Revisiting the origin of the high metallicities of sub-damped Lyman-alpha systems

Miroslava Dessauges-Zavadsky,† Sara L. Ellison2 and Michael T. Murphy3

1Observatoire de Genève. Université de Genève, 51 Ch. des Maillettes, 1290 Sauverny, Switzerland
2Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 1A1, Canada
3Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Mail H39, PO Box 218, Victoria 3122, Australia

Accepted 2009 March 23. Received 2009 February 15

ABSTRACT
Sub-damped Lyman-alpha systems (sub-DLAs) have previously been found to exhibit a steeper metallicity evolution than the classical damped Lyman-alpha systems (DLAs), evolving to close to solar metallicity by \( z \sim 1 \). From new high-resolution spectra of 17 sub-DLAs, we have increased the number of measurements of [Fe/H] at \( z < 1.7 \) by 25 per cent and compiled the most complete literature sample of sub-DLA and DLA abundances to date. We find that sub-DLAs are indeed significantly more metal-rich than DLAs, but only at \( z < 1.7 \); the metallicity distributions of sub-DLAs and DLAs at \( z > 1.7 \) are statistically consistent. We also present the first evidence that sub-DLAs follow a velocity width–metallicity correlation over the same velocity range as DLAs, but the relation is offset to higher metallicities than the DLA relation. On the basis of these results, we revisit the previous explanation that the systematically higher metallicities observed in sub-DLAs are indicative of higher host galaxy masses. We discuss the various problems that this interpretation encounters and conclude that in general sub-DLAs are not uniquely synonymous with massive galaxies. We rule out physically related sources of bias (dust, environment, ionization effects) and examine systematics associated with the selection and analysis of low-redshift sub-DLAs. We propose that the high metallicities of sub-DLAs at \( z < 1.7 \) that drives an apparently steep evolution may be due to the selection of most low-redshift sub-DLAs based on their high Mg\( II \) equivalent widths.

Key words: ISM: abundances – galaxies: ISM – quasars: absorption lines.

1 INTRODUCTION
Quasar absorption line (QAL) systems are very valuable tools for the census of metals from the present epoch all the way back to the farthest detectable quasars [quasi-stellar objects (QSOs)]. Much attention has recently been directed towards the sub-damped Lyman-alpha systems (sub-DLAs), QAL systems with H\( I \) column densities in the range \( 10^{19} < N(\text{H} I) < 2 \times 10^{20} \text{cm}^{-2} \). The sub-DLAs outnumber the higher H\( I \) column density damped Lyman-alpha systems (DLAs) by factors of 4–8 and may therefore contribute significantly to the cosmological metals budget. Two major surveys for high-redshift sub-DLAs have been undertaken (Dessauges-Zavadsky et al. 2003; Péroux et al. 2005), and recently much effort has been dedicated to building up a sub-DLA sample at \( z < 1.7 \) (Meiring et al. 2006, 2007, 2008, 2009; Péroux et al. 2006a, 2008). These surveys have yielded abundance measurements ([Fe/H] or [Zn/H]) for 30 and 35 sub-DLAs at redshifts above and below \( z = 1.7 \), respectively.

*Based on observations collected at the European Southern Observatory, Chile, under programmes ID No. 078.A–0003(A) and 080.A–0014(B).
†E-mail: miroslava.dessauges@unige.ch

Péroux et al. (2003) were the first to point out a stronger metallicity evolution with time in sub-DLAs than DLAs. This has been further supported by the enlarged sample of sub-DLAs and has led Kulkarni et al. (2007) to conclude: (1) the mean metallicity of sub-DLAs is higher than that of DLAs and reaches a near-solar level at \( z \leq 1 \). Several sub-DLAs at low redshifts even exhibit solar or supersolar abundances (Péroux et al. 2006b; Prochaska et al. 2006), while no DLA is known so far with such a high metallicity. (2) The contribution of sub-DLAs to the total metal budget may be several times greater than that of DLAs at \( z < 1 \). Nevertheless, sub-DLAs seem to contribute no more than a few per cent of the total amount of metals in the Universe at \( z \sim 2.5 \) (Péroux et al. 2007).

