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First stars in Damped Lyman Alpha systems

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ABSTRACT
In order to characterize Damped Lyman Alpha 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 dSph galaxies. The model explains the observed $N_{\rm HI}$-Fe relation of DLAs along with the chemical abundances of [Fe/H]< -2 systems. In this picture, the recently discovered $z_{abs} \approx 2.34$ C-enhanced DLA (Cooke et al. 2011a), pertains to a new class of absorbers hosting first stars along with second-generation long-living low-mass stars. These "PopIII DLAs" are the descendants of H_2-cooling minihalos with $M_h \approx 10^7 M_\odot$, that 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 $T_g \approx (40 - 1000)$ K, and strongly C-enriched by long-living, extremely metal-poor stars of total mass $M_* \approx 10^{2-4} M_\odot$.

Key words: galaxies: abundances, evolution, stellar content - cosmology : theory - stars: Population II

1 MOTIVATION

Damped Lyα absorption systems (DLAs) are high-column density neutral gas reservoirs, $N_{\rm HI} \geq 10^{20.3}{\rm cm}^{-2}$, 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 $[Fe/H] \approx [-3.5, -0.5]$ (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 $N_{\rm HI} = 10^{20.55\pm0.10}{\rm cm}^{-2}$ observed in the spectrum of the QSO J0035-0918 at $z_{abs} \approx 2.34$ (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 (SN) with $m_* \approx 25 M_\odot$ (Kobayashi et al. 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, SSF07; Salvadori, Ferrara & Schneider 2008; Salvadori, & Ferrara 2009, SF09).

2 MODEL SUMMARY AND VALIDATION

The model key points can be summarized as follows (see SSF07 and SF09 for details):

(i) Hierarchical merger histories of a MW-sized dark mat-

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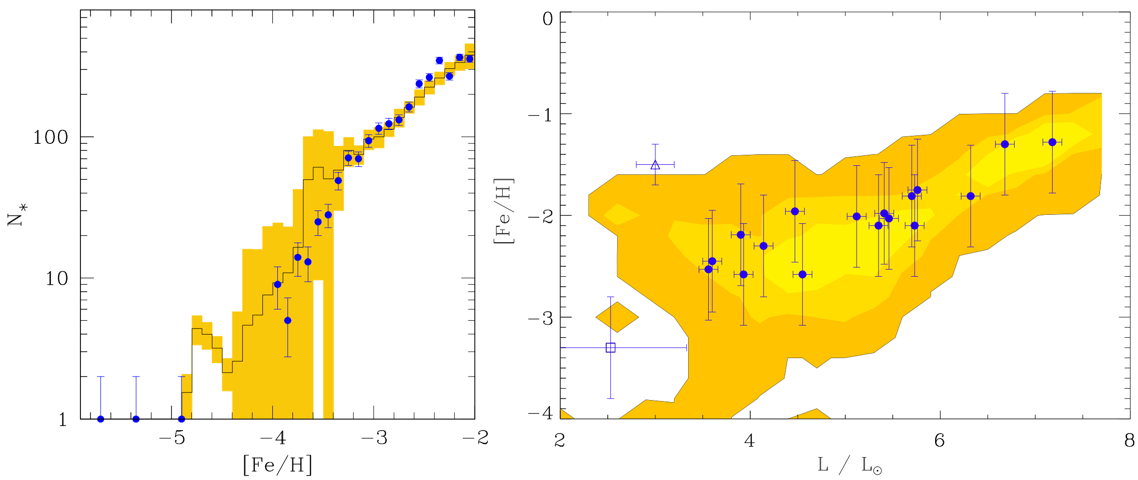

Figure 1. *Left panel*: observed (points with error-bars) and simulated (histogram) metallicity distribution function of Galactic halo stars. The data points are the sample by Beers & Christlieb (2006) with the inclusion of the three hyper-iron poor stars (Christlieb et al. 2002, 2006; Frebel et al. 2005). The histogram is the average MDF value over 50 merger history of the MW, re-normalized to the total number of observed stars with [Fe/H]$\leq$ 2. The shaded area represents $\pm 1\sigma$ errors. *Right panel*: observed (points with error-bars) and simulated (contours) iron-luminosity relation for the MW dSph galaxies. 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 colored shaded areas correspond to regions that include the $(99, 95, 68)$% of the total number of possible dSph candidates selected in 50 merger histories of the MW.

ter (DM) halo are reconstructed from $z = 20$ via a Monte Carlo algorithm based on the Extended Press-Schechter theory (SSF07).

