Mon. Not. R. Astron. Soc. **337,** L27–L30 (2002)

Nitrogen abundances in damped Lyman α systems: the combined effects of SNII and SNIa in a hierarchical clustering scenario

Patricia B. Tissera,[1,2]★ Diego G. Lambas,[1,3]† Sofia A. Cora[1,4]‡ and Mirta B. Mosconi[3]

[1] *Consejo Nacional de Investigaciones Científicas y Técnicas, Rivadavia, 1917 Buenos Aires, Argentina*
[2] *Instituto de Astronomía. y Física del Espacio, C. C. 67, Suc. 28, 1428 Buenos Aires, Argentina*
[3] *Observatorio Astronómico de la Universidad Nacional de Córdoba, Laprida 854, 5000 Cordoba, Argentina*
[4] *Observatorio Astronómico de La Plata, Universidad Nacional de La Plata, 1900 La Plata, Argentina*

Accepted 2002 October 10. Received 2002 October 7; in original form 2002 July 15

ABSTRACT

The combined enrichment of supernovae (SN) types II and I in a hierarchical clustering scenario could produce regions with low N content with respect to α elements, consistent with observed values measured in damped Lyman α systems (DLAs). We have studied the formation of DLAs in a hierarchical clustering scenario under the hypothesis that the building blocks of current field galaxies could be part of the structures mapped by DLAs. In our models the effects of the non-linear evolution of the structure (which produces bursty star formation histories, gas infall, etc.) and the contributions of SNIa and SNII are found to be responsible of producing these N regions with respect to the α elements. Although SNIa are not main production sites for Si or O, because of the particular timing between SNIa and SNII, their contributions can help to produce clouds with such abundances. Consistently, we found the simulated low nitrogen DLAs to have subsolar [Fe/H]. We show that low nitrogen DLAs have experienced important star formation activity in the past with higher efficiency than normal DLAs. Our chemical model suggests that SNIa play a relevant role in the determination of the abundance pattern of DLA and, that the observed low nitrogen DLA frequency could be explained taking into account the time-delay of ≈0.5 Gyr introduced by these supernova to release metals.

Key words: galaxies: abundances – galaxies: evolution – galaxies: formation – cosmology: theory.

1 INTRODUCTION

The study of chemical properties of the structure at different redshifts have provided important clues for the problem of galaxy formation and evolution (Contini et al. 2002). In particular, DLAs have been used to probe the abundances of the neutral hydrogen over a large range of redshift, becoming a powerful tool to study the enrichment of the interstellar medium. Several elements have been detected belonging to the Fe group and the so-called α elements. Owing to the fact that Fe and the α elements are thought to have originated in different events: supernovae (SN) Ia and II, respectively, and consequently, there may be a lag between their ejection into the interstellar medium (ISM), their relative abundances as a function of redshift could test the star formation (SF) history of galaxies.

Recently, there have been new results on nitrogen abundances in DLAs which have fostered the discussion on its possible nucleosynthesis sites (Pettini et al. 2002, hereafter Pet02; Prochaska et al. 2002, hereafter Pro02), principally owing to a group of low N (LN) abundance DLAs which lie in the region between secondary and primary production according to certain models (e.g. Henry, Edmunds & Koppen 2000).

Previous works that studied the N abundances in H II regions and Galactic stars have shown the need for primary and secondary production, since the N abundance clearly increases at a faster rate than those of Si or O for high metallicity. However, complications arise owing to the fact that N can be produced in both massive and intermediate-mass stars (IMS). The former would release it shortly after their birth while the latest evolve over a longer period of time estimated by Henry et al. (2000) in 250 Myr. This last mechanism would introduce a lag in the N release which combined with the SF history, might leave characteristic patterns in the abundance distributions. Pet02 has suggested that this delay could explain the LN DLAs if IMS are the main production sites for the primary N component. However because of the shortness of this time delay,

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★E-mail: patricia@iafe.uba.ar
†John Simon Guggenheim Fellow.
‡Postdoctoral Fellow of Fundación Antorchas at Max-Planck Institute for Astrophysics, Germany.

the estimated number turned out to be smaller than the number of already observed LN DLAs. These authors estimated one out of seven in the range $z = 6$ and $\langle z = 2.6\rangle$ for a ΛCDM cosmology ($h = 0.65$), while the observed frequency is four out of ten DLAs with $\langle z = 2.6\rangle$.