The difference in metallicity between sub-DLAs and DLAs has led Khare et al. (2007) to suggest that sub-DLAs and DLAs may be associated with two distinct populations of galaxies. Indeed, since high metallicities are generally associated with more massive galaxies according to the mass–metallicity relation (Tremonti et al. 2004; Savaglio et al. 2005; Erb et al. 2006; Maiolino et al. 2008), Khare et al. (2007) concluded that sub-DLAs may arise in massive spiral/elliptical galaxies and DLAs in low-mass (<10\( ^9 \text{M}_\odot \)) galaxies.

In this Letter, we form the largest sample of low-redshift sub-DLAs with abundance determinations, and we present evidence...
against the hypothesis that sub-DLAs are in general associated with massive galaxies.

2 SAMPLES, OBSERVATIONS, COLUMN DENSITIES

Our sample of sub-DLAs consists of 17 systems at $z < 1.7$ chosen from the compilation of Rao, Turnshek & Nestor (2006).1 We have obtained high-resolution [full width at half-maximum (FWHM)] $\approx 7–8 \text{ km s}^{-1}$, high signal-to-noise ratio (S/N > 10 per pixel from 3300 to 6800 Å) spectra with the Ultraviolet-Visual Echelle Spectrograph (UVES) on the Very Large Telescope (VLT) Kueyen European Southern Observatory (ESO) telescope at Cerro Paranal, Chile and the High Resolution Echelle Spectrometer (HIRES) on the Keck I telescope at Mauna Kea, Hawaii. Our sample is supplemented with two additional sub-DLAs at $z > 1.7$ towards QSOs B0216+08 and B1037–270 retrieved from the UVES ESO/ST-ECF Science Archive Facility.2 We reduced the UVES and HIRES echelle spectra using, respectively, the publicly available UVES-popler pipelines3 and the xidl HIRED redux pipeline.4 The ionic column densities were measured using the Voigt profile fitting technique and the $\chi^2$ minimization routine FITLYMAN in MIDAS. The H I column densities were taken from Rao et al. (2006) obtained from Hubble Space Telescope (HST) spectra, except for the sub-DLA towards QSO B2048+196 for which we considered the revised $N$(H i) value by Meiring et al. (2009). For the two sub-DLAs at $z > 1.7$ towards QSOs B0216+08 and B1037–270, the $N$(H i) were obtained from UVES archive spectra. A complete description of the data acquisition, reduction and full abundance analysis will be presented in a forthcoming paper (Dessauges-Zavadsky et al., in preparation).

In Table 1, we summarize our sub-DLA sample and the derived abundances of Fe and Zn. The sample includes six new sub-DLAs with close to solar metallicities ($\approx 1/5$ solar) and three systems with supersolar metallicities. With these new data, we enlarge the sample of sub-DLAs at $z < 1.7$ with metallicity measurements ([Fe/H] or [Zn/H]) by 25 per cent, bringing it to a total of 47 systems; 32 systems at $z > 1.7$ complete the sub-DLA sample (for references, see Section 1). For comparison, we use our compilation of DLA metallicity measurements, the most complete to date, which accounts 27 systems at $z < 1.7$ and 144 at $z > 1.7$ (Dessauges-Zavadsky et al., in preparation).

3 RESULTS

Zn is often favoured as a metallicity indicator in gas-phase studies, since it is nearly undepleted and traces Fe very closely in Galactic stars (e.g. Pettini et al. 1999). However, there are still very few [Zn/H] measurements available, particularly in sub-DLAs at high redshifts (6 [Zn/H] measurements at $z > 1.7$). Conversely, [Fe/H] abundances are available for the majority of absorbers. Although Fe is depleted on to dust grains, the distributions of [Zn/Fe] ratios in sub-DLAs and DLAs at $z < 1.7$ are statistically consistent (Kolmogorov–Smirnov (KS) confidence level (c.l.) to reject the null-hypothesis = 23 per cent; see Dessauges-Zavadsky et al., in preparation). This suggests that sub-DLAs and DLAs (at least at low redshifts) have, on average, similar differential dust depletion levels. Hence, we should still be able to compare the sub-DLA and DLA metallicities and evolution thereof differentially, even if the absolute values are affected by dust depletion.