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

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

(iv) The SF rate is taken to be proportional to the mass of cold gas, $\dot{M} = \epsilon_* M_g/t_{ff}$, where ϵ_* is the SF efficiency and t_{ff} the halo free-fall time. In minihalos ϵ_* is reduced as $\epsilon = \epsilon_*[1 + (T_{vir}/2 \times 10^4 \mathrm{K})^{-3}]^{-1}$ 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 $Z_{\rm cr} = 10^{-3.8} Z_\odot$ (Schneider et al. 2002). At lower metallicity, PopIII stars form with a reference mass value $m_* = 25 M_\odot$ and explosion energy $E_{SN} = 10^{51}$ erg consistent with *faint* SNe.

(v) The abundance evolution of different chemical elements† (from C to Zn) is traced in both the ISM and in the GM by taking into account mass- and metallicity-dependent stellar evolutionary timescales (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 $Z_w = Z_{ISM} + \eta(M_g) M_Z/M_{ej}$, where M_Z is the mass of newly formed metals, M_{ej} is the mass of gas ejected out of the halo, and η is a function of the gas mass $\eta = 0.5 + 0.65 \tanh[(\log 10(M_g) - 7.0)/2.0]$ that varies in the range $\eta = [0, 1]$.

(vii) The probability for newly formed halos to reside in a GM metal enriched region is $P(z) = Q_Z/Q_{\delta > \delta_c}$, where $Q_Z(z) = 1 - \exp(\Sigma_i 4\pi R_b^3(i)/V_{MW}(z))$ is the filling factor of metal bubbles within the MW physical volume‡, and $Q_{\delta>\delta_c}(z)$ is the volume filling factor of fluctuations with overdensity above the critical threshold, $\delta > \delta_c = 1.686$, for the linear collapse (Miralda-Escudé, Haehnelt & Rees 1999). The latter quantity describes the abundance of high-density regions, in which metals *first* penetrate (Tornatore, Ferrara & Schneider 2007). Objects in enriched (primordial) regions are assigned an initial metallicity $Z_{vir} = Z_{GM}/Q_Z$ ($Z_{vir} = 0$).

The model is calibrated by best-fitting the SF and feedback efficiencies to reproduce the global properties of the MW (stellar/gas mass and metallicity). In Fig. 1 we show that the average metallicity distribution of [Fe/H]< -2 stars over 50 possible MW merger histories matches the observed Galactic halo MDF. In the same Figure, the theoretical Fe-Luminosity relation for dSph galaxies has been obtained by evolving in isolation star-forming halos with $M_h < M_{2\sigma}$, candidates to remain MW satellites (Diemand, Madau &

† For $m_* < 8 M_\odot$ 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).

‡ We assume $V_{MW}(z) = 5(1+z)^{-3}$ Mpc^3.