We profit from having a chemical enrichment model within a cosmological context that allows a detailed description of the formation and evolution of the structure together with the metallicity properties of the ISM and the stellar population (Mosconi et al. 2001, hereafter Mos01). By using this chemodynamical code, Tissera et al. (2001, hereafter Tis01) and Cora et al. (2002) have shown that the progenitors of current normal galaxy population in the field in hierarchical clustering scenarios could give origin DLA clouds. The [Fe/H], [Zn/H] and [α/H] abundances were found to be in very good agreement with the observed values and show the same level of evolution if the observational filter defined by Boissé et al. (1998) is applied ($F = [\mathrm{Zn/H}] + \log \mathrm{N_{HI}}$ with $18.8 < F < 21$). Our models include chemical feedback from SNII and SNIa. In this version, we have not included metal production from intermediate stars except for those binary systems which are taken as progenitors of SNIa. Hence, the results discussed here would show the effects of the enrichment by SNII and SNIa with rates set by the SF history of the galactic objects which are given by their evolution within a hierarchical clustering scenario.

2 ANALYSIS

We performed simulations of a 5 h^{-1} Mpc side box with initial conditions consistent with standard cold dark matter models ($\Omega = 1$, $\Lambda = 0$, $\Omega_b = 0.10$, $\sigma_8 = 0.67$ and $H = 100\ h^{-1}$ Mpc km^{-1} s^{-1} with $h = 0.5$). We used 64^3 particles with $\mathrm{M_p} = 1.4 \times 10^8\ h^{-1}\ \mathrm{M_\odot}$. The gravitational softening used is 1.5 h^{-1} kpc and the minimum smoothing length is 0.75 h^{-1} kpc. The SF scheme is based on the Schmidt law with a SF time-scale proportional to the dynamical one (Tissera et al. 1997). Our simulations include the chemical model developed by Mos01, which allow the description of the enrichment of the stars and gas as the galactic objects are assembled. For massive stars ($\mathrm{M} > 8\ \mathrm{M_\odot}$), we adopted the yields of Woosley & Weaver (1995, WW95) and for SNIa those of Thielemann, Nomoto & Hashimoto (1993) with a time-delay of 0.5 Gyr. The SF and SN parameters used in this paper are those that, on average, reproduce the abundance properties of nearby galaxies (Mos01).

We identified galaxy-like objects at different z at their virial radius ($\delta\rho/\rho \approx 200$). In order to diminish numerical resolution problems, we only analyse the substructure resolved with more than 2000 particles within the virial radius. In total, we will study 66 galactic objects distributed within $0.26 \leqslant z \leqslant 2.35$. We draw random line-of-sights (LOS) through these structures from three different random observers situated at $z = 0$, and estimated the H column densities along them, generating 198 LOS with N (H I) $> 2 \times 10^{20}$ atoms cm^{-2}. More details on the simulations and methods can be found in Tis01. The relative [K/J] abundance of elements K and J in the simulated DLAs are estimated by adding the corresponding metal masses in the gaseous component belonging to each substructure along the LOS.

We estimated the [N/Si] and (N/O) for the simulated DLAs in order to confront them with observations from Pro02 and Pet02, respectively. Fig. 1 shows [N/Si] versus [Si/H] and (N/O) versus $12 + (\mathrm{O/H})$ for simulated DLAs. As it can be seen from this figure, the N abundances for the simulated DLAs are within the observational range. These abundances have been the results of the contribution from massive stars estimated by using WW95 yields which are the only N production site taken into account in our models. WW95 ejecta have a significant dependence of the N production on metallicity. Our results show that N nucleosynthesis in massive stars can account fairly well for the observed N abundances in DLAs with low O (or Si) content. Even more, there are some simulated LN DLAs that have very low N abundances with respect to the α elements at abundance levels in agreement with observations. The solid lines denote the limits that we have chosen to divide the samples into a low- and high-N DLA ones. We will focus on the analysis of these LN DLAs and their origin.

