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Chemical Evolution of Dwarf Irregular and Blue Compact Galaxies

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Abstract

Dwarf irregular galaxies (DIG) and blue compact galaxies (BCG) are very interesting objects for studying galaxy evolution. They are rather simple objects with low metallicity and large gas content, suggesting that they are either young or have undergone discontinuous star formation activity (bursts). Models of chemical evolution where galactic winds are taken into account are reviewed and their results discussed in the light of the most recent observational data. The peculiar galaxy IZw18 is discussed as a case of an almost primordial galaxy and it is suggested, on the basis of chemical abundance ratios, that objects similar to IZw18 could be important contributors to the population of systems giving rise to QSO-absorption lines at high redshift (damped Lyman-α systems).

1 Chemical evolution models

Due to their metal content, gas fraction and colours DIG and BCG are believed to undergo short and intense bursts of star formation. Another characteristic of DIG and BCG is that they show a large spread in their physical and chemical properties. Matteucci and Chiosi (1983) were among the first in studying the chemical evolution of DIG and BCG galaxies in detail, trying to explain the observed spread (if real). They concluded that closed-box models cannot account for the Z-logμ (where $\mu = M_{gas}/M_{tot}$) distribution even if the number of bursts varies from galaxy to galaxy. They suggested some possible solutions to explain this spread:

- different IMF's from galaxy to galaxy
- different amounts of galactic wind from galaxy to galaxy
- different amounts of infall from galaxy to galaxy.

In the following years Matteucci and Tosi (1985) presented a numerical model where galactic winds powered by SNe were taken into account. The difference between this paper and that by Matteucci and Chiosi (1983) was that in the latter case the galactic winds were studied only in the framework of a simple analytical model. Matteucci and Tosi (1985) concluded that different wind rates from galaxy to galaxy represent a possible explanation for the observed spread in the abundances of O,N vs. $\log\mu$ but they could not reproduce the observed spread in the N/O vs. O/H diagram. To explain such a spread they suggested different amounts of primary N being produced in different galaxies, as already argued by Pagel and Edmunds (1981). More recently, Kumai and Tosa (1992) suggested different fractions of dark matter from galaxy to galaxy as a possible explanation for the spread in the Z-$\log\mu$ diagram. On the other hand, Pilyugin (1992,1993) forwarded the idea that the spread in the properties of these galaxies, in particular the observed spread in He/H vs. O/H and N/O vs. O/H, are due to self-pollution of the HII regions coupled with "enriched" or "differential" galactic winds. The idea of "differential" galactic winds has then been further developed by Marconi et al. (1994)(hereafter MMT94). Garnett (1990) and Olofsson (1995) claimed the time delay of the N release as a possible explanation for the spread in N/O. However, recent data compilation (Lipman, 1995) shows that at low metallicities the scatter in N/O is no more apparent. One of the causes for this can be that WR galaxies (i.e. galaxies with Wolf-Rayet features) have been omitted from the data sample and another that the quality of the data is improved (see also the discussion of MMT94).

2 The Model of Marconi et al. 1994 (hereafter MMT94)

This model is basically the same as that of Matteucci and Tosi (1985). Star formation is assumed to proceed in short but intense bursts. The **novelty** of this model relative to previous ones is that the contribution to the chemical enrichment of SNe of different type (II,Ia and Ib) is taken into account together with "differential" galactic winds.

In particular, the main assumptions of the model are:

- One-zone with instantaneous mixing of gas.
- No I.R.A. (Instantaneous Recycling Approximation).
- The temporal evolution of the abundances of H, He, C, N, O and Fe is followed in detail.
- A number of bursts of star formation from 1 to 15 is taken into account. The duration of a single burst is assumed to be 100Myr.
- The efficiency of the star formation in each burst is $10Gyr^{-1}$.
- The assumed initial mass function (IMF) is that of Salpeter (1955).
- Galactic winds powered by SNe and occurring at a rate proportional to the star formation rate are present. The winds develop only during the burst of star formation and they can be normal or differential (i.e. metal enriched). The assumption is made that in normal winds all the elements present in the interstellar medium (ISM) are lost, whereas in differential winds only certain elements are lost. In particular, MMT94 have assumed that the elements produced by type II SNe are preferentially lost in a galactic wind, whereas the elements restored by stellar winds (especially those from low and intermediate mass stars) and by type Ia SNe are not. In this framework O and part of Fe (that made in type II SNe) are lost from the galaxy while He and N, which are mainly produced in low and intermediate mass stars, are not. Type Ia SNe, which are responsible for the bulk of iron production (with the assumed Salpeter IMF), are not likely to trigger a wind since they explode mainly during the interburst phase and have a large