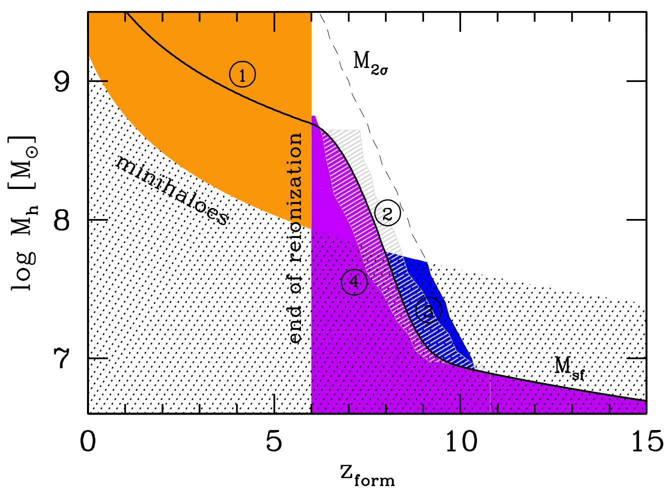

Figure 2. Dark matter content of MW satellites ($M_h < M_{2\sigma}$) as a function of their formation redshift. The two lines show the evolution of: the minimum mass of star-forming haloes, M_{sf} (solid), the halo mass corresponding to 2σ density peaks (dashed). The dotted shaded area identifies the region populated by H_2-cooling minihalos with $T_{vir} < 10^4$ K. The number labels and colors specify different populations of satellites (see the text). The gray shaded area delimits the evolution of M_{sf} predicted by assuming an early (upper limit) and a late (lower limit) reionization history (Gallerani et al. 2007).

Moore 2001; SF09 for details). In Fig. 2 $M_{sf}(z)$ is compared with that obtained by using data-constrained reionization models. To this end we compute the dissociating LW background intensity associated with an early/late reionization history (Gallerani, Choudhury & Ferrara 2006) by using the results provided in Fig. 6 by Ahn et al. (2009); we then convert the flux into a critical mass following Machacek, Brian & Abel (2001) and extrapolate to higher masses. At each redshift our M_{sf} is within the range allowed by the two reionization histories (gray shaded area).

3 THE DWARF GALAXY ZOO

We now apply our model to DLAs starting from the origin of the C-enhanced, [Fe/H]≈ -3 DLA at $z_{abs} = 2.34$. Two possibilities must be considered: (a) a recently virialized halo, later merging into the MW, or (b) a satellite galaxy which assembled at earlier epochs and evolved in isolation. The first possibility can be excluded on the basis of a metallicity argument: metal-free regions of the MW environment are expected to disappear at $\langle z\rangle \approx 8.7 \pm 1.5$ when $P = Q_Z/Q_{\delta>1.686} > 1$. Afterward, newly virializing halos form from metal enriched GM gas, whose initial abundances $[X/H]_{vir} = \langle [X/H]\rangle_{GM}/Q_Z$. Since at $z = 2.3$, $Q_Z = 0.989 \pm 0.005$ and $\langle [Fe/H]\rangle = -1.28 \pm 0.02$, protogalaxies with an initial iron abundance [Fe/H]< -1.3 cannot form anymore.

In the second hypothesis, the dark matter (DM) halo hosting the DLA must be associated to density fluctuations $< 2\sigma$ at its final assembling epoch in order to evolve in isolation (no further merger or accretion) and become a satellite. By inspecting Fig. 2 we can distinguish among different populations of objects that satisfy this condition: (1) Lyα-cooling halos that assembled *after* the end of reionization; Fornax and LeoI, the most luminous among the observed dSphs, are predicted to belong to this domain; (2) star-forming Lyα-cooling halos that assembled *before* the end of reionization; classical dSphs, $L > 10^5 L_\odot$, such as Sculptor (SF09) are members of this population. (3) H_2-cooling, inefficiently star-forming minihalos that appeared at $z \approx 8-10$; this is the domain of ultra-faint dSphs (SF09). (4) *"sterile"* halos that formed before the end of reionization and unable to trigger SF ($M_h < M_{sf}$). We selected the satellite candidates in 50 possible merger histories of the MW, and evolve them in isolation down to redshift $z = 2.34$, when we compute their H I column density, $N_{\rm HI}$, assuming that the gas is *fully* neutral with a molecular weight $\mu = 1.22$:

$$N_{\rm HI} \approx 2 n_{\rm HI} r_g \approx \frac{3}{2\pi}\,\frac{M_g/\mu m_p}{\alpha^2 r_{vir}^2}$$

$$= 5.2\times 10^{13}\,\frac{M_g}{\alpha^2}\left(\frac{M_h}{10^8 M_\odot}\right)^{-2/3}\left(\frac{10}{1+z_{form}}\right)^{-2}\ \mathtt{cm}^{-2} \quad (1)$$

the gas radius is written as $r_g = \alpha r_{vir}$, with $\alpha = 0.18$ for star-forming galaxies, that have presumably developed a disk (Ferrara, Pettini & Shchekinov 2000), and $\alpha = 0.8$ otherwise. DLAs are canonically defined as systems with $N_{\rm HI} > 2\times 10^{20}$ cm^{-2} (Wolfe et al. 2005). Interestingly, we find that systems which populate Zone (2), i.e. the progenitors of classical dSphs, have already exhausted most of their gas by $z = 2.34$, i.e. $\log(N_{\rm HI}/\mathtt{cm}^{-2}) \ll 20.3$. On the other hand, many objects among those formed in Zones (1), (3) and (4), have H I column densities compatible with DLAs. We will then focus on these candidates.