Fig. 1 shows the [Fe/H] measurements obtained in sub-DLAs and DLAs plotted as a function of redshift. The large black and red crosses represent, respectively, the weighted mean metallicities, $\langle [\text{Fe/H}] \rangle$, of sub-DLAs in five redshift bins containing 16 or 12 systems each and of DLAs in six redshift bins containing 27 or 26 systems each. The 1σ errors of the means include sampling and measurement uncertainties and are calculated using the statistical techniques described in Kulkarni & Fall (2002). The weighted mean metallicities as well as the H I column density weighted mean metallicities, $\langle [\text{Fe/H}] \rangle = \log \frac{\sum \log(N(_{\text{HI}}))}{\sum N(_{\text{HI}})}$, derived in each redshift bin are tabulated in online material. The unweighted means refer to the average metallicity of galaxies, while the H I

---

Table 1. New sub-DLA systems.

| QSO name | Other name (J2000) | $V$ [mag] | $z_{\text{QSO}}$ | $z_{\text{sub-DLA}}$ | Instrument | log $N$(H i) [cm$^{-2}$] | [Fe/H] | [Zn/H] |
|----------|--------------------|----------|-----------------|---------------------|------------|----------------|--------|--------|
| QSO B0009–016 | J001210.9–012208 | 17.6 | 1.998 | 1.3861 | UVES/VLT | 20.26 ± 0.02 | −1.39 ± 0.04 | < −2.02 |
| QSO J0021+0043 | J002133.3+004300 | 17.7 | 1.245 | 0.5203 | UVES/VLT | 19.54 ± 0.03 | −1.82 ± 0.05 | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... |
| QSO J0157–0048 | J015733.8–004824 | 17.9 | 1.548 | 1.4157 | UVES/VLT | 19.90 ± 0.07 | −0.78 ± 0.08 | −0.43 ± 0.11 |
| QSO B0216+080 | J021857.3+081728 | 18.1 | 2.996 | 1.7687 | UVES archive | 20.20 ± 0.10 | −1.17 ± 0.10 | −0.81 ± 0.16 |
| QSO B0352–275 | J033540.6–272420 | 17.9 | 2.823 | 1.4054 | UVES archive | 20.18 ± 0.15 | −0.53 ± 0.15 | +0.05 ± 0.15 |
| QSO B0424–131 | J042707.3–130254 | 17.5 | 2.166 | 1.4080 | UVES archive | 19.04 ± 0.04 | −1.04 ± 0.04 | < −0.84 |
| QSO J1109–0026 | J100930.5–002618 | 17.4 | 1.244 | 0.8428 | UVES/VLT | 20.20 ± 0.06 | −1.17 ± 0.06 | < −1.41 |
| ... | ... | ... | ... | ... | ... | ... | ... | ... |
| QSO J1028–0100 | J102837.1–010028 | 18.2 | 1.531 | 0.6321 | UVES/VLT | 19.95 ± 0.07 | −0.34 ± 0.08 | < −0.20 |
| ... | ... | ... | ... | ... | ... | ... | ... | ... |
| QSO B1037–270 | J103921.9–271916 | 17.4 | 2.193 | 2.1395 | UVES archive | 19.60 ± 0.10 | −0.35 ± 0.10 | −0.05 ± 0.10 |
| QSO J1054–0020 | J105441.0–002048 | 18.3 | 1.021 | 0.9513 | UVES archive | 19.28 ± 0.02 | −0.12 ± 0.02 | −0.19 ± 0.05 |
| QSO B1327–206 | J133007.8–205617 | 17.0 | 1.165 | 0.8514 | UVES archive | 19.40 ± 0.02 | −0.95 ± 0.04 | −0.46 |
| QSO J1525+0026 | J152510.6+002633 | 17.0 | 0.801 | 0.5674 | HIRES/Keck | 19.78 ± 0.08 | −1.04 ± 0.10 | ... |
| QSO B2048+196 | J205112.7+195007 | 18.5 | 2.367 | 1.1161 | HIRES/Keck | 20.00 ± 0.15 | −0.23 | +0.33 ± 0.09 |
| QSO J2352–0028 | J235253.5–002852 | 18.2 | 1.628 | 0.8730 | HIRES/Keck | 19.18 ± 0.09 | −1.13 ± 0.11 | < 0.22 |
| ... | ... | ... | ... | ... | ... | ... | ... | ... |

Note: Values reported as lower limits refer to saturated lines and values reported as upper limits correspond to 4σ non-detections.