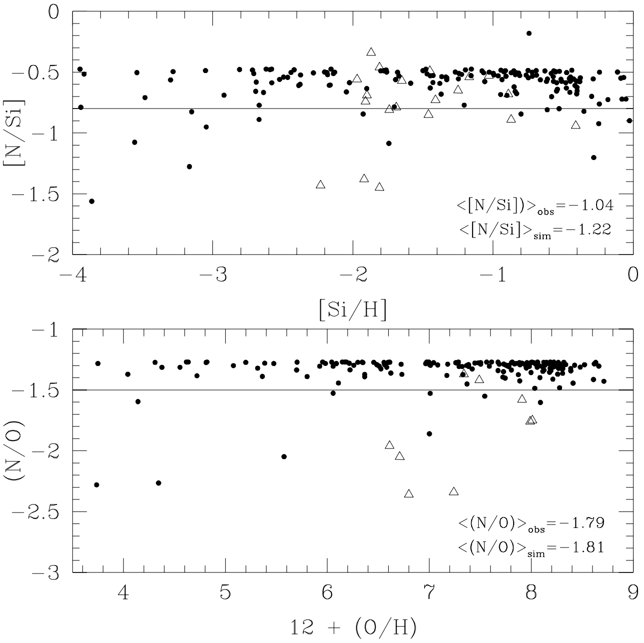

Figure 1. [N/Si] versus [Si/H] (upper panel) and (N/O) versus $12 + (\mathrm{O/H})$ (lower panel) for the simulated DLAs (circles) and observations (triangles) from Prochaska et al. (2002, upper panel) and Pettini et al. (2002, lower panel). The solid lines denote the chosen limits between HN and LN DLAs: $[\mathrm{N/Si}] = -0.8$ dex and $(\mathrm{N/O}) = -1.5$ dex. The mean abundances for the simulated and observed LN DLAs have been plotted.

We estimated the mass in stars along LOS, finding that LN DLAs have associated stellar populations with masses larger than $10^7\ \mathrm{M_\odot}$ to up $\approx 3 \times 10^8\ \mathrm{M_\odot}$. Their impact parameters are distributed within 5–20 kpc, consistently with those of DLAs with higher N content (HN-DLAs). From these two results we conclude that simulated LN DLAs mapped neither very central regions nor regions with very low mass in stars.

For the purpose of further understanding how these low-N abundances regions arise in the simulations (which do not include IMS enrichment), we analysed the Fe content respect to α elements such as Si. The main sites of Fe production are SNIa which have a time-delay of 0.5 Gyr for its release. Hence, Fe enrichment lags behind α elements and is very much linked to the SF and evolution histories of the systems. In Fig. 2 we have plotted [Si/H] versus [Fe/Si] for the simulated DLAs distinguishing between those that have high/low [N/Si] (open/filled circles) abundances. It can be clearly seen that the two groups segregate accordingly to their α enhancement with LN DLA showing subsolar [Si/Fe]. This result could be explained by considering that W7 model for SNIa of Thielemann et al. (1993) produces Si and O as well as Fe. Generally, the former are not taken into account because their main sites of productions are SNII. However, SNIa contribute as well with α elements and it turns out that the

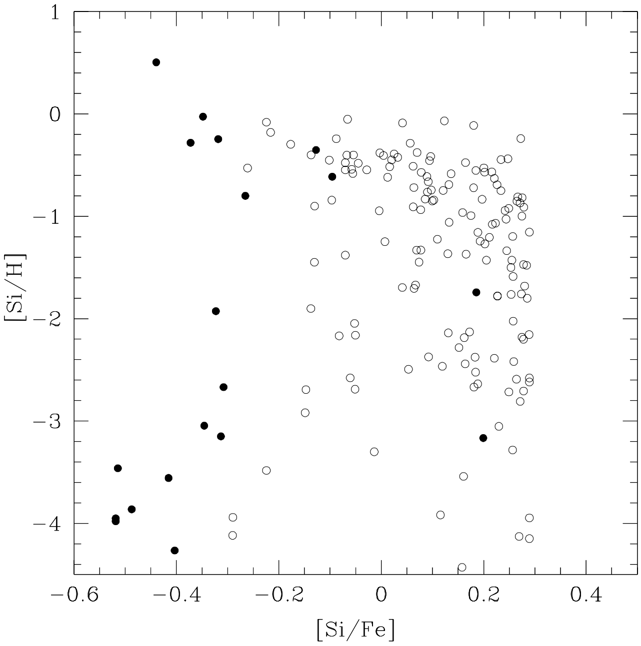

Figure 2. [Si/H] versus [Si/Fe] for the simulated DLAs, distinguishing between those with high (open circles) and low (filled circles) N content. We use [N/Si] = −0.8 as a limit between these subsamples.

