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Evolution of Stars and Metals in Damped Lyman-alpha Galaxies

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Abstract. A unique tool to investigate distant young galaxies is to study the absorption lines they produce in the spectra of background quasars. The damped Lyman-alpha (DLA) quasar absorption line systems allow us to empirically trace galaxy evolution. We discuss results of abundance surveys of DLAs and their implications for the evolution of the global metallicity in galaxies. We also describe deep imaging studies with the Hubble Space Telescope (HST) and ground-based facilities, directed at investigating the luminosities and star formation rates of the absorbers. These observations are helping to clarify the absorber-galaxy connection, and shedding light on the evolution of stars and metals in normal galaxies over the past 80% of the cosmic history.

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

1. Introduction

One of the important goals of modem astrophysics is to understand how galaxies form and evolve and how the production of elements proceeds in young galaxies. The average star formation history of the Universe has been estimated from emission properties of galaxies detected in deep imaging and redshift surveys such as the Canada-France Redshift Survey and the Hubble Deep Field (e.g., Lilly et al. 1996; Madau et al. 1996, 1998). This emission history of galaxies is tied intimately to the history of gas consumption and metal production in galaxies, because the global densities of gas, metals, and stars are coupled through conservation type relations. Constraining the history of metal production thus puts constraints on the histories of star formation and gas consumption.

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Unfortunately, it is difficult to directly determine the chemical composition of normal galaxies at cosmologically significant redshifts. Flux-limited imaging surveys and even other methods such as the Lyman-break technique preferentially pick out the brighter and more actively star-forming galaxies. In principle, a less biased sampling of distant galaxies can be obtained by means of the absorption lines they superpose in the radiation from background quasars. By measuring the strengths of the absorption lines, it is possible to study the composition of the intervening galaxies. Since the absorption line strengths depend mainly on the gas column densities along the line of sight, the method is expected to give a random sample of galaxies irrespective of their apparent brightnesses.

The DLA absorption systems in quasar spectra are those that show radiation damping wings in the Lyman-alpha line, and, as such, have high H I column densities $N_{\rm HI} \geq 2 \times 10^{20}$ cm^{-2}. The DLAs contain most of the neutral gas in galaxies, nearly enough to form all of the stars visible today (Wolfe et al. 1995). DLAs are therefore believed to be progenitors of present-day galaxies and play an important role in studies of galaxy evolution.

2. Evolution of Metallicity

The Lyman-alpha damping wings in DLAs enable accurate determinations of the H I column densities. Furthermore, it is possible to measure absorption lines of a large number of elements. DLAs therefore have the best determinations of element abundances among the quasar absorbers, and in fact, are presently our principal source of information about the chemical content of normal high-z galaxies. Zn is a good probe of the total (gas + solid phase) metallicity in DLAs because Zn tracks Fe in most Galactic stars, it is undepleted on interstellar dust grains, and the lines of the dominant ionization species Zn II are unsaturated. Abundances of depleted elements such as Cr, Fe or Ni relative to Zn probe the dust content (e.g., Pettini et al. 1997a; Kulkarni et al. 1997). Several studies of element abundances in DLAs have been carried out using 4-m and 8-m class optical telescopes (e.g., Meyer et al. 1989; Lu et al. 1996; Kulkarni et al. 1996, 1997, 1999; Pettini et al. 1994, 1997b; Prochaska & Wolfe 1999, 2000; Prochaska et al. 2001).

In principle, a study of [Zn/H] in DLAs as a function of redshift can probe evolution of interstellar metallicity in galaxies. In particular, the $N_{\rm HI}$-weighted mean metallicity,

$$\overline{Z} = \frac{\Sigma N({\rm Zn\ II})_i / \Sigma N({\rm H\ I})_i}{({\rm Zn/H})_\odot} Z_\odot, \quad (1)$$

measures the global mean metalicity (Kulkarni & Fall 2002). Most cosmic chemical evolution models (e.g., Malaney & Chaboyer 1999; Pei et al. 1999) predict the global metallicity to rise from nearly zero at high z to nearly solar at $z = 0$. The present-day mass-weighted mean metallicity of local galaxies is also nearly solar (Kulkarni & Fall 2002). DLAs should follow this behavior if they trace an unbiased sample of galaxies.