---

1 Since the submission of this Letter, Meiring et al. (2009) have obtained data for a smaller sub-DLA sample with which we have four QSOs in common.

2 Programmes ID No. 65.P–0038(A), 69.B–0108(A), 70.A–0017(A), 71.B–0136(A), 072.A–0346(A) and 073.B–0787(A).

3 http://astronomy.swin.edu.au/~mmurphy/UVES_popler

4 http://www.ucolick.org/~xavier/HIRedux/index.html

© 2009 The Authors. Journal compilation © 2009 RAS, MNRAS 396, L61–L65

by guest on 30 July 2018
The high metallicities of sub-DLAs

weighted means refer to the mass-weighted metallicity of neutral gas. Since the bulk of N(H I) is not in sub-DLAs, the unweighted means are the appropriate quantity to trace and compare the metallicity evolution of the two samples of absorbers.

Clearly, the mean [Fe/H] metallicity of sub-DLAs at low redshifts is substantially larger than that of DLAs by about 0.7 dex (4σ significance level). At z > 1.7, the mean metallicity of sub-DLAs drops by 0.5 dex and reaches a value similar to the mean metallicity of DLAs. This reveals two major differences in the metallicity evolution of sub-DLAs and DLAs. First, the sub-DLAs show a more rapid metallicity evolution with time than the DLAs. Performing a least-square fit to the unweighted mean [Fe/H] metallicity versus redshift data points, we find for sub-DLAs a slope $m = -0.41 \pm 0.07$ dex/Δz and a zero point $b = -0.26 \pm 0.13$ dex, while the slope for DLAs is less than half this value, $m = -0.19 \pm 0.04$ dex/Δz, with a zero point $b = -1.03 \pm 0.09$ dex. The best-fitting slopes to the H I weighted mean metallicities are identical within statistical uncertainties, both for sub-DLAs and DLAs, to the slopes derived for the unweighted mean metallicities. They underline the robustness of this result, previously claimed by Péroux et al. (2003, 2007) and Kulkarni et al. (2007).

Secondly, the metallicity difference between sub-DLAs and DLAs is confined to low redshifts. This is well illustrated in the two panels on the right-hand side of Fig. 1 that show the [Fe/H] distributions of sub-DLAs and DLAs in two separate redshift intervals, z ≤ 1.7 and z > 1.7. At z < 1.7, sub-DLAs are clearly more metal-rich than DLAs, while at z > 1.7 this large metallicity difference is no longer apparent (see the respective cumulative functions). The KS test shows that the null-hypothesis that the metallicities of the low-redshift sub-DLAs and DLAs are drawn from the same population can be rejected at 99.9992 per cent c.l. This c.l. falls to an inconclusive 90 per cent for the metallicity distributions of the high-redshift sub-DLAs and DLAs. This suggests that at high redshifts sub-DLAs have similar metallicities to DLAs, which diverge from that of DLAs at low redshifts only. With a mean metallicity $[Zn/H] = +0.18 \pm 0.11$ in sub-DLAs and $[Zn/H] = -0.66 \pm 0.09$ in DLAs at $z < 1.7$, the $[Zn/H]$ measurements further confirm the bias of low-redshift sub-DLAs towards higher metallicities relatively to DLAs.