range of explosion times (from $\simeq 3 \cdot 10^7$ to a Hubble time) inducing them to explode in isolation. On the other hand, type II SNe explode in associations and all in a short time interval (from few million years to 30 Myr) so that they are likely to induce chimneys. From the theoretical point of view, a selective loss of metals has been studied by DeYoung and Gallagher (1990) who showed that SNII explosions can trigger chimneys which eject metal-enriched material outside the disk in low mass galaxies.

To account for differential winds MMT94 assumed the parameter $w_i = WR/SFR$, namely the ratio between wind rate and star formation rate, to be different from zero only for the elements mainly produced in type II SN explosions, such as α-elements. On the other hand, in the case of normal winds the parameter w_i has the same value for all the chemical elements.
The existence of galactic winds in dwarf galaxies seems to be supported by some recent observational evidence: Meurer et al (1992), Papaderos et al. (1994), Lequeux et al. (1995) and Marlowe et al. (1995). For example, Papaderos et al. estimate a galactic wind flowing at a velocity of 1320 Km/sec for VIIZw403; the escape velocity estimated for this galaxy is $\simeq$ 50 Km/sec. Lequeux et al.(1995) suggest a galactic wind in Haro2=MKn33 flowing at a velocity of $\simeq 200 Km/sec$. Moreover, Martin (this conference) discusses the mass of hot gas likely to escape from the galaxy IZw18.

- The possibility of accretion of primordial gas is also taken into account as in Matteucci and Tosi (1985).

3 Nucleosynthesis

The nucleosynthesis prescriptions adopted in MMT94 are:

- **Low and intermediate mass stars**: Renzini and Voli (1981), for two different α-values, $\alpha = 1.5$ and $\alpha = 0$, $\eta = 0.33$ and two different values of M_{up}, namely the mass limit for degenarate C-ignition, $M_{up} = 8M_\odot$ and $M_{up} = 5M_\odot$.

- **Massive stars**: Woosley (1987) yields for stars with mass $M > 10M_\odot$.

- **SN Ia**: Nomoto et al. (1986).

The nucleosynthesis of Nitrogen and its primary/secondary nature is, unfortunately, still quite uncertain. The amount of primary N produced in AGB stars depends crucially on the occurrence of the third dredge-up. If 3th dredge-up does not occur, primary N should drop to $\simeq$ 10% of the amount predicted by Renzini and Voli (1981). The primary/secondary origin of N in massive stars is even less clear. Recent calculations by Weaver and Woosley (unpublished) show that is possible, in principle, to produce primary N in low metallicity massive stars but this production is crucially dependent on the treatment of convection. Moreover, there is some confusion about how to interpret the observed log(N/O) vs. 12+log(O/H) diagram (Figure 2). In fact, most of the authors tend to interpret the apparent trend shown by different galaxies and Galactic HII regions as representative of the physical law governing the growth of N/O in time. This is clearly not correct, since the observed points refer to the final stages of objects which have had quite different time evolutions. Therefore, the inferred primary/secondary nature of N from the observed trend is meaningless. To this purpose is better to concentrate on single objects (e.g. a spiral or a dwarf galaxy) and try to reproduce their present-time observed values of N/O.

The nucleosynthesis of He is also uncertain: recent calculations by Maeder (1994) predict large amounts of He to be restored by massive stars through stellar winds, but only for stars of high metal content (at least solar), and therefore it does not apply to BCG and DIG. The He yields used by Marconi et al. (1994) are those from Maeder and Meynet (1989).