combination of SF history and the particular evolutionary track of the simulated systems can make the α-element production of these events non-negligible respect to that of SNII, if the gas component is mainly affected by SNIa. This is clear from Fig. 2 where the simulated LN DLAs have subsolar [Si/Fe] demonstrating that Si lags behind Fe (that is mainly produced by SNIa), while the rest of the simulated DLAs have the opposite behaviour with solar or suprasolar abundances (showing that SNII production dominates in these cases). On the other hand, LN DLAs have comparable [Si/H] abundances to those of the rest of the simulated DLAs but, have lower [N/Si], making evident a deficiency of N which is only produced by SNII.

Hence, we found that these LN H I regions may have been enriched by a first generation of stars after which SF stops, and then, by SNIa. Because the simulated structure forms in a hierarchical scenario which is consistently described by our models, gas infall can also play a role by being a continuous source of pristine material. As the result of the combination of these processes, the Si content is similar to those of HN DLAs because of the extra SNIa contribution, the Fe content is high and the N is low respect to the Si. The fact that the simulated LN DLAs tend to have a large fraction of baryons in stars and impact parameter 5 kpc $< b <$ 20 kpc (with no trend to be in the outer regions) suggest that they belong to regions that have depleted an important fraction of their gas component. This may be the cause of the cease in the SF activity needed to explain their abundance characteristics.

In order to further investigate this point, we estimated two parameters along the LOS: the DLA star formation efficiency (ϵ_{DLA}) defined as the ratio between the masses in stars and in H along the LOS, and the mean formation redshift of the stellar population (z_{DLA} given in redshift) associated with DLAs (i.e. measured along the LOS). The assessment of the SF efficiency was done in the following way. We calculated the ϵ_{DLA} that splits the LN DLAs into a high and a low SF efficiency samples with equal number of members. Then, we estimated the percentage of HN-DLAs that would belong to the high ϵ_{DLA} sample, finding that only 5 per cent have such high efficiencies.

For the mean formation redshift, we found that stars in LN DLAs have $z_{\mathrm{DLA}} = 4.29$ while those in HN-DLAs have $z_{\mathrm{DLA}} = 1.93$. Clearly, the stellar populations associated with LN DLAs are, on average, significantly older. The total mass in stars associated to simulated LN DLAs, their high redshift of formation and their high SF efficiency, confirm that these regions experienced important SF with high efficiency in the past, which afterward ceased.

We also found that LOS are not always good tracers of the global properties of their host galaxies. For example, the range of mean (N/O) for the simulated DLA galaxies is $\approx[-1.5, -1.3]$, and we found no difference between the mean SF efficiencies of DLA galaxies hosting LN DLAs and of HN-DLAs. In the simulations, only the astrophysical properties of the matter along the LOS, correlates with their abundance properties along LOS.

From Fig. 1 we can also see that observed DLAs with low N have slightly higher O and Si content than the corresponding simulated LN DLAs. This can be understood because we are comparing DLAs at different redshift intervals: [1.78, 4.47] and [0.25, 2.35] for the observations and simulations, respectively. The simulated LN DLAs tend to be low H I density column regions. Higher N (H I)s in the simulated redshift interval have had time to be more enriched moving up to higher N and Si abundances.

Note that the simulated N abundances have a much better agreement with observations when compared to the Si than to the O abundances. We are not sure that this is an intrinsic problem of the nucleosynthesis of the ejecta adopted or if these elements are differentially affected by dust, for example. However, both Pet02 and Pro02 claim that differential dust depletion and obscuration are not important for their analysis of the observed abundances.