Figure 1. [Fe/H] metallicities of 76 sub-DLAs (black filled circles) and 161 DLAs (red open squares) plotted as a function of redshift, with the area of each symbol inversely scaled to the 1σ error on the abundance. The large black and red crosses correspond, respectively, to the unweighted mean metallicities of sub-DLAs and DLAs. In each bin, the mean is plotted at the median redshift, with the horizontal bars indicating the redshift range spanned by the systems in that bin. The least-square fits to the unweighted means are shown by the black solid line for sub-DLAs and the red solid line for DLAs. For comparison, the dashed line gives the metallicity evolution of the star-forming galaxies (Li 2008). The two plots on the right-hand side show the [Fe/H] distributions of sub-DLAs (shaded histograms) and DLAs (open histograms) with their respective cumulative functions in two separate redshift intervals, z < 1.7 (upper panel) and z > 1.7 (lower panel).

Ledoux et al. (2006) found a correlation between the velocity widths, Δv, of lines of low-ionization species and metallicities, over two orders of magnitude in metallicity, for DLAs and a few high-N(H I) sub-DLAs at 1.7 < z < 4.3. Assuming that Δv is a measure of mass, it has been suggested that this velocity width–metallicity relation may be the consequence of an underlying mass–metallicity relation, consistent with the mass–metallicity relation observed for local and high-redshift galaxies (for references, see Section 1). The mass–metallicity relation for DLAs has, in addition, been recently reproduced from simulations by Pontzen et al. (2008).

Fig. 2 shows the velocity widths and metallicities for sub-DLAs and DLAs of our sample and our literature compilation. The velocity widths of lines of low-ionization species were derived following the prescriptions of Ledoux et al. (2006). With our enlarged sample of sub-DLAs, it can be seen that sub-DLAs also exhibit a correlation between the velocity widths and metallicities over the same range of Δv as DLAs (Kendall’s tau probability of 0.016 per cent), but with a slightly larger scatter than DLAs and offset to higher metallicities by 0.4–0.6 dex at a given Δv (see the linear least-square bisector fits). The KS test shows that the null-hypothesis that the velocity widths...
of sub-DLAs and DLAs are drawn from the same population can be rejected at only 92 per cent c.l. Our results therefore contrast with the conclusions drawn from smaller sub-DLA samples: (i) Bouchez (2008) argued that sub-DLAs have roughly constant metallicities as a function of the Mg II equivalent width (EW); and (ii) Meiring et al. (2007) obtained a velocity width–metallicity relation in which all the low-redshift sub-DLAs were confined to the upper-right corner of Fig. 2, with high metallicities and larger velocity widths. Although there is still a tendency for sub-DLAs to have higher velocity widths (59 per cent of sub-DLAs have $\Delta v > 100 \, \text{km} \, \text{s}^{-1}$ compared to 43 per cent of DLAs), Fig. 2 clearly shows that sub-DLAs inhabit the same $\Delta v$ range as DLAs.

4 DISCUSSION AND CONCLUSIONS

With our enlarged sample of sub-DLAs, we conclude: (1) sub-DLAs have a more rapid metallicity evolution with time than DLAs (in agreement with previous studies); (2) sub-DLAs are significantly more metal-rich than DLAs, but only at $z < 1.7$; and (3) sub-DLAs follow a velocity width–metallicity correlation, although the relation is offset to higher metallicities than the DLA relation.

On the basis of the high metallicities observed in sub-DLAs and the existence of a mass–metallicity relation amongst galaxies at $0 < z < 3$, Khare et al. (2007) proposed that sub-DLAs arise in more massive galaxies than DLAs. With the new data presented in this Letter, this interpretation encounters a number of problems.

The first problem is directly related to the main argument that led Khare et al. (2007) to link sub-DLAs to massive galaxies, namely the mass–metallicity relation and the velocity width–metallicity relation. If the velocity width of lines of low-ionization species in the velocity width–metallicity relation of Ledoux et al. (2006) is a proxy for mass and sub-DLAs are associated mostly with massive galaxies, we expect sub-DLAs to exhibit almost exclusively large velocity widths. As discussed above and illustrated in Fig. 2, sub-DLAs actually have velocity widths that span the full range of values of DLAs.

