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First stars in damped Lyα systems

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ABSTRACT

In order to characterize damped Lyα absorption systems (DLAs) potentially hosting first stars, we present a novel approach to investigate DLAs in the context of Milky Way (MW) formation, along with their connection with the most metal-poor stars and local dwarf galaxies. The merger tree method previously developed is extended to include inhomogeneous reionization and metal mixing, and it is validated by matching both the metallicity distribution function of Galactic halo stars and the Fe–luminosity relation of dwarf spheroidal galaxies. The model explains the observed $N_{\rm H\,I}$–Fe relation of DLAs along with the chemical abundances of [Fe/H] < -2 systems. In this picture, the recently discovered $z_{\rm abs} \approx 2.34$ C-enhanced DLA pertains to a new class of absorbers hosting first stars along with second-generation long-living low-mass stars. These 'Population III DLAs' are the descendants of H_2-cooling minihaloes with $M_{\rm h} \approx 10^7\,{\rm M_\odot}$, which virialize at $z > 8$ in neutral, primordial regions of the MW environment and passively evolve after a short initial period of star formation. The gas in these systems is warm $T_{\rm g} \approx (40–1000)$ K, and strongly C-enriched by long-living, extremely metal-poor stars of total mass $M_* \approx 10^2–10^4\,{\rm M_\odot}$.

Key words: stars: carbor – stars: Population III – galaxies: abundances – galaxies: evolution – cosmology: theory.

1 MOTIVATION

Damped Lyα absorption systems (DLAs) are high column density neutral gas reservoirs, $N_{\rm H\,I} \geq 10^{20.3}$ cm^{-2}, observed at intermediate redshifts, $z \leq 5$, in the spectra of distant quasars. Although their nature is still unclear (Pettini 2004), the key role of DLAs to understand galaxy formation (Wolfe, Gawiser & Prochaska 2005) is widely recognized. So far, more than 1000 DLAs have been observed and the iron abundance measured in ≈150 systems [Fe/H] ≈ [−3.5, −0.5] (Prochaska et al. 2007). Among these, very metal-poor (VMP) DLAs with [Fe/H] < -2 can be used to study the initial phases of heavy element enrichment of the interstellar medium (ISM) of early galaxies. Indeed, if VMP stars observed today in the Galactic halo and in nearby dwarf spheroidal galaxies (dSphs) are the living fossils of the first stellar generations, VMP DLAs may well constitute the gas reservoir out of which such pristine stellar populations formed. Following the medium-resolution study of VMP DLAs by Penprase et al. (2010), Cooke et al. (2011b) have recently presented a high spectral resolution sample, including 22 VMP systems. In these DLAs, [C/O] ≈ −0.3 and [Fe/O] ≈ −0.4 independently of [Fe/H] and with little scatter, in agreement with measurements in VMP Galactic halo stars (Fabbian et al. 2009). So far, the only exception to this general trend is represented by a DLA with [Fe/H] ≈ −3 and $N_{\rm H\,I} = 10^{20.55\pm0.10}$ cm^{-2} observed in the spectrum of the QSO J0035−0918 at $z_{\rm abs} \approx 2.34$ (Cooke et al. 2011a). This system has [C/Fe] = 1.53, i.e. ≈20 times larger than any other DLA. Moreover, its abundance pattern shows a clear 'odd–even' effect and is consistent with the predictions for the yields of $Z = 0$ faint supernovae (SNe) with $m_* \approx 25\,{\rm M_\odot}$ (Kobayashi, Tominaga & Nomoto 2011). Are we observing for the first time a DLA whose gas retains the imprint left by the first stars?

To characterize DLAs potentially hosting the first stars or their ashes, we propose a novel approach that simultaneously follows the evolution and chemical properties of DLAs and their connection with the most metal-poor stars and galaxies observed in the local Universe based on the results obtained using the merger tree code GAMETE (Salvadori, Schneider & Ferrara 2007, hereafter SSF07; Salvadori, Ferrara & Schneider 2008; Salvadori & Ferrara 2009, hereafter SF09).

2 MODEL SUMMARY AND VALIDATION

The model key points can be summarized as follows (see SSF07; SF09, for details).

