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Do damped and sub-damped Lyman-alpha absorbers arise in galaxies of different masses?

Varsha P. Kulkarni [a,*], Pushpa Khare [b], Debopam Som [a], Joseph Meiring [c], Donald G. York [d], Celine Péroux [e], James T. Lauroesch [c]

[a] Department of Physics and Astronomy, University of South Carolina, Columbia, SC 29208, USA
[b] Department of Physics, Utkal University, Bhubaneswar 751004, India
[c] Department of Physics and Astronomy, University of Louisville, Louisville, KY 40292, USA
[d] Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA
[e] Laboratoire d Astrophysique de Marseille, OAMP, UniversiteAix-Marseillé and CNRS, 13388 Marseille cedex 13, France

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ABSTRACT

We consider the questions of whether the damped Lyman-alpha (DLA) and sub-DLA absorbers in quasar spectra differ intrinsically in metallicity, and whether they could arise in galaxies of different masses. Using the recent measurements of the robust metallicity indicators Zn and S in DLAs and sub-DLAs, we confirm that sub-DLAs have higher mean metallicities than DLAs, especially at $z \lesssim 2$. We find that the intercept of the metallicity-redshift relation derived from Zn and S is higher than that derived from Fe by 0.5–0.6 dex. We also show that, while there is a correlation between the metallicity and the rest equivalent width of Mg II λ2796 or Fe II λ2599 for DLAs, no correlation is seen for sub-DLAs. Given this, and the similar Mg II or Fe II selection criteria employed in the discovery of both types of systems at lower redshifts, the difference between metallicities of DLAs and sub-DLAs appears to be real and not an artefact of selection. This conclusion is supported by our simulations of Mg II λ2796 and Fe II λ2599 lines for a wide range of physical conditions. On examining the velocity spreads of the absorbers, we find that sub-DLAs show somewhat higher mean and median velocity spreads (Δv), and an excess of systems with $\Delta v > 150$ km s^{-1}, than DLAs. Compared to DLAs, the [Mn/Fe] vs. [Zn/H] trend for sub-DLAs appears to be steeper and closer to the trend for Galactic bulge and thick disk stars, possibly suggesting different stellar populations. The absorber data appear to be consistent with galaxy down-sizing. The data are also consistent with the relative number densities of low-mass and high-mass galaxies. It is thus plausible that sub-DLAs arise in more massive galaxies on average than DLAs.

1. Introduction

The evolutionary history of galaxies is written in part in the interstellar abundances of the chemical elements. Deciphering this history from observations of distant galaxies is an important aspect of understanding the various processes responsible for evolution of galaxies. Besides the stellar mass function, yields, supernova rates, etc., the metallicity of a galaxy is also governed by the depth of its gravitational potential well, which determines the ability to retain the metals produced from star formation. Indeed, the interstellar metallicity (as determined from nebular emission lines) is found to be correlated tightly with the stellar mass of the galaxy at $z \sim 0$ and also at $0.4 < z < 3$ (e.g., Tremonti et al., 2004; Savaglio et al., 2005; Erb et al., 2006).

Quasar absorption lines provide a powerful complementary tool for studying distant galaxies. The damped Lyman-alpha (DLA; log $N_{HI} \geqslant 20.3$) and sub-damped Lyman-alpha (sub-DLA; $19.0 \leqslant$ log $N_{HI} < 20.3$) absorbers are the primary neutral gas reservoir at $0 < z < 5$ (e.g., Storrie-Lombardi and Wolfe, 2000; Péroux et al., 2005; Prochaska et al., 2005), and offer the most precise element abundance measurements in distant galaxies.

As per most chemical evolution models, the mean interstellar metallicity of galaxies should reach a near-solar value at low redshift, as a result of progressive generations of star formation. Surprisingly, most DLAs observed at $0.1 < z < 3.9$ are metal-poor (e.g., Kulkarni et al., 2005, 2007; Prochaska et al., 2007, and references therein). By contrast, a substantial fraction of the sub-DLAs observed at $0.6 < z < 1.5$ are metal-rich, some even super-solar (e.g., Kulkarni et al., 2007; Meiring et al., 2008, 2009a,b; Péroux et al., 2006, 2008, and references therein). Based on the observed mass-metallicity relation for galaxies, Khare et al. (2007) suggested that

* Corresponding author. Tel.: +1 803 777 6293; fax: +1 803 777 3065.
E-mail address: kulkarni@sc.edu (V.P. Kulkarni).