The second difficulty with the identification of sub-DLAs with massive galaxies is to reconcile their metallicity evolution with the now popular scenario of ‘downsizing’. In this paradigm, massive galaxies build up their stellar mass and metals at earlier epochs than lower mass galaxies and already are relatively metal-rich by $z \sim 2$ (e.g. Panter et al. 2008). Contrary to what is expected of massive galaxies, sub-DLAs are fairly metal-poor at high redshifts and only develop their metallicities at $z < 1.7$ (see Fig. 1). Moreover, the relative rates of sub-DLA and DLA metallicity evolution are inconsistent with a simple division in mass (see e.g. fig. 3 of Panter et al. 2008). However, when splitting our full sample of sub-DLAs plus DLAs by their velocity width (and not their $N$(H I)), we observe at high redshifts, $z > 2$, that systems with $\Delta v > 100 \, \text{km} \, \text{s}^{-1}$ have higher metallicities ($[\text{Fe/H}] = -1.29 \pm 0.07$) than systems with $\Delta v < 100 \, \text{km} \, \text{s}^{-1}$ ($[\text{Fe/H}] = -1.53 \pm 0.18$). The KS test shows that the null-hypothesis that the metallicities of these two sub-samples of absorbers at $z > 2$ are drawn from the same population can be rejected at 99.9991 per cent c.l. This result is in line with the expectations of both the downsizing picture and the velocity width as a proxy for mass also supported by the recent simulations of Pontzen et al. (2008). Neither sub-DLAs nor DLAs appear as the dominant feature of the sub-sample of absorbers at $z > 2$ with $\Delta v > 100 \, \text{km} \, \text{s}^{-1}$ or the sub-sample of absorbers at $z > 2$ with $\Delta v < 100 \, \text{km} \, \text{s}^{-1}$; the former (the latter) sub-sample is composed of 22 per cent (19 per cent) sub-DLAs and 78 per cent (81 per cent) DLAs. This suggests that the $N$(H I) limit between sub-DLAs and DLAs is not simply due to a distinction in mass.

The third objection to the massive galaxy hypothesis is the slope of the metallicity evolution of sub-DLAs which appears to be much steeper than that of luminous (massive) star-forming galaxies at $1 < z < 3$ (e.g. Li 2008, and see the dashed line in Fig. 1).

Finally, the fourth inconsistency in connecting sub-DLAs with massive galaxies is that they outnumber DLAs by a factor of up to 8, whereas massive galaxies are far less common than low-mass galaxies. Even when assuming that only the most metal-rich sub-DLAs arise in massive galaxies, at $z < 1.7$ more than 70 per cent of sub-DLAs have $[\text{Zn/H}]$ metallicities $> 2.5$ solar and hence lead to a too large proportion of massive galaxies. Although massive gas-rich galaxies may have a higher absorption cross-section, Rosenberg & Schneider (2003) have shown that in the local Universe the number density of DLAs is still dominated by sub-$M_\odot$ galaxies.

So, how can the high metallicities of the low-redshift sub-DLAs be explained? It has often been suggested that dust in the higher column density DLAs leads to an observed distribution of metallicities that is biased towards low values. Indeed, if dust extinction is a strong function of the metal column density as observed in interstellar medium clouds (e.g. Vladilo 2004), the metal-rich DLAs may be more affected by dust selection than metal-rich sub-DLAs (Vladilo & Péroux 2005; Meiring et al. 2008; Péroux et al. 2008). Such an effect could make DLAs appear less metal-rich than sub-DLAs. So far, however, there is no evidence at either high or low redshifts for a large number of high-extinction DLAs with elevated metallicities (e.g. Ellison et al. 2001; Murphy & Liske 2004; Ackerman et al. 2005; Ellison, Hall & Lira 2005; Pontzen et al. 2008; Pontzen & Pettini 2009) that would be required to explain the $+0.7$ dex difference in metallicity between the low-redshift sub-DLAs and DLAs. Most recently, Ellison & Lopez (2009) found that dust depletions in $0.6 < z < 1.7$ sub-DLAs and DLAs in the complete Optical and Radio Absorption Line System (CORALS) survey are consistent with magnitude limited samples.