4 Observational data

For the sake of homogeneity MMT94 have chosen only galaxies whose spectra show the lines: $[OII]\lambda\lambda 3727-29$, $[OIII]\lambda\lambda 4959-5007$, $[NII]\lambda 6584$ and $[HeI]\lambda 5876$.
Typical errors on these abundances are ± 0.2 dex (Pagel et al. 1980) In particular, for the He/H vs. O/H diagram they compared with the data of Pagel et al. (1992), while for the N/O vs. O/H diagram they assembled a sample of 92 galaxies from different sources including Pagel et al. (1992).

5 Main Results of MMT94

MMT94 constructed several models by varying N_{burst}, t_{burst}, star formation efficiency, type of galactic wind, IMF and nucleosynthesis prescriptions. A comparison of predictions with data for He/H vs. O/H shows that most of the models provide too much O and not enough He (see Fig. 1). In particular, models with STANDARD nucleosynthesis ($\alpha = 1.5$, $M_{up} = 8M_{\odot}$) only secondary N from massive stars- and no winds predict too much O even with a couple of bursts (Matteucci and Tosi, 1985).

Models with normal winds reduce O but also He and their predictions lie at the bottom of the observed distribution. Only models with differential winds and a large number of bursts (e.g. 15) predict O and He eventually in the observed range. Therefore, only differential galactic winds can reproduce the observed He/H vs. O/H distribution, in agreement with Pyliugin's conclusions. However, the problem arises when one compares the predictions of the same models for N/O vs. O/H (see Fig.2). This comparison shows that good models for He predict too much N. One way out is to drop the STANDARD nucleosynthesis prescriptions, in particular by assuming that no primary N is produced in AGB stars (i.e. α=0.). Shifting the age of the last burst towards more recent epochs (N is mainly produced in long-living stars) it can help but does not solve the problem. It should be noticed that the theoretical curves, both in Figure 1 and 2, are obtained by joining the predicted abundances immediately after each burst of star formation. This has been done by the sake of simplicity; in fact, the time behaviour of the abundances in the burst regime is shaped like a saw-toothed line. This is due to the fact that during the burst the abundances of elements formed in short-living stars predominate, whereas in the interburst phases only the elements formed in long-living stars increase (see also Pilyugin 1992,1993). Finally, one can change the IMF (slope and/or m_l, namely the lower mass cut-ff for the initial mass function): in particular, going from $m_L = 0.1$ to $5M_{\odot}$ implies larger He and O and still too much N, whereas a flattening of the IMF slope goes in the right direction but enhances too much O, unless strong differential winds are also assumed.
In conclusion, the best fit of both He/H vs. O/H and N/O vs. O/H distributions is obtained when N_{burst}=7-10, differential winds with w_i=1-10 and $\alpha = 0$ are assumed.
However, before drawing any firm conclusion, the stellar nucleosynthesis of N should be revised: in particular, new calculations for the yields of N in low and intermediate mass stars are strongly required. The galaxy IZw18, as can be seen from both Fig.1 and 2 shows peculiar abundance ratios and these general conclusions cannot be applied to this object (see discussion on IZw18 in section7).