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the sub-DLAs may be more massive compared to DLAs. Here we examine various selection effects that could potentially be responsible for this conclusion with an updated sample of DLA/sub-DLA metallicities, and compare other properties of DLAs and sub-DLAs. We use the nearly undepleted elements Zn and S, which makes our analysis "cleaner" and more conservative than studies based on depleted elements such as Fe. This also allows us to make meaningful comparisons of the observed DLA/sub-DLA metallicity evolution with known trends for galaxies.

2. Sample description, observed trends, and metallicity indicator

2.1. Sample description

Comparison of the metallicity evolution of DLA and sub-DLA galaxies was made in Kulkarni et al. (2007) based on Zn data for 119 DLAs and 30 sub-DLAs. In this paper, we examine this issue further using Zn and S for 154 DLAs and 58 sub-DLAs. The twofold increase in the number of sub-DLAs since 2007 has come primarily from our recent measurements (20 systems from Meiring et al. (2008), Péroux et al. (2008) and Meiring et al. (2009a)), complemented by a few measurements from the literature (Nestor et al., 2008; Quast et al., 2008; Noterdaeme et al., 2008; Dessauges-Zavadsky et al., 2009). To avoid any prior bias toward high or low metallicity, we exclude systems which were specifically observed because of hints that they are rich in metals or molecules. (Thus, we exclude two metal-rich sub-DLAs from Prochaska et al. (2006), one metal-rich sub-DLA from Srianand et al. (2008), and the metal-strong DLAs from Herbert-Fort et al. (2006). In any case, we note Kulkarni et al. (2007) showed that adding the metal-strong systems did not change the conclusions about relative evolutions of DLAs and sub-DLAs.).

2.2. Observed trends

Fig. 1 shows the N_{HI}-weighted mean metallicity vs. look-back time relation for the 154 DLAs and 58 sub-DLAs in our sample, calculated using the procedures outlined in Kulkarni and Fall (2002). Upper limits on Zn have been treated with survival analysis. Also shown for reference are the predictions for metallicity evolution in two theoretical models. The light dot-dashed curve shows the mean interstellar metallicity in the chemical evolution model of Pei et al. (1999) with the optimum fit for the cosmic infrared background intensity. This model also uses observational constraints from optical galaxy surveys and the comoving HI density of DLAs to calculate the coupled global evolution of stellar, gaseous, and metal content of galaxies. The light dot-double-dashed curve shows the mean metallicity of cold interstellar gas in a semianalytic model of galaxy formation in the cold dark matter merging hierarchy by Somerville et al. (2001). This model, referred to as the "collisional starburst model" by Somerville et al. assumes star formation in bursts triggered by galaxy mergers in addition to a quiescent star formation at constant efficiency.

The sub-DLA global mean metallicity appears to be higher than that of DLAs, reaching a near-solar value at low z, consistent with the models (see also York et al., 2006; Prochaska et al., 2006). The linear regression slope for the sub-DLA N_{HI}-weighted mean metallicity vs. redshift data (-0.46 ± 0.18) appears to be steeper than that for DLAs (-0.22 ± 0.07). The slope for sub-DLAs has larger uncertainties due to the smaller sample size. The corresponding linear regression estimates of the intercepts, i.e. expected metallicities at $z = 0$, are 0.18 ± 0.29 for sub-DLAs and -0.63 ± 0.16 for DLAs, which differ at 2.4 σ level. The bold curves in Fig. 1 show the best fits to the DLA and sub-DLA data (plotted in terms of look-back time). The results do not change substantially if the