Can large-scale physical differences account for the metallicity differences between low-redshift sub-DLAs and DLAs? Recently, Ellison et al. (2008) have shown that for a given mass, galaxies are more metal-rich if they have smaller half-light radii or lower specific star formation rates. Ellison et al. (2009b) have also shown that galaxies in dense environments have slightly higher metallicities. However, the metallicity offsets for both effects are far too small ($\sim 0.05$ dex) to explain the differences between sub-DLAs and DLAs we observe.

What about photoionization effects? The lower H I column densities of sub-DLAs may imply that the neutral hydrogen is partially ionized, in which case the observed Fe II to H I ratio may not be a robust measure of the total [Fe/H] abundance. The magnitude of these corrections is quite sensitive to the ionizing background, leading to some variation amongst results in the literature (Dessauges-Zavadsky et al. 2003; Prochaska et al. 2006; Meiring et al. 2007, 2008; Péroux et al. 2007). Substantial ionization corrections are, however, certainly needed in some sub-DLAs. The larger difference between the median $N$(H I) of sub-DLAs and DLAs at low rather than high redshifts$^5$ and the change in the shape of the ionizing background between $z \sim 3$ and $z \sim 1$ also raise the possibility that the typical ionization corrections for sub-DLAs may be higher at $z < 1.7$ than $z > 1.7$. However, there is currently no strong evidence to support this as an explanation for the much steeper evolution of sub-DLA metallicities. In general, ionization corrections

---

$^5$ The difference between the median $N$(H I) of sub-DLAs and DLAs is 1.04 dex (0.76 dex) at $z < 1.7$ ($z > 1.7$) with the median log $N$(H I) of sub-DLAs being equal to 19.81 (19.94).
sub-DLAs are similar when calculated with a Haardt–Madau spectrum at both $z \sim 3$ and $z \sim 0.5$ (Milutinovic, private communication) and Meiring et al. (2007, 2008) found corrections that are typically $<0.2$ dex for their low-redshift sub-DLAs.

Having ruled out physically related sources of bias (dust, environment and ionization corrections), we consider systematics associated with the selection and analysis of low-redshift sub-DLAs. This is additionally motivated by our finding that the sub-DLAs only show significant enhancement in $[\text{Fe}/\text{H}]$ at redshifts that require HST observations of the Lyα line. Ellison, Murphy & Dessauges-Zavadsky (2009a) have investigated possible systematic uncertainties in the H I column density determinations of sub-DLAs from low-resolution spectra in comparison to high-resolution spectra. They have found that $N(\text{H} I)$ derived from low-resolution spectra tend to be overestimated by typically 0.1 dex (up to 0.3 dex), but in the wrong direction to explain the high metallicities observed in the low-redshift sub-DLAs.

Next, we consider the process through which the majority of our low-redshift sub-DLAs were identified: the Mg II EW selection. Most of the low-redshift sub-DLAs in both this study and the literature come from compilations of sub-DLAs that have been obtained as a ‘by-product’ of low-redshift DLA searches. These DLA surveys have used metal lines to pre-select candidate DLAs from ground-based spectra for HST follow-up. Rao et al. (2006) have found that there are no DLAs in their unbiased sample (i.e. excluding previously known 21-cm absorbers) with rest-frame Mg II $\lambda 2796$ EWs lower than 0.6 Å. Pre-selecting candidate DLAs based on their Mg II EWs therefore appears to be a reasonable selection strategy of EWs lower than 0.6 Å. Pre-selecting candidate DLAs based on their Mg II EWs tends to be overestimated by typically 0.1 dex (up to 0.3 dex), but in the wrong direction to explain the high metallicities observed in the low-redshift sub-DLAs.