It is therefore of great interest to ask whether or not DLAs actually show an increase in the global mean metallicity with decreasing redshift. Surprisingly, there has been great debate about

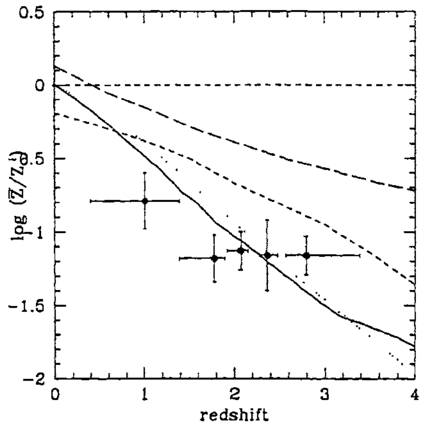

Figure 1. Global metallicity-redshift relation, i.e. N(HI)-weighted mean Zn metallicity vs. redshift for published DLA data (Kulkarni & Fall 2002). Vertical error bars denote 1 σ uncertainties. Horizontal "error bars" denote redshift spreads of points in each bin. Horizontal dashed line denotes solar level. Short-dashed, dotted, solid, and long-dashed curves show, respectively, the mean metallicity expected in cosmic chemical evolution models of Malaney & Chaboyer (1996), Pei & Fall (1995), Pei et al. (1999), and Somerville et al. (2001).

this issue in the past few years, with most studies advocating no evolution in the global mean metallicity inferred from DLAs. We recently examined this question by compiling a sample of 57 Zn measurements (36 detections and 21 limits) from the literature at redshifts $0.4 < z < 3.4$ (Kulkarni & Fall 2002). This sample includes results from a survey of DLA abundances for $0.6 < z < 2.3$ that we performed with the Multiple Mirror Telescope (MMT; Kulkarni et al. 1999; Ge et al. 2001). We applied a variety of statistical techniques, including a binned linear χ^2 fit to $\bar{Z}$ vs. z, an unbinned N(H I)-weighted nonlinear χ^2 fit to an exponential relation, survival analysis to treat limits on Zn, and a comparison of the observations with models of cosmic chemical evolution.

Fig. 1 shows the N(HI)-weighted mean metallicity $\bar{Z}$ vs. redshift relation. Treating limits with survival analysis, the slope of the metallicity-redshift relation is -0.26 ± 0.10, consistent at $\approx 2 - 3\sigma$ level with both model predictions (-0.25 to -0.61) and with no evolution. The main reason for the large uncertainty in the slope is the small number of measurements available, especially at $z < 1.5$. We are presently carrying out abundance surveys of DLAs at $0.1 < z < 1.5$ using the MMT and the HST. These studies will help to determine whether or not the global metallicity inferred from DLAs shows the rise predicted in the cosmic chemical evolution models. A lack of metallicity evolution would contradict the high global star formation rate (SFR) at $1 < z < 1.5$ inferred from the Hubble Deep Field and other galaxy surveys (e.g., Madau et al. 1996). It would imply that either DLAs systematically trace only metal-poor dwarf or low surface brightness galaxies, or the more metal-rich and dustier DLAs obscure their background quasars.

3. Luminosities and Star Formation Rates

Part of the difficulty in understanding the nature of DLAs is that most attempts to detect and spectroscopically confirm high-z DLA galaxies with $z_{abs} < z_{em}$ have been unsuccessful. It is thus not clear whether high-z DLAs are protospirals (Wolfe et al. 1986; Prochaska & Wolfe 1998), gas-rich dwarfs (York et al. 1986; Matteucci et al. 1997), merging protogalactic pieces (Haehnelt et al. 1998), or low surface brightness galaxies (Jimenez et al. 1999).

With the goal of detecting continuum and line emission from the underlying galaxies and measuring their luminosities and SFRs, we have been carrying out deep imaging studies of high-redshift absorbers. With HST NICMOS, we obtained diffraction-limited images of quasars with DLAs at $z \approx 1.9$, at FWHM of 0.15-0.17″, to search for redshifted H-α line emission and the nearby continuum (Kulkarni et al. 2000, 2001). After careful subtraction of the quasar point spread function, we were able to search regions as close as ~ 0.2″ from the quasar. These high-resolution images show no disks or spheroidal objects, but at best a few compact features (see Figs. 2a and 2b for an example). If these features are associated with the DLAs, the DLAs would be $\approx 1-5$ kpc in size and $\approx 0.6-1.5 \times 10^{10} h_{70}^{-2} L_{\odot}$ in luminosity (for $H_0 = 70\,h_{70}$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$). The limits are even more severe if the features are associated with the quasar host galaxies or are artifacts. Comparing the broad and narrow band images, the 3 σ upper limits on the SFRs are $1.3 - 4.0\ M_{\odot}\ yr^{-1}$. Overall, the data suggest that these high-redshift DLAs may be dwarf or low surface brightness galaxies, contrary to the proto-spiral model.