4 DLAS AND FIRST STARS

A comparison between the properties of candidate and observed DLAs at $z \approx 2.34$ is given in Fig. 3 and Fig. 4. Objects formed in different Zones result in distinct DLA populations, differing in their chemical abundances and $N_{\rm HI}$. Systems in Zone (3) are segregated in the C-rich, metal-poor, low-$N_{\rm HI}$ regions of the plots, matching the properties of the C-enhanced DLA. What is the origin of these systems?

According to our model, C-enhanced DLAs are hosted by $M_h \approx 10^{6.9-7.2} M_\odot$ H_2-cooling minihalos, which virialized before the end of reionization out of *metal-free*, neutral regions of the MW environment. Because of their low DM content the star formation history of such a primordial proto-galaxies is extremely short. Some tens of Myrs after the onset of star-formation the intensity of LW background becomes high enough ($M_{sf} > M_h$) to suppress further SF activity, thus turning them into "sterile" minihalos. Metal-free stars are hosted by this population of DLAs, to whom we will hereafter refer as PopIII DLAs.

The metal-enrichment by first stars gently proceeds in these objects, mainly because of ineffective cooling by H_2 molecules and their low gas-mass content, $M_g \approx 10^{5.5} - 10^{6.3} M_\odot$, favoring metals and gas loss ($M_g^{ej} \approx 10^{5-6} M_\odot$). As soon as $Z > Z_{\rm cr} = 10^{-3.8} Z_\odot$, however, "normal" PopII stars can form and contribute to enrichment. Given the yields by faint SNe, the PopIII-to-PopII transition occurs when $[Fe/H]_{cr} \approx -4.8$, implying that most of the iron observed in these systems originates from these second generations of stars. The mass of relic stars in PopIII DLAs is

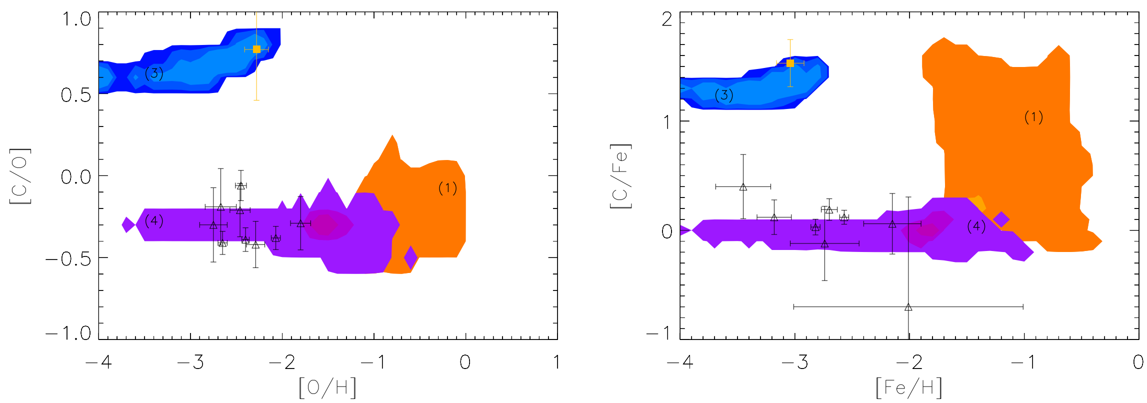

Figure 3. Gas abundances of DLAs with respect to the solar values (Asplund et al. 2009). Points are the observed values in VMP DLAs at $z_{abs} = (2.07 - 4.21)$ (triangles, Cooke+2011b) and in the C-enhanced DLA at $z_{abs} = 2.34$ (square, Cooke+2011a). The color shaded areas show the results of the model for the three different populations of DLAs at $z \approx 2.34$: PopIII (blue), very metal-poor (violet), and metal-poor DLAs (orange). For each population the intensity of the colors correspond to regions containing the $(99, 95, 68)\%$ of DLAs.