(i) Hierarchical merger histories of a Milky Way (MW)-sized dark matter (DM) halo are reconstructed from $z = 20$ via a Monte Carlo algorithm based on the extended Press–Schechter theory (SSF07).

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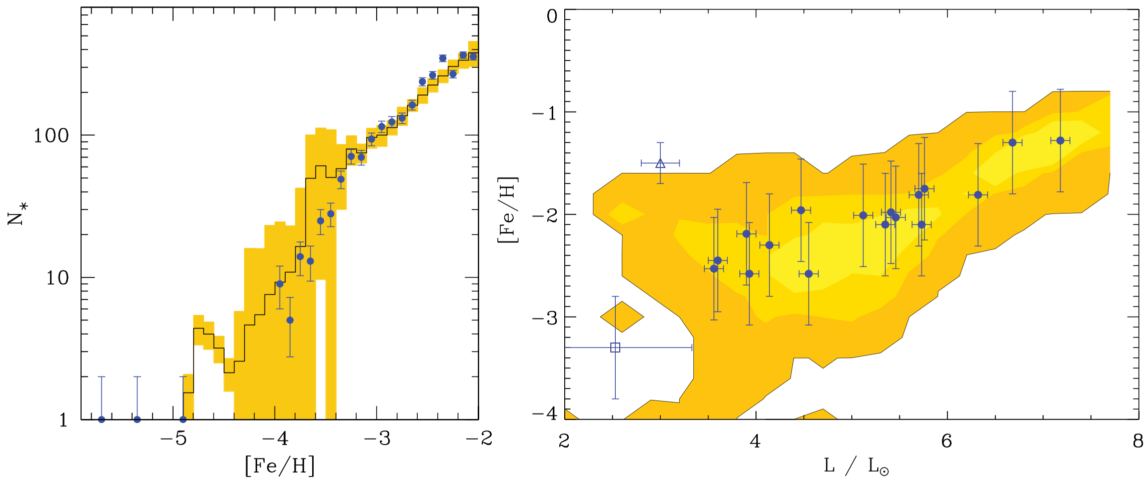


Figure 1. Left-hand panel: observed (points with error bars) and simulated (histogram) MDF of Galactic halo stars. The data points are the sample by Beers & Christlieb (private communication) with the inclusion of the three hyper-iron-poor stars (Christlieb et al. 2002, 2006; Frebel et al. 2005). The histogram is the average MDF value over 50 merger histories of the MW, renormalized to the total number of observed stars with [Fe/H] ≤ 2. The shaded area represents $\pm 1\sigma$ errors. Right-hand panel: observed (points with error bars) and simulated (contours) iron–luminosity relation for the MW dSphs. The data points are by Kirby et al. (2008) with the inclusion of the two faintest dSphs (Willman et al. 2005; Geha et al. 2009). The colour-shaded areas correspond to regions that include (99, 95 and 68) per cent of the total number of possible dSph candidates selected in 50 merger histories of the MW.

(ii) Star formation (SF) is followed along the tree in haloes exceeding a mass threshold, $M_{\rm sf}$, whose evolution (Fig. 2) is governed by (a) the photodissociating Lyman–Werner (LW) background, quenching H_2 formation in $T_{\rm vir} < 10^4$ K minihaloes; (b) the gas temperature in ionized regions of the Galactic medium (GM), preventing gas infall in haloes with $T_{\rm vir}$ lower than a threshold value, $T_{\rm th}$. We assume that SF is active in $T_{\rm vir} > T_{\rm th} = 2 \times 10^3$ K minihaloes at $z > 10$ (Dijkstra et al. 2004). At lower z, $T_{\rm th}$ (and hence $M_{\rm sf}$) is assumed to linearly increase up to the value set by the end of reionization $T_{\rm th} \approx 2 \times 10^4$ K (Kitayama et al. 2000) for $z < z_{\rm rei} = 6$.

(iii) *Inhomogeneous* reionization is modelled by random sampling the reionization history implied by $M_{\rm sf}(z)$ to switch off (on) gas accretion in minihaloes that form in ionized (neutral) regions.