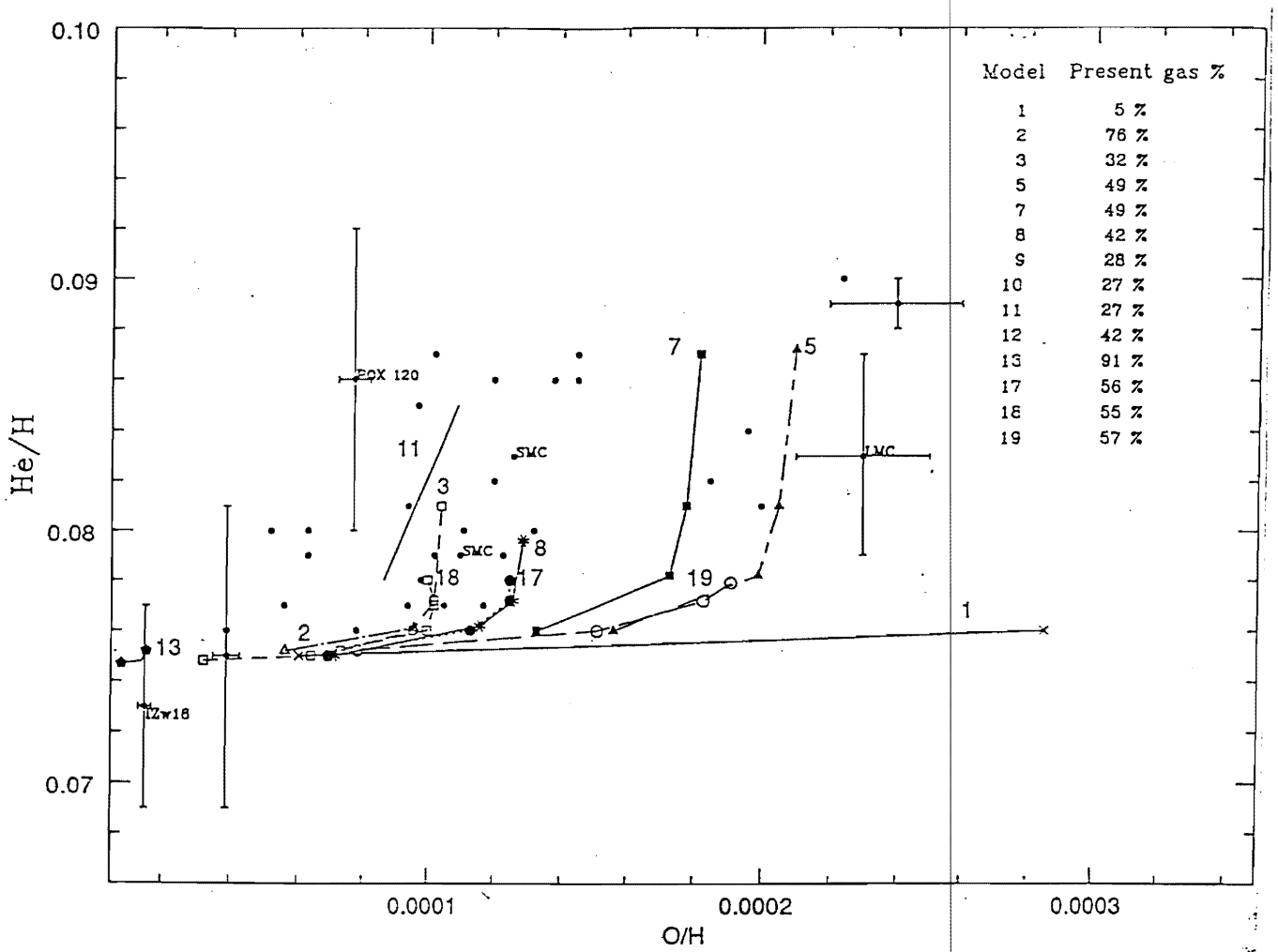

Figure 1: Predicted He/H vs. O/H from models with different number of bursts, IMF, m_L, M_{up} and nucleosynthesis. The model description can be found in MMT94. The dots represent the data point from Pagel et al. (1992) The data referring to SMC, LMC, IZw18 and Pox20 are explicitely indicated.