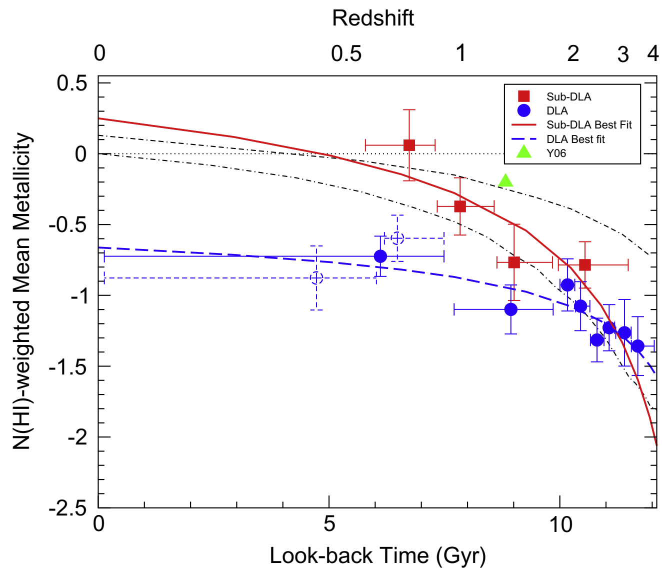

Fig. 1. N(H I)-weighted mean metallicity vs. look-back time relation for 154 DLAs and 58 sub-DLAs with Zn or S measurements. Filled circles show 8 bins with 19 or 20 DLAs each. Unfilled circles refer to the lowest time bin for DLAs split into 2 bins with 10 DLAs each. Squares denote 4 bins with 14 or 15 sub-DLAs each. Horizontal bars denote ranges in look-back times covered by each bin. Vertical error bars denote 1 σ uncertainties. The triangle shows the formal lower limit to the average metallicity for a composite spectrum from 698 absorbers with average log $N_{\rm H\,I} \sim 20$ (sample 24) from York et al. (2006). The bold solid and dashed curves show the best fits obtained from linear regression of the metallicity vs. redshift data for sub-DLAs and DLAs, respectively. The light dot-dashed and dot-double-dashed curves show, respectively, the mean metallicity in the models of Pei et al. (1999) and Somerville et al. (2001). Sub-DLAs appear to be more metal-rich and faster-evolving than DLAs, especially at lower redshifts.

metallicities are unweighted (a slope of -0.47 ± 0.16 and an intercept of 0.22 ± 0.24 for sub-DLAs, and a slope of -0.25 ± 0.05, intercept of -0.47 ± 0.11 for DLAs.) Below some redshift around 2, the mean metallicity of sub-DLAs exceeds that of DLAs. Determining exactly where that happens (e.g., at $z < 1.7$ or $z < 2.2$) will require a larger database.

2.3. The choice of the metallicity indicator

We have used measurements of Zn or S, since these nearly undepleted elements offer the most direct "dust-free" metallicity

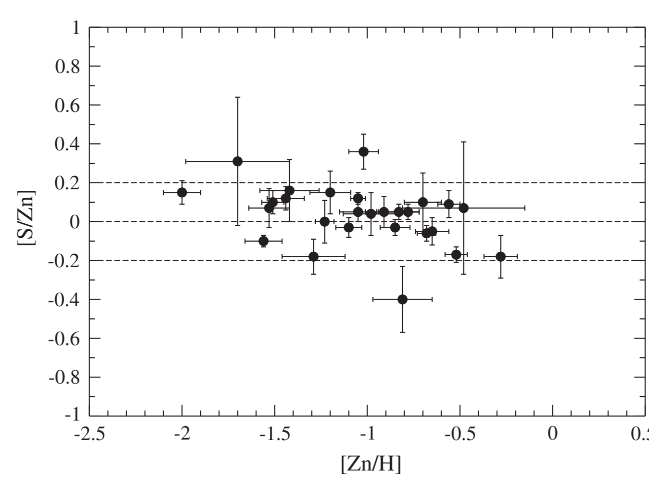

Fig. 2. [S/Zn] vs. [Zn/H] for absorbers with detections of S and Zn. Dashed horizontal lines denote the solar level and ±0.2 dex levels. S/Zn tracks the solar ratio within ±0.2 dex for most of the absorbers.