expected to vary between $M_* \approx 10^{2-4} M_\odot$, the most star-rich systems being the most enriched ones. 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]$= -3.0 \pm 0.2$ we find [C/H]$= -1.6 \pm 0.5$, [N/H]$= -3.8 \pm 0.9$ and [O/H]$= -2.4 \pm 0.4$). The associated $N_{\rm HI}$ decrease (Fig. 4) is caused by gas consumption in the most star-rich systems, due to both astration and gas loss. 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).

The properties of VMP DLAs are well reproduced (Fig. 3) by [Fe/H]< -2 *starless* systems formed in Zone (4), *passively evolving* since their assembly epoch, $6 < z < 10$. They form through merging of primordial and metal-enriched progenitors, virialized out of neutral regions of the MW environment. The metallicity spread of these systems depends on the gas enrichment in progenitor minihalos. Abundance ratios, instead, closely reflect those of the GM at the time of formation. Although the overall GM metallicity increases with time, abundances ratios get locked to the dominant stellar population which contribute to the enrichment, i.e. *type II SNe*. As a consequence, [C/O] and [C/Fe] ratios show little dispersion and are independent of Z, but also of redshifts, because of the passive evolution of these starless DLAs. These findings are in perfect agreement with the new observational results by Becker et al. (2011).

Finally, [Fe/H]> -2 DLAs are $T_{vir} > 10^4$ K halos forming through merging of star-rich progenitors either before (Zone 4) or after (Zone 1) the end of reionization. Their systematically higher Z is a consequence of self-enrichment by a substantial ($M_* \approx 10^6 - 10^{9.5} M_\odot$) population of long-living stars. Similarly, the high [C/Fe] ratios reflect the strong contribution by AGB stars. The gas mass in these DLAs is $M_g = 10^7 - 10^{9.5} M_\odot$, thus resulting in higher $N_{\rm HI}$ values, despite of the lower formation z and larger $M_h \approx 10^{8-11} M_\odot$ (eq. 1). Note however that the $N_{\rm HI}$ derived for these DLAs must be interpreted as an upper limit. In fact, $M_h > M_{sf}$ objects (Fig. 3) are actively star-forming at $z = 2.34$, with $\dot{M} \approx (0.1 - 10) M_\odot {\rm yr}^{-1}$, and hence part of their gas is presumably ionized. Moreover, the [Fe/H] value ([C/Fe]) has to be interpreted as a lower (upper) limit, since the contribution by SN type Ia may be significant in star-rich DLAs (Calura, Matteucci & Vladilo 2002). The same interpretation has to be applied to [Fe/H] measurements, as Fe is depleted onto dust grains (Noterdaeme et al. 2008). Barred these limitations, included the unknown number of surviving satellites, we note that the apparent concentration of [Fe/H]> -2 DLAs in a small region of the $N_{HI} - Fe$ plane (Fig. 4) implies that these absorbers are only partially representative of the progenitors of MW-like systems (Pontzen et al. 2008).