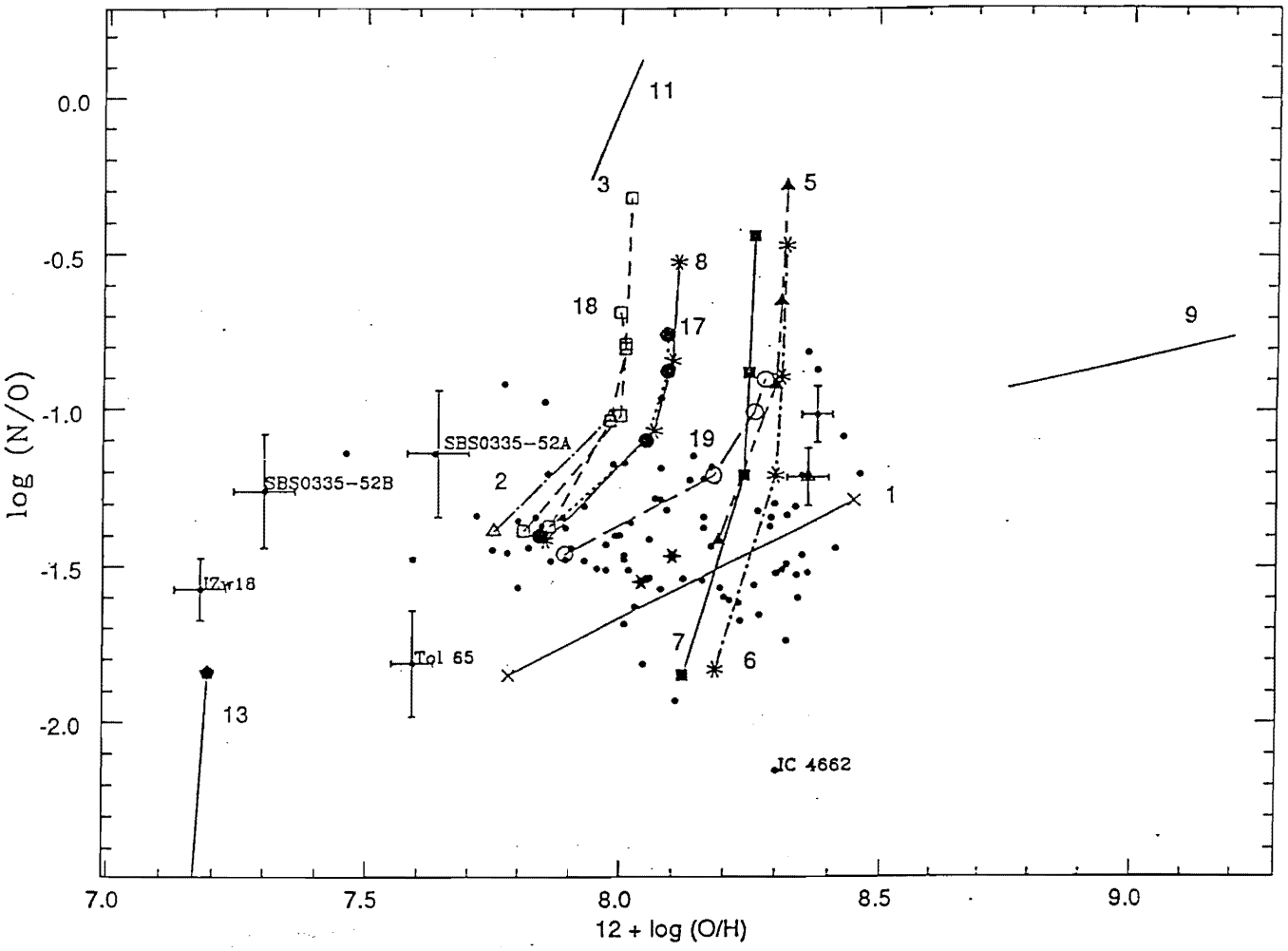

Figure 2: Predicted log(N/O) vs. 12+log(O/H) by the same models as in Figure 1. The data points come from different sorces as indicated in MMT94

6 Some comments about $\frac{\Delta Y}{\Delta Z}$ and [O/Fe]

MMT94 predicted a $\frac{\Delta(He/H)}{\Delta(O/H)} = 6$ (in number) for no winds or normal winds and $\frac{\Delta(He/H)}{\Delta(O/H)} = 30$ to 300 for differential winds, depending on the number of bursts of star formation.
Pagel et al. (1992) deduce from their data a $\frac{\Delta(He/H)}{\Delta(O/H)} = 58$, in good agreement with a least-square fit of the predictions of our best models which gives $\frac{\Delta(He/H)}{\Delta(O/H)}$=70.
Other interesting predictions are those for the abundances of α-elements relative to iron. The [O/Fe] ratios predicted by most of MMT94's models tend to be **overabundant** relative to the solar value; this is due to the predominance of Type II SNe during the short and intense bursts. However, models with strong differential winds and large number of bursts (10 to 15) can give negative [O/Fe] ratios. The reason for that in the case of strong differential winds is the preferential loss of oxygen relative to iron -which is mostly produced in type Ia SNe-, whereas in the case of a larger number of bursts is it due to the fact that the star formation regime becomes similar to a continuous star formation one, where type Ia SNe are no longer negligible. Recent observations of BCG (Thuan et al. 1995) suggest an average [O/Fe]=+0.34 dex, which indicates that the number of bursts in these galaxies (with the exception of IZw18 which will be discussed later) should not exceed 10 and that differential winds

should be not too strong ($w_i \leq 10$).