(iv) The SF rate is taken to be proportional to the mass of cold gas, $\dot{M} = \epsilon_* M_{\rm g}/t_{\rm ff}$, where ϵ_* is the SF efficiency and $t_{\rm ff}$ the halo free-fall time. In minihaloes ϵ_* is reduced as $\epsilon = \epsilon_*[1 + (T_{\rm vir}/2 \times 10^4\,{\rm K})^{-3}]^{-1}$ due to the ineffective cooling by H_2 molecules (SF09). Low-mass, Population II (PopII) stars form according to a Larson IMF when the gas metallicity exceeds $Z_{\rm cr} = 10^{-3.8}\,{\rm Z}_\odot$ (Schneider et al. 2002). At lower metallicity, PopIII stars form with a reference mass value $m_* = 25\,{\rm M}_\odot$ and explosion energy $E_{\rm SN} = 10^{51}$ erg consistent with *faint* SNe.

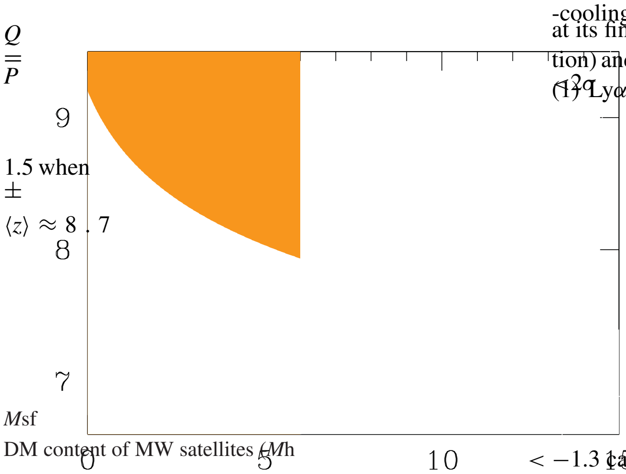
(v) The abundance evolution of different chemical elements[1] (from C to Zn) is traced in both the ISM and in the GM by taking into account mass- and metallicity-dependent stellar evolutionary time-scales (Raiteri, Villata & Navarro 1996) and SN feedback (Salvadori, Ferrara & Schneider 2008).

(vi) To account for the *incomplete mixing* of SN ejecta within the ISM of gas-poor galaxies, gas outflows have a metallicity $Z_w = Z_{\rm ISM} + \eta(M_{\rm g}) M_Z / M_{\rm ej}$, where M_Z is the mass of newly formed metals, $M_{\rm ej}$ is the mass of gas ejected out of the halo and η is a function of the gas mass $\eta = 0.5 + 0.65 \tanh\,[(\log10(M_{\rm g}) - 7.0)/2.0]$ that varies in the range $\eta = [0, 1]$.

(vii) The probability for newly formed haloes to reside in a GM metal-enriched region is $P(z) = Q_Z/Q_{\delta > \delta_{\rm c}}$, where $Q_Z(z) = 1 - \exp(\Sigma_i 4\pi R_{\rm b}^3(i)/V_{\rm MW}(z))$ is the filling factor of metal bubbles withinwithin

[1] For $m_* < 8\,{\rm M}_\odot$ stars, we use yields by van den Hoek & Groenewegen (1997) ($Z \geq 10^{-3}$) and by Meynet & Maeder (2002) ($Z \leq 10^{-5}$); for more massive stars, we use Woosley & Weaver (1995) with a systematic halving of the Fe yield (Timmes, Woosley & Weaver 1995); yields for faint SNe are from Kobayashi et al. (2011).

