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Evolution of metals and dust in the universe*

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Abstract. With the aim of determining the evolution of metals and dust in the universe, we have observed 8 Damped Lyman-alpha Absorbers (DLAs) with the Multiple Mirror Telescope and the Hubble Space Telescope at $0.1 < z < 1.5$, including several absorbers discovered in the Sloan Digital Sky Survey. These measurements have more than doubled the sample of Zn and Cr measurements at $z < 1.5$ and added three measurements at $z < 0.4$, where none existed before. In contradiction with the predictions of most chemical evolution models, our data suggest that the global mean metallicity of DLAs, as measured by the gas phase abundance of Zn, at best evolves weakly with redshift over the range $0.09 < z < 3.9$ and does not seem to rise to the solar level even at very low redshifts. The dust content, as determined by [Cr/Zn], does not show much change with redshift.

Keywords : cosmology: observations – galaxies: abundances – galaxies: evolution – quasars: absorption lines

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1. Introduction

Observations of the UV luminosity density of galaxies in the redshift surveys and the Hubble Deep Field studies indicate that the global average star formation rate and, therefore, the chemical enrichment rate of galaxies was high at z $\geq$ 1.5. Most cosmic chemical evolution models (e.g., Malaney and Chaboyer 1996; Pei, Fall, and Hauser 1999; Somerville, Primack and Faber 2001) thus, predict that the global mean interstellar metallicity in galaxies rises from nearly zero at high redshifts to nearly solar at $z = 0$. It is of great importance to determine whether the observed global mean metallicities of galaxies agree with predictions of the cosmic chemical evolution models.

Damped Lyman-alpha absorption systems (QSO absorption systems with HI column density $\geq 2 \times 10^{20}$ cm^{-2}; hereafter DLAs) have been used to determine the evolution of the gas phase abundances in the universe because (1) it is believed that DLAs constitute most of the neutral gas in the galaxies at high redshifts, enough to form all stars visible today (Wolfe et al. 1995), (2) in the absence of selection effects, DLAs are expected to provide an unbiased sample of normal galaxies as they are selected only through the presence of large amounts of neutral hydrogen, (3) DLAs have sufficiently large amounts of neutral hydrogen so that ionization corrections for H, Zn, Cr etc are relatively small, and (4) DLAs are our principal source of information about the metal content of interstellar matter in galaxies over 80% of the age of the universe.

A large number of elements have been observed in DLAs. In particular, Fe, Zn, Si, S and O have been used as probes of the metallicity in these systems. We prefer to use Zn to determine the total (gas + solid phase) metallicity in DLAs because (1) Zn tracks Fe in most Galactic stars, (2) it is relatively undepleted on interstellar dust grains, and (3) the lines of the dominant ionization species, Zn II, are most often unsaturated. Abundances of depleted elements such as Cr, Fe or Ni relative to Zn probe the dust content of the absorbers.

The issue of metallicity evolution in DLAs has not been fully understood, the main reason for the uncertainty being the small number of measurements, especially at z $<$ 1.5 (Kulkarni and Fall 2002). This is because, though for $0.6 < z < 1.3$, the Zn II lines can be accessed with ground-based telescopes, they lie in blue wavelengths where many spectrographs have lower sensitivity. Also, the Ly α for $z < 1.5$ and the Zn II lines for $z < 0.5$ can only be accessed with space telescopes.

With the aim of enhancing the DLA sample at $z < 1.5$ we have observed 8 DLAs with the 6.5 m Multiple Mirror Telescope (MMT) and the Hubble Space Telescope (HST), with $0.09 < z < 1.36$, the results for which we present here. The observations are presented in section 2 and the results are presented in section 3.

Table 1. Target DLAs and abundances.

QSO	z_{em}	z_{abs}	[Zn/H]	[Cr/Zn]
Q0738+313	0.635	0.0912	< -1.1	>-0.1
Q0738+313	0.635	0.2212	<-0.7	>-0.7
Q0827+243	0.939	0.5247	<-0.0	...
Q0952+179	1.472	0.2378	<-1.0	>-0.6
Q0933+733	2.525	1.4790	-1.6	-0.2
SDSS J110729.03+004811.1	1.392	0.7405	-0.6	-0.3
SDSS J172739.03+530229.1	1.444	0.9449	-0.5	-0.4
SDSS J172739.03+530229.1	1.444	1.0311	-1.4	-0.3