In Fig. 3, we show the rest-frame Mg II $\lambda 2796$ EWs and metallicities for sub-DLAs and DLAs at $z < 1.7$ of our sample and the sample of Ellison et al. (2009a). Clearly, sub-DLAs are metal-rich for their Mg II EWs compared with the DLAs, and this despite that the Mg II $\lambda 2796$ EW distributions of sub-DLAs and DLAs at $z < 1.7$ are statistically consistent (see their cumulative functions; KS c.l. to reject the null-hypothesis = 10 per cent). This offset can be explained in terms of kinematics. Ellison (2006) and Ellison et al. (2009a) showed that (low-redshift) sub-DLAs have higher velocity widths for a given Mg II EW than DLAs (parametrized by the D-index). Since we have already shown that $\Delta v$ is correlated with metallicity in sub-DLAs (Fig. 2), we then expect that sub-DLAs selected on their high Mg II EWs will have higher metallicities. We conclude that the Mg II selection bias is a viable explanation for the systematically higher metallicities in low-redshift sub-DLAs (but for a contrasting opinion, see Kulkarni et al. 2007). The ultimate test of this explanation would be to conduct a blind sub-DLA survey at $z < 1.7$.

In summary, we conclude that in general sub-DLAs are not uniquely synonymous with massive galaxies and that their high metallicities observed at $z < 1.7$ that drives an apparently steep evolution may be due to selection effects.

ACKNOWLEDGMENTS

We are grateful to Nikola Milutinovic for supplying results from his Cloudy models, and we thank Max Pettini and Jason X. Prochaska for very helpful exchanges. MD-Z is supported by the Swiss National Funds and SLE by an NSERC Discovery grant. MTM thanks the Australian Research Council for a QEII Research Fellowship (DP0877998).

REFERENCES

Akerman C. J. et al., 2005, A&A, 440, 499
Bouché N., 2008, MNRAS, 389, L18
Dessauges-Zavadsky M. et al., 2003, MNRAS, 345, 447
Ellison S. L., 2006, MNRAS, 368, 335
Ellison S. L., Lopez S., 2009, MNRAS, submitted
Ellison S. L. et al., 2001, A&A, 379, 393
Ellison S. L., Hall P. B., Lira P., 2005, AJ, 130, 1345
Ellison S. L. et al., 2008, ApJ, 672, L107
Ellison S. L., Murphy M. T., Dessauges-Zavadsky M., 2009a, MNRAS, 392, 998
Ellison S. L. et al., 2009b, MNRAS, in press (arXiv:0903.4684)
Erb D. K. et al., 2006, ApJ, 644, 813
Khare P. et al., 2007, A&A, 464, 487
Kulkarni V. P., Fall S. M., 2002, ApJ, 580, 732
Kulkarni V. P. et al., 2007, ApJ, 661, 88
Ledoux C. et al., 2006, A&A, 457, 71
Li L.-X., 2008, MNRAS, 388, 1487
Maiolino R. et al., 2008, A&A, 488, 463
Meiring J. D. et al., 2006, MNRAS, 370, 43
Meiring J. D. et al., 2007, MNRAS, 376, 557
Meiring J. D. et al., 2008, MNRAS, 384, 1015
Meiring J. D. et al., 2009, MNRAS, 393, 1513
Murphy M. T., Liske J., 2004, MNRAS, 354, L31
Panter B. et al., 2008, MNRAS, 391, 1117
Péroux C. et al., 2003, MNRAS, 345, 480
Péroux C. et al., 2004, MNRAS, 352, 1291
Péroux C. et al., 2005, MNRAS, 363, 479
Péroux C. et al., 2006a, MNRAS, 372, 369
Péroux C. et al., 2006b, A&A, 450, 53
Péroux C. et al., 2007, MNRAS, 382, 177
Péroux C. et al., 2008, MNRAS, 386, 2209
Pettini M. et al., 1999, ApJ, 510, 576
Pontzen A. et al., 2008, MNRAS, 393, 557
Ponette A. et al., 2008, MNRAS, 390, 1349
Prochaska J. X. et al., 2006, ApJ, 648, L97
Rao S. M., Turnshek D. A., Nestor D. B., 2006, ApJ, 636, 610
Rosenberg J. L., Schneider S. E., 2003, ApJ, 585, 256
Savaglio S. et al., 2005, ApJ, 635, 260
Tremonti C. A. et al., 2004, ApJ, 613, 898
Vladilo G., 2004, A&A, 421, 479
Vladilo G., Péroux C., 2005, A&A, 444, 461

This paper has been typeset from a TeX/LaTeX file prepared by the author.