-cooling haloes that assembled
at its final assemblingepoch in order to evolve in isolation (no further merger or accretion) and become a satellite. By repeating the same procedure, we have already inferred
2.34, i.e. log(NHI
(1) Lyα
most of their gas by z /cm−2



< −1.3 cannot form anymore.In the second hypothesis, the DM halo hosting the DLA mustbe a

Figure 2. DM content of MW satellites (Mh) as a function of their formation redshift. The two lines show the evolution of the minimum mass of star-forming haloes,

0.41
±
2.4
=−

Zcr=
Z

10−3.8Z⊙, however, 'normal' PopII stars can form and contribute to enrichment. Given the yields by faint SNe, the PopIII-to-PopII transition occurs when [Fe/H]cr≈8, implying that most of

0.02, protogalaxies with an initial ironabundance [Fe/H]

1.28 ±
predicted by assuming an early (upper
⟩=−

105–106M⊙). As soon as
Mej

0.9 and [O/H]
±
passively evolv-

into the MW; or (b) a satellite galaxy which assembled at ear-lier epochs and evolved in isolation. The first possibility can beexcluded on the ba
gions of the MW environment are expected to disappear at

⟨[Fe/H]

10. They form through

0.005and
±

als and gas loss (

105.5–106.3M⊙, favouring met-
g≈

of primordial and metal-enriched progenitors, virialized
eutral regions of the MW environment. The metallicity
these systems depends on the gas enrichment in progen-
haloes. Abundance ratios, instead, closely reflect those of
the time of formation. Although the overall GM metallic-
ses with time, abundance ratios get locked to the dominant
pulation which contribute to the enrichment, i.e. Type II
I). As a consequence, [C/O] and [C/Fe] ratios show little
and are independent of

686
NHI decrease (Fig. 4) is caused by gas consumption

[X/H]⟩GM

1.22:
$\mu =$

0.989
2.34, when wecompute their H

the iron observed in these systems originated from these second generation stars. The mass of relic stars in PopIII DLAs is expected to vary between $M_* \approx$

systems formed in Zone (4)
[Fe/H]
associated

limit) and a late (lower limit) reionization history (Gallerani et al. 2006).

in the most star-rich systems, due to both astration and gas loss.
starless
Note that our model does not predict any [C/O] increase towards low [O/H] values, as reported by medium-resolution observations (Penprase et al. 2010).
since their assembly epoch. 6
The properties of VMP DLAs are well reproduced (Fig. 3) by
[Fe/H]

*fully*neutral with a molecular weight

The rise of the C abundance at increasing metallicity (Fig. 3) reflects the gradual contribution by low-metallicity AGB stars, mainly producing C, some O and limited amounts of N (for systems with [Fe/H]

5

NHI

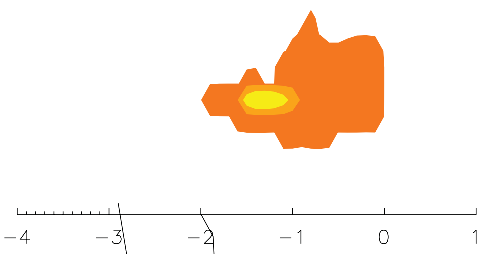
h sf). We selectedthe satellite candidates in 50 possible merger histories of the MW,

column density, , assuming that the gas is

H I≈2n H Ir g≈3

0.18 for star-forming galaxies, which have presumably developed a disc (Ferrara, Pettini & Shchekinov 2000), and α
= 0.8 otherwise. DLAs are
defined as systems with
g=αr vir with α

10
×
2
> 10^{20} cm^{-2} (Wolfe et al. 2005). Interestingly, we find that systems which populate Zone


−4
−3
−2
−1
0
1

As stated, the C-enhanced DLA is a minihalo. However, we cannot exclude a different interpretation, in which such absorber might be a newly formed halo virializing at $z \approx 2.3$ from a rare, metal-free region of the intergalactic medium and actively forming PopIII stars. Since the total mass of the star-forming DLA is $M_{\rm h} > 10^{9.5}\,{\rm M}_{\odot} \approx M_{\rm sf}(z = 2.3)$, strong feedback is required to substantially remove the initial gas mass and match the observed $N_{\rm H\,I}$. By determining the DM content and SF rate of the C-enhanced DLA, it would be possible to disentangle these two pictures. We finally note that our simple semi-analytical model, which holds similarities with that proposed by Abel & Mo (1998) for Lyman limit systems, prevents us from making specific predictions on the number of DLAs at $z = 2.34$. However, the relative contribution of C-enhanced DLAs to the total population is expected to be extremely low, ≈0.01 per cent, thus explaining the rarity of these systems.

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