2. Observations

Our MMT sample originally consisted of 11 quasar absorbers at $0.09 < z < 1.5$, for which either a damped Ly α line was observed in HST spectra, or a strong DLA was expected on the basis of Mg II or Fe II lines (Rao and Turnshek 2000) available in the SDSS Early Data Release spectra (Schneider et al. 2002). In particular, we chose systems that have $W^{\rm rest}_{\rm MgII2796} > 1.0$ Å, $W^{\rm rest}_{\rm FeII2344} > 0.8$ Å and some other indicator of high $N_{\rm HI}$ (Fe I, C I, Mg I, Mn II, Ni II, Ca II, Cr II, Zn II or Si II λ1808). Later, HST observations of Ly α lines in these systems (HST GO project No. 9382; PI: S. Rao) confirmed the DLA nature of several of these absorbers while 3 others were found to be sub-DLAs (systems with HI column density between $10^{19} - 2 \times 10^{20}$ cm^{-2}). For HST observations, the sample consisted of confirmed DLAs with $0.09 < z < 0.52$. Table 1 lists the relevant properties of the observed "classical DLAs" i.e. systems with log $N_{\rm HI} \geq 20.3$. Data reduction was done with Image Reduction and Analysis Facility and Space Telescope Science Data Analysis System. For MMT data the Zn II λ 2026 line and Mg I λ 2026 line as well as the Zn II λ 2062 line and Cr II λ 2062 line are blended together. A profile fitting analysis was performed for these lines along with the lines $\lambda\lambda$ 2056 and 2066 of Cr II simultaneously, assuming the velocity dispersion parameter to be the same for all these ions. Wherever necessary, the column density of Mg I was obtained from the equivalent width of Mg I λ 2853 line observed in the SDSS spectra, using the b value obtained for the unblended Cr II lines.

3. Results and discussion

The abundances of Zn and those of Cr relative to Zn for the DLAs in our sample are given in Table 1. For most of the systems, even for those at the lowest redshifts, the abundances of Zn are sub-solar. The only super-solar abundance that we have obtained is for the system with redshift of 0.716 toward SDSS J1323-0021 which has neutral hydrogen column density of 1.6×10^{20} cm^{-2} and hence is a sub-DLA.

To examine the implications of our data for the mean metallicity-redshift relation of DLAs, we combined our data with other Zn measurements at higher redshifts. We only included the classical DLAs in our study and, also, excluded systems with radial velocities within 3000 km s^{-1} from the quasar emission redshifts, since these systems may be associated with the QSOs and may not represent intervening population of galaxies. The combined sample contains a total of 87 DLAs with Zn detections or limits, in the redshift range $0.09 < z < 3.90$. We have normalized them all to the same set of oscillator strengths and solar abundances that we have used for our data.

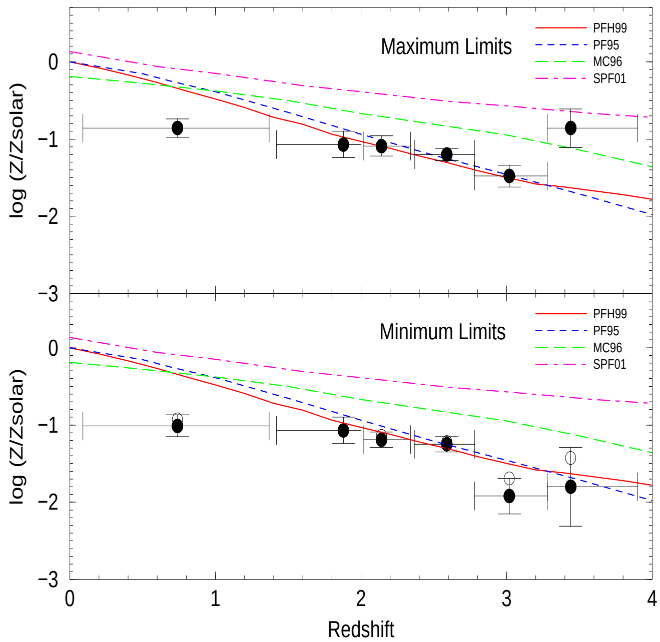

Figure 1. The global metallicity-redshift relation deduced from damped Ly-α absorbers. The circles show the logarithm of the $N_{\rm HI}$-weighted mean Zn metallicity relative to the solar value vs. redshift for the sample of 87 DLAs. The filled circles in the top and bottom panels show, respectively, the metallicity for the maximum-limits and minimum-limits cases. The unfilled circles in the bottom panel show the metallicity obtained by using elements other than Zn to constrain the metallicities in cases of Zn limits. Vertical error bars denote 1 σ uncertainties. Horizontal bars show the bin extent. Each point is plotted at the median redshift in its bin. The short-dashed, long-dashed, solid, and short-dash-long-dashed curves show, respectively, the mean metallicity (not corrected for dust obscuration) in the cosmic chemical evolution models of Pei and Fall (1995), Malaney and Chaboyer (1996), Pei et al. (1999), and Somerville et al. (2001).

Of the 87 systems in the combined sample, 51 are detections and 36 are limits. We constructed two extreme samples, a "maximum-limits" sample, treating the Zn limits as detections, and a "minimum-limits" sample treating the Zn limits as zeros. For any individual system, these cases cover the full range of possible values the Zn column densities can take. For the sake of pictorial illustration, we divided each of these samples into six redshift bins with 14 or 15 absorbers each. Results are shown in Figure 1. Clearly, the N_{HI}-weighted mean metallicity of DLAs does not rise fast enough to reach solar or near-solar metallicities at $z = 0$.

