same model predicts N, Si and Fe abundances roughly 10 times higher than solar whereas C, Ne, Mg and O abundances are roughly solar. This is because some elements are produced by long living stars and therefore they continue to be produced even after star formation has ceased (t> 1 Gyr in this model), whereas others, produced by short living stars do not increase any more after star formation is over. Silicon, in spite of being an α- element such as O, Ne

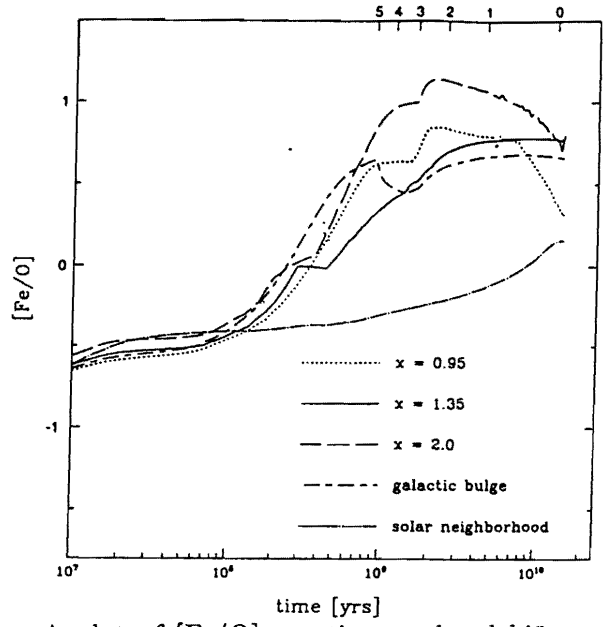

Figure 6. A plot of [Fe/O] vs. time and redshift for the ISM of a giant elliptical galaxy for different IMF prescriptions.In particular for IMFs with different slope x over the whole mass range. Predictions for the solar neighbourhhod and the galactic bulge are also shown for comparison. The figure is taken from Matteucci and Padovani (1993).

and Mg and therefore produced in massive stars, is also produced in a non-negligible way by type Ia SNe and it shows a behaviour intermediate between that of O (mainly produced in type II SNe) and that of N and Fe (mainly originating from low and intermediate mass stars). These predicted overabundances are consistent with the few abundance estimates available for QSO. The model shows also that for C, Ne, Mg and O the abundances after 1 Gyr are almost constant in time while the abundances of N, Si and Fe becomes weakly dependent on time for redshifts lower than 3. This could perhaps explain the longstanding puzzle of the similarity of QSO spectra at different redshifts.

- Abundance ratios of Fe relative to α-elements (or viceversa) can be used as a cosmic clock to constrain QSO's ages since they depend mainly on the relative lifetimes of the progenitors of α-elements (mainly SNeII) and of Fe (mainly SNeIa). In particular, overabundances of Fe relative to α-elements would indicate that the QSO are older than 1 Gyr, as clearly indicated in Fig. 6. The same conclusion was reached by a similar study of Hamman and Ferland (1993). However, all of this reasoning is based on the assumption that the QSO activity is due to accretion of gas on a central black hole and the situation could be different if one assumes the "starburst model" for QSO of Terlevich et al. (1992). According to this model the activity of QSO could be explained solely by young stars and supernova remnants without the presence of a black hole. In the framework of a young starburst (less than 1 Gyr) our model predicts low Fe/α ratios at variance with observations.

4. Dwarf Irregular Galaxies and Damped Ly-α Systems

The metallicity, gas content and colors of dwarf irregular galaxies indicate that they are either young or have experienced a sporadic star formation activity

(bursts). For most of these galaxies the second hypothesis is the most likely to be true although a different star formation regime can probably be envisaged for dwarf irregulars (DIG) and blue compact galaxies (BCG). In particular, DIG should have almost a continuous (gasping) star formation regime (Tosi et al. 1991; Greggio et al. 1993), whereas the BCG should experience few bursts of star formation. However, one cannot exclude that some of these galaxies are truly young objects in the sense that they have started forming stars only recently. The best known case of this type is the BCG IZw18, which shows the lowest metal abundance known in local galaxies. Its oxygen abundance derived from HII regions is 1/30 of the solar value ($\simeq 1.75 \cdot 10^{-5}$ by number). Kunth et al. (1994) claimed an even lower O abundance in the HI envelope of IZw18, roughly 1/1000 of the solar value ($\simeq 7.9 \cdot 10^{-7}$ by number) (but see Pettini and Lipman, 1995). These very low O abundances argue in favor of an almost primordial object and the discontinuity in metallicity between the HII and HI regions (if real) supports the view of Kunth and Sargent (1986) that HII regions are self-enriched. Kunth et al. (1995) applied the model of Marconi et al. (1994) for the evolution of DIG and BCG to IZw18.