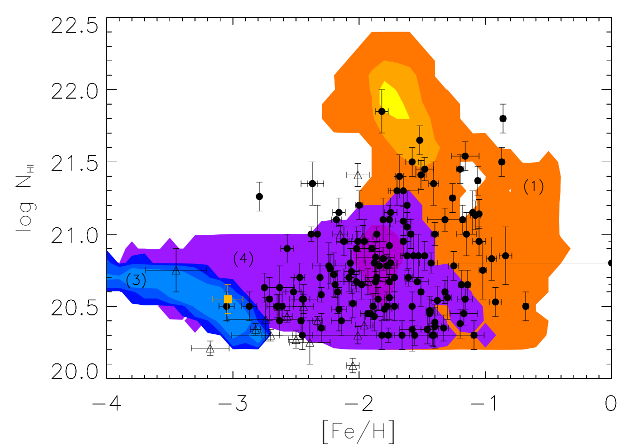

Figure 4. $N_{\rm HI}$ distribution vs. iron abundances of DLAs. Points with error-bars are observed values for metal-poor DLAs at $z_{abs} = (1.9 - 4.9)$ (circles, Prochaska et al. 2007), VMP DLAs at $z_{abs} = (2.07 - 4.21)$ (triangles, Cooke+2011b) and for the C-enhanced DLA at $z_{abs} = 2.34$ (square, Cooke+2011a). The color shaded areas show the results of the model for the three different populations of DLAs predicted to exist at $z = 2.34$ (see Fig. 3).

5 DISCUSSION

The recently discovered $z_{abs} \approx 2.34$ C-enhanced DLA pertains to a new class of systems, dubbed PopIII DLAs, hosting the first stars along with second generations of long-living stars. These systems are associated to H_2-cooling minihalos that virialize at $z > 8$ in neutral and primordial regions of the MW environment, and only experience a short period of SF before the increasing LW background burns out their H_2. Once "sterilized" these minihalos passively evolve as an inert gas reservoir, $M_g \approx 10^{5.5} - 10^{6.3} M_\odot$, retaining the imprint of the stellar generations they hosted. Their gas temperature, T_g, is regulated by the balance between molecular/metal radiative cooling and photo-heating by the external ionizing radiation (Black 1981):

$$n_{HI}\ \Lambda(T_g, Z) = \langle\epsilon\rangle K_{ph} \qquad (2)$$

where n_{HI} is the gas density, $\Lambda(T_g, Z)$ the gas cooling rate (Maio et al. 2007), $\langle\epsilon\rangle \approx 20$ eV the mean UV background photon energy, and K_{ph} the optically-thick H I photo-ionization rate (Abel & Mo 1998). $K_{ph} \approx 4.1 \times 10^{-15} J_{21}(N_{HI}/10^{19}\mathrm{cm}^{-2})^{-\beta}\mathrm{s}^{-1}$ with $\beta = 1.6$ and $J_{21} = 1$. We find that [Fe/H]> -6 minihalos have $T_g \approx (40 - 1100)\mathrm{K} < T_{vir}$, implying that these systems can likely *survive* photo-evaporation thanks to self-shielding and metal cooling. Their gas temperature increases with decreasing metallicity, in agreement with the results by Kanekar et al. (2009). The C-enhanced DLA has $T_g \approx 70$ K while in [Fe/H]≈ -5 ($Z \approx 10^{-4} Z_\odot$) systems $T_g \approx 1000$ K.

The peculiar abundance pattern observed in the $z_{abs} \approx 2.34$ DLA does not result from $Z = 0$ faint SNe, but rather from the enrichment by low-metallicity SNII and AGB stars, which may start to form as soon as $Z > Z_{\rm cr} = 10^{-5\pm1} Z_\odot$. While SNII nucleosynthetic products are mostly lost in winds, AGB metals are retained in the ISM, causing a dramatic increase of [C/Fe]. The chemical evolution of [Fe/H]> -5 DLAs is *independent* on the assumed yields and IMF of PopIII stars, confirming the role of ordinary PopII stars in driving the enrichment of VMP systems (SSF07), recently emphasized by the detection of a $Z \leq 5 \times 10^{-5} Z_\odot$ star with a "normal" chemical abundance pattern (Caffau et al. 2011). If $Z_{cr} < 10^{-4} Z_\odot$, as suggested by the existence of such star, the PopIII-PopII transition would be even quicker. The mass of relic stars in PopIII DLAs is found to be $M_* \approx 10^{2-4} M_\odot$, implying that they are the gas-rich counterpart of the faintest dSphs.

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 Inter Galactic Medium, and actively forming PopIII stars. Since the total mass of the star-forming DLA is $M_h > 10^{9.5} M_\odot \approx M_{sf}(z = 2.3)$, strong feedback is required to substantially remove the initial gas mass and match the observed $N_{\rm HI}$. By determining the dark matter 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, prevent 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, $\approx 0.01\%$, thus explaining the rarity of these systems.

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