These high values of [O/Fe] impose also a constraint on the IMF suggesting that an IMF steeper than Salpeter (x=1.35) is excluded since it will produce lower [O/Fe] ratios than observed.

7 The galaxy IZw18

IZw18 is a BCG but its chemical properties are rather peculiar, in particular its lowest metal content which makes this object a good candidate for a truly primordial galaxy. In fact, the O abundance (in number) derived from the HII regions is 1/30 of the solar value ($\simeq 1.75 \cdot 10^{-5}$). Kunth et al. (1994) found an even lower O abundance in the HI envelope of IZw18 ($\simeq 7.9 \cdot 10^{-7}$ by number), $\simeq 1/1000$ of the solar value (but see Pettini and Lipman, 1995). This strong discontinuity supports the view of Kunth and Sargent (1986) that HII regions could be self-enriched. Pantelaki and Clayton (1987) excluded self-enrichment of the HII regions for IZw18 because of their nearly solar N/O ratio. They argued that such a high N/O cannot be produced only in a recent and short burst since N is synthetized mostly in long living stars. However, they did not take into account the possibility of differential galactic winds. On the other hand, Kunth, Matteucci and Marconi (1995) applied MMT94 model with differential galactic winds to IZw18 and reached different conclusions.
In particular, they explored two possibilities:

i) the present burst of star formation is polluting the HI through enriched galactic winds,

ii) the present burst is not the first one and previous bursts have contributed to the HI metal content.

They assumed the initial mass of the star forming region of IZw18 to be of the order of $6 \cdot 10^6 M_\odot$ and a burst duration varying from 10 to 50 Myr. The choice of such initial mass for the active HII region together with a higher intensity of the star formation ($50 Gyr^{-1}$) relative to the other BCG leaded to a predicted star formation rate in the present burst of the order of $0.03 M_\odot yr^{-1}$, in very good agreement with observational estimates (see Kunth et al., 1995 for references). Models of population synthesis adopting the Salpeter (1955) IMF for IZw18 (Mass-Hesse and Kunth, 1991) allow a burst duration no longer than 20 Myr. This fact, together with the N abundance (see Figures 2 and 3), represents an important constraint for modelling IZw18.
In case i) they assumed that during the burst the enriched material in the galactic wind mixes completely with the HI. The assumption of complete mixing during a single burst of 20Myr duration is supported by the finding of Roy and Kunth (1995) that Rayleigh-Taylor and Kelvin -Helmoltz instabilities can mix hot and HI gas in a timescale 10 times shorter than the lifetime of an OB association (i.e. $\simeq 6 \cdot 10^6$ years). The problem with only one burst is rather that the ejected O might not have had enough time to recombine in order to be observed as neutral in the HI gas. Therefore, Kunth et al. (1995) also computed a model with 2 bursts separated by more of 10^9 yr, always with the last one being still active now. In this case, during the interburst phase all the material produced (also the material not ejected with the wind) by stars during the first burst is assumed to mix with the surrounding HI gas and the resulting abundances are therefore the initial abundances in the second burst. It is worth noticing that in the case of 2 bursts there is no mixing problem, since turbulent mixing can act on a timescale of the order of $5 \cdot 10^8$ years.
In order to reproduce the high N/O ratio it was assumed, in some models, that N is produced as a primary element in massive stars. This was already proposed by Matteucci (1986) to explain the [N/O] vs. [O/H] distribution in the solar neighbourhood. However, primary nitrogen in massive stars is not enough by itself, in the framework of 1 or 2 bursts of star formation, to explain the observed N/O, so that strong differential winds (i.e. O-enriched) are also assumed ($W_i = 80$), much higher than adopted for more normal BCG and DIG by MMT94. It is worth noting that even with this strong O-enriched wind the observed O abundance in the HII of IZw18 can be very well reproduced. From model results one can see that the observed N/O in IZw18 can be reproduced even with standard nucleosynthesis but the burst duration should be at least 50 Myr, at variance with the suggestion from the population synthesis models, and always requiring the presence of a strong differential wind.