For the binned data (with six bins in the range $0.09 < z < 3.90$), the linear regression slope of the logarithm of the metallicity vs. redshift relation is -0.18 ± 0.06 for the maximum-limits sample and -0.22 ± 0.08 for the minimum-limits sample. The linear regression intercept of the metallicity-redshift relation (which corresponds to predicted present-day metallicity) is -0.74 ± 0.15 for the maximum-limits sample, -0.75 ± 0.18 for the minimum-limits sample. The results change very little if the Zn upper limits are replaced with the constraints from other elements.

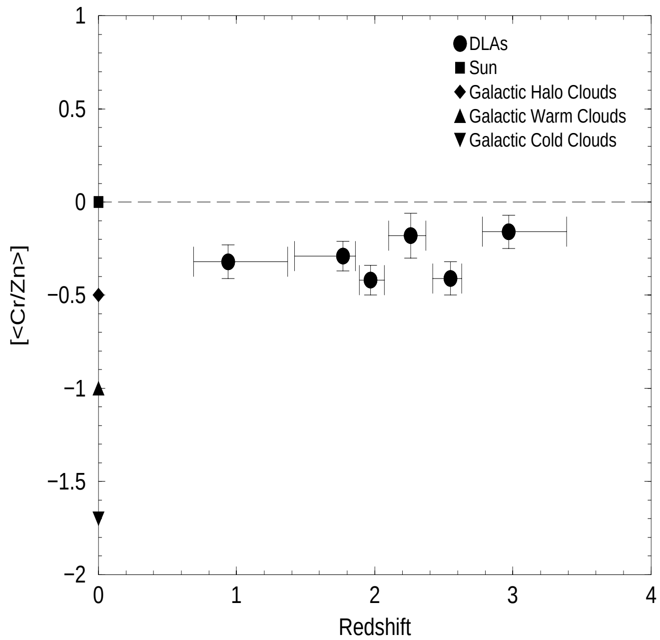

Figure 2. Binned unweighted mean of logarithmic abundance of Cr relative to Zn $\langle[\mathrm{Cr/Zn}]\rangle$ vs. redshift for DLAs from our sample and other data from the literature. The zero level denotes the solar level.

The refractory elements such as Si, Ti, Cr, Mn, Fe, Co, and Ni are expected to be depleted if the DLAs contain dust, while volatile elements like Zn are almost undepleted in interstellar clouds. [Cr/Zn] is, therefore, taken to be a measure of the amount of dust. The values obtained for our sample are given in Table 1. To study the redshift evolution of the dust content we combined our data with those from the literature. As before we only used the classical DLAs which were separated by > 3000 km s^{-1} from the QSO redshift. We, also, excluded cases where only upper or lower limits are available for Cr and/or Zn, and scaled the measurements to the same set of oscillator strengths for the Zn II and Cr II lines used by us. In Fig. 2, we plot [Cr/Zn] vs. redshift for this combined sample of 41 DLAs. Our MMT data have provided 4 new [Cr/Zn] measurements for DLAs at $z < 1.5$ and nearly doubled the existing sample of [Cr/Zn] measurements at these redshifts. In addition our MMT data have provided [Cr/Zn] ratio for one candidate DLA and three sub-DLAs . A linear regression fit to the unbinned [Cr/Zn] vs. redshift data gives a slope of 0.07 ± 0.01, and an intercept of -0.48 ± 0.02 implying a slow decrease in [Cr/Zn] with decreasing redshift.

To summarize, in all the 3 DLAs at $z < 0.4$ for which our observations offer meaningful constraints on the Zn abundance, the metallicities appear to be substantially sub-solar ($\leq 10 - 20\%$ solar). The global mean metallicity of DLAs shows at most a slow increase with decreasing redshift and does not appear to rise up to solar or near-solar values at $z = 0$ in contradiction with the chemical evolution models. This suggests that the observed DLAs, especially those at low redshifts, probably differ from the general population of galaxies represented by the global star formation history of the universe.

This weak evolution in the DLA global mean metallicity could be partially explained by the fact that our sample at redshifts smaller than 0.6 seems to be dominated by dwarf or low surface brightness galaxies. It is possible that current DLA samples, especially those at low redshifts, are biased against more enriched galaxies because the latter may cause more dust obscuration of the background quasars. We note, however, that the low-redshift samples are still small, and the fact that most of the DLAs in our sample are metal-poor could be an effect of small number statistics. Metallicity measurements of more low-redshift DLAs are necessary to further improve the statistics of the mean metallicity-redshift relation and to study the scatter around the mean. Observations of low-redshift DLAs toward optically faint quasars are especially necessary in the future to improve the constraints on the mean metallicity-redshift relation for DLAs, and to quantify potential dust selection effects.

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