3 DISCUSSION AND CONCLUSIONS

Our models describe the formation and evolution of galaxy-like objects consistently with a cosmological model. In particular, we worked in a hierarchical clustering scenario, hence, we followed the history of assembly of galaxies including mergers and interactions. As it has been shown (e.g. Tissera 2000), the SF history of galaxy-like objects in such scenarios are significantly affected by their merger histories. Most objects show SF histories with starbursts linked to mergers and interactions either driven by secular evolution or their actual fusions (Scannapieco & Tissera 2002). Moreover, the relative mass distributions of baryons and dark matter could be also modified by mergers and, as a consequence, the response to external factors such as interactions, could be different at different stages of evolution affecting their SF histories (Tissera et al. 2002). Since the chemical history is directly linked to the SF process, the enrichment of the ISM and SP requires the adequate description of these mechanisms. Another important process affecting the SF history and the metallicity of the systems is gas infall which is naturally taken them into account by our models.

We show that chemical enrichment by SNIa and SNII could account for the N distribution in DLAs with 12 + (O/H) $\leqslant$ 8.5, including low-N DLAs.[1] Our findings suggest that LN DLAs may be the result of SNII and SNIa contributions together with bursty SF and gas infall. These regions have high SF efficiencies and old

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[1] However, the N production of SNII is not enough to generate the observed steep increase of this element respect to primary ones in high metallicity regions. We expect that the inclusion of IMS production will produce the observed trend.

SPs. Simple calculations using the yields given by WW95 and Thielemann et al. (1993), the Salptter Initial Mass Function and a ratio between SNI and SNII rates of 3 (see Mos01) give that the Si production of SNII and SNI at low metallicity is of the same order. We estimate that the contributions of two stellar populations with mean metallicity of $Z = 0.01\,\mathrm{Z}_{\odot}$ and $Z = 0.0001\,\mathrm{Z}_{\odot}$ could approximately account for the reported abundances. (Note that these are rough values just to give an idea to illustrate this fact.) Our models keep detailed records of the chemical content and production of the ISM and the stellar populations as well as of mergers and gas infalls so that the abundances are obtained consistently with the history of formation and evolution.

There are two main achievements of this work. First, it clearly shows the importance of using models that follows the non-linear evolution of the structure which affects the SF history and metal enrichment of both, stellar and gaseous, components. Secondly, and as a consequence of the previous fact, we suggest that SNIa may have played a more important role than hitherto thought. Following the reasoning presented by Pet02, it can be estimated that the time delay for SNIa explosions (≈0.5–1 Gyr) could resolve the inconsistency posed by the short life-time of IMS (250 Myr according to Henry et al. 2000). Note that the physical mechanism introducing the time-delay in our model is different from that proposed by Pet02. In our case, SNIa are responsible of producing lags among the elements. Hence, a decrease in the SNIa life-time would lead to an increase in the LN DLA frequency, since these events would have had time to take place in younger SPs as well. Following to Pet02's reasoning, SPs younger than 0.5 Gyr would not have the chance to produce LN DLAs. Hence, in 1.8 Gyr (time between $z = 2.6$ and $z = 6$ in a Λ-CDM cosmology) a period of 1.3 Gyr is left for SNIa to enrich the ISM. For a time-delay of 0.5 Gyr, we estimate a LN DLA frequency comparable to that deduced by Pet02 from observations (i.e. approximately four out of ten). We would like to stress that this SNIa time-delay also reproduces the abundance patterns of galaxies at $z = 0$ and the chemical evolution and primary element contents of observed DLAs (Tis01). Note that a lower limit to SNIa life-time can be estimated from this analysis, since a shorter/longer time would produce too many/few LN DLAs.

Finally, another important point derived from this analysis is that the global properties of DLA galaxies could be being misinterpreted by looking at those of DLAs. LOS give information on very local regions which might not trace the global properties of the structure they are intercepting. A larger and careful statistical analysis of DLAs is needed before drawing firm conclusions on the chemical evolution of the Universe from the information provided by DLAs.

ACKNOWLEDGMENTS

We thank the referee of this paper, Fabio Governato, for thoughtful comments that helped to improved this paper. This work was partially supported by CONICET, APCyT and Fundación Antorchas.

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