This choice of the differential wind results in strong constraints on [O/Fe] which is predicted to be lower than for the other BCG ([O/Fe]=$\simeq$+0.1), with a [Fe/H] of $\simeq$ -1.85.
The peculiarity in the abundance pattern observed in IZw18 makes this object quite unique and resembling primordial galaxies. In fact, Matteucci et al. (1995) suggested that an even more extreme system than IZw18 (e.g. a system with even stronger galactic winds than IZw18) could perhaps explain the pattern of abundances that has been recently found in the damped Ly-α (DLA) system at redshift z_{abs}=3.39 towards QSO 0000-2619 (Vladilo et al., 1995;Molaro et al. 1995). This system has the lowest recorded metallicity for a damped Ly-α system ($Z_{DLA} \simeq -2.5$), and an extremely high value for log(N/O)=-0.56 $\pm$0.24 with 12+log(O/H)=5.8$\pm$0.17. These abundances cannot be explained by models fitting the disk of our galaxy but only by a model like the best model adopted for IZw18 but with a much more efficient differential galactic wind (w_i = 1000), as shown in Figure 3. On the other hand, another DLA system (z_{abs}=2.27936 towards QSO2348-1479) observed by Pettini et al. (1995) can be very well fitted by the predictions of Kunth et al's best model for IZw18 but for a burst age shorter than 20 Myr. It is worth noting that Pettini et al. found a much lower N/O than the DLA of Molaro et al. (1995). However, the former authors use the abundance of S to derive N/O by assuming that [O/S]=0.0 whereas the latter use the real O abundance.
The similarity between IZw18 and these DLA systems could perhaps indicate that IZw18 is a survivor primordial blue compact galaxy otherwise observed only at high redshift.