Recently, we have also started a deep Ly-α survey of absorber fields using the NASA Goddard Space Flight Center's Fabry Perot (FP) imager at the Apache Point Observatory 3.5 m telescope (Kulkarni et al. 2003). Using the FP as a tunable narrow-band filter (400-700 km s^{-1} FWHM), we have reached 3 σ flux sensitivity of 1.0×10^{-17} erg s^{-1} cm^{-2} in integrations of 400-720 minutes per object. Fig. 2c summarizes the SFR measurements from our NICMOS studies, together with those from other searches in the literature for Ly-α and H-α emission in quasar absorbers. The SFR limits based on the lack of Ly-α emission in our APO FP fields are consistent with the lowest limits shown in Fig. 2c. The curves show the predictions of Bunker et al. (1999), for the cross-section-weighted SFR for large proto-spiral disks (LD5) and subgalactic pieces in a hierarchical scenario (H5). These models are based on the closed-box global SFR model of Pei & Fall (1995), which agree with the luminosity density of galaxies from the deep galaxy imaging surveys.

Clearly, most absorbers fall far below the large-disk model predictions, but are more consistent with the hierarchical scenario, suggesting that many of the absorbers may arise in star-forming dwarf galaxies that merged later to form present-day galaxies. However, several of the detections and upper limits, including our FP results, are considerably below even the hierarchical prediction. Further deep imaging studies will shed light on whether this apparent discrepancy is caused by effects of dust extinction, or whether the absorbers have truly low SFRs. A combination of such imaging and spectroscopic studies will help to clarify where quasar absorbers fit in the global picture of galaxy evolution, and help to bring together the absorption and emission views of the Universe.

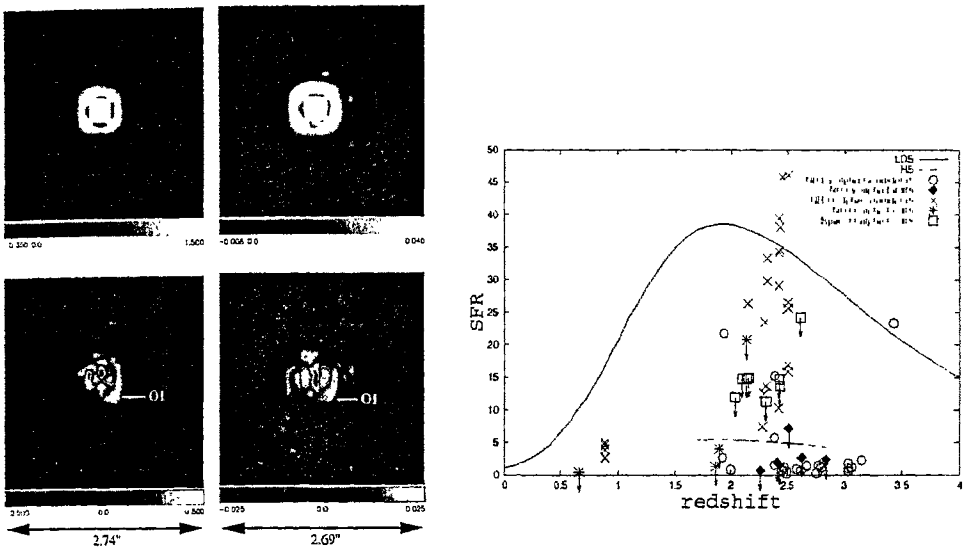

Figure 2. (a) Left: 2.7″ × 2.7″ region of HST NICMOS non-coronagraphic 1.6 μm broad-band image of LBQS 1210+1731, before (top) and after (bottom) PSF subtraction (Kulkarni et al. 2000). (b) Center: 2.7″ × 2.7″ region of the NICMOS non-coronagraphic 1.9 μm narrow-band image of LBQS 1210+1731, before (top) and after (bottom) PSF subtraction. The feature marked O1 denotes a possible candidate for the DLA absorber at $z = 1.89$. (c) Right: Measurements of SFRs (in $M_\odot$ yr^{-1}) for objects in the fields of heavy-element quasar absorption systems, based on narrow-band imaging and spectroscopic searches for Ly-α and H-α emission lines. The data points and 3 σ upper limits are from our NICMOS studies (Kulkarni et al. 2000, 2001) and other sources in the literature. All measurements are normalized to $q_0 = 0.5$ and $H_0 = 70$ km s^{-1} Mpc^{-1}. The solid (upper) and dashed (lower) curves show, respectively, the calculations of Bunker et al. (1999) for the predicted cross-section-weighted SFR in the large-disk and hierarchical scenarios, based on the closed-box global SFR model of Pei & Fall (1995).

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