This model assumes that the star formation proceeds in short but intense bursts of star formation which trigger strong but short galactic wind episodes. The galactic winds are mainly induced by type II SNe, given the short duration of the bursts as compared to the typical timescale for the appearence of type Ia SNe. These winds can either contain well mixed gas or be enriched in heavy elements. This last case has been invoked to explain the observed He vs O relation shown by these galaxies (Pilyugin 1993; Marconi et al. 1994). The existence of such winds can be justified by the fact that type IISNe, which explode in aggregates, can trigger chimneys which can eject metal-enriched material outside a galaxy of relatively low mass.

4.1. Main Results for DIG and BCG

Models with a number of bursts between 1 and 15 lasting no longer than 100 Myr with a Salpeter-like IMF plus enriched galactic winds can represent the majority of the observed properties of DIG and BCG (Marconi et al. 1994).

On the other hand, the abundance pattern observed in IZw18 (solar N/O and very low O/H) combined with its blue colors and large amount of gas can be explained if this galaxy is experiencing its first or, at maximum, second burst of star formation. The burst duration should be less or equal to 20 Myr, as suggested by population synthesis models (Mas-Hesse and Kunth, 1991) and trigger a very strong enriched galactic wind relative to the other BCG (Kunth et al. 1995). From the nucleosynthesis point of view, Kunth et al. (1995) concluded that primary N from massive stars is also required if one wants to reproduce the observed amount of N (quite high for a galaxy of such a low O) only in one burst of star formation without overproducing oxygen.

4.2. Similarity between IZw18 and DLA Systems

In Fig. 7 we show a plot of N/O vs. O/H with the predictions of all the models discussed in this paper: the solar neighbourhood model calculated for different assumptions about the nucleosynthesis of N, the model for a typical elliptical galaxy and the models for IZw18. In Fig. 7 also shown are models similar to

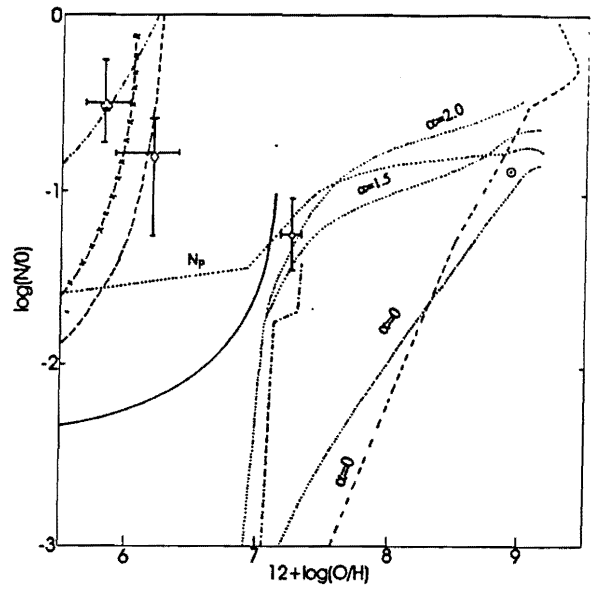

Figure 7. Predicted N/O vs. O/H for the solar neighbourhood(dotted lines) for different choices of α (Renzini and Voli, 1981). The line indicated by N_p refers to a model; with $\alpha = 1.5$ and primary N from massive stars. The sun is shown for comparison. The short-dashed line labelled α=0 represents the model of a typical elliptical. The continuous and dashed-dotted lines are models for IZw18 (Mod. 5 and 1 from Kunth et al. 1995, respectively) The three curves in the upper left corner of the figure are models from Matteucci et al. (1995) for DLA. The star represents IZw18 (Skillman and Kennicutt, 1993), while the spade and the clover represent the Green et al. (1995) and the Molaro et al. (1995) systems, respectively.

those for IZw18 but with more extreme assumptions about the star formation and wind efficiencies. In particular, these models have stronger star formation and wind rates. Matteucci et al. (1995) noticed the similarity between the abundance pattern observed in IZw18 and in a couple of DLA systems at high redshift observed by Molaro et al. (1995) and Green et al. (1995). These DLA also show a quite high N/O relatively to their very low O/H abundance. This is even stranger in DLA than in IZw18 since we know that the DLA are truly young objects while IZw18 could, in principle, have suffered previous bursts of star formation now hidden by the present burst. Nitrogen, in fact, is mainly produced in low and intermediate mass stars and therefore is restored on timescales larger than 30 Myr, making difficult a strong N production on short timescales.

In Fig. 7 are shown the observed N/O for the DLA systems together with the N/O of IZw18. One of the systems, that towards QSO 0000-2619, has $z_{abs} = 3.39$ while the other towards QSO 1331+1700 has $z_{abs} = 1.775$. As is evident from the figure models with strong star formation and strong enriched wind can fit the two DLA very well. This might suggest that some of DLA are dwarf irregular galaxies experiencing their first burst of star formation and at the same time the similarity of IZw18 with these objects confirms the primordial nature of this galaxy. On the other hand, other DLA systems (Pettini et al. 1995) do not show such a high N/O and they could indicate that the absorbers, in this case, are protospirals (Matteucci et al. 1995).

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