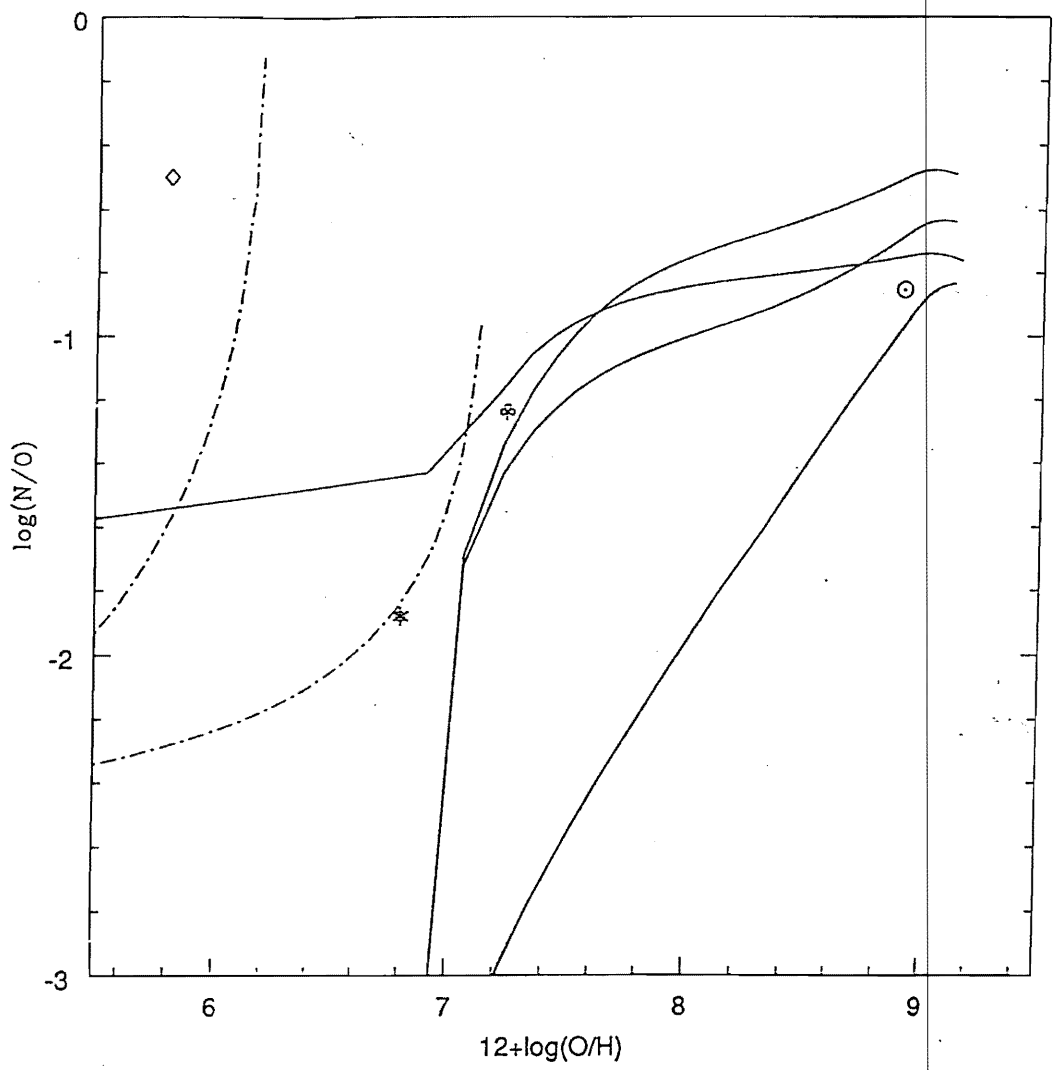

Figure 3: Predicted N/O vs. O/H for the solar neighbourhood of our Galaxy (continuous lines) and for one-burst objects similar to IZw18 (dot-dashed lines). In particular, the models for the solar neighbourhood are calculated under different assumptions about N production; the curve at the extreme right represents the choice of only secondary N, the two curves rising linearly and then flattening represents models with primary N from intermediate mass stars for different values of α (1.5 and 2.0), the line with the initial plateau represents the model where primary N from massive stars is assumed. The dot-dashed models are Model 5 of Kunth et al. (1995) (the lower curve) and a similar model but with a much higher efficiency of galactic wind (the upper curve). Both these models assume primary N in massive stars. In the figure are also shown the position of the sun, IZw18 (the clover, see Kunth et al. for reference), the DLA system of Pettini et al. (the snow) and the DLA system of Molaro et al. (the spadesuit)

8 Conclusions on IZw18

In summary, from the comparison between observational constraints and the best models of Kunth et al. (1995), we can summarize their conclusions on IZw18 as follows:
-IZw18 has experienced 1 or at most 2 bursts of star formation. In the first case an uncertainty remains about the possibility that all the newly produced elements could have mixed with the HI in 20 Myr and that the Oxygen could recombine in order to be observed in the neutral gas. In the second case an interburst period of 1 Gyr allows complete mixing of all the elements produced in the first burst with the surrounding HI. In both cases one is able to reproduce the low observed O abundance in the HI.
-The duration of the last burst must have been between 10 and 20 Myr, with a minimum of 10 Myr.
-Observations of NI (1199-1200 Å) absorption line in the HI could allow to distinguish between the 1 or 2 burst scenario but unfortunately the available data do not allow any firm conclusion.
-N produced as a primary element in massive stars, as suggested by recent calculations (Weaver and Woosley, unpublished), allows to reproduce the observed N/O even with a single burst lasting 20 Myr.
-A negligible He production (0.0005) for IZw18 is found, making this galaxy the ideal object in which to measure the primordial He abundance.
-High N/O and low [O/Fe] ratios are also observed in high-redshift DLA systems suggesting that some of these systems could be young blue compact galaxies with extreme properties such as IZw18 suffering their first burst of star formation (Matteucci et al., 1995).

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