The Chemical Enrichment History of Damped Lyman-alpha Galaxies

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Abstract. Studies of damped Lyα absorption systems in quasar spectra are yielding very interesting results regarding the chemical evolution of these galaxies. We describe some preliminary results from such a program.

1. Introduction

Damped Lyα absorption systems in quasar spectra are generally believed to trace the absorption from interstellar gas in high-redshift galaxies, possibly from the disks or proto-disks of spirals (Wolfe 1988). They can be studied in the redshift range $0 < z < 5$ by combining UV and optical observations. The damped Lyα galaxies are particularly suited for probing the chemical evolution of galaxies over a large fraction of the Hubble time for several reasons: (1) they are relatively common and easy to identify in quasar spectra, so building up a large sample is possible; (2) given their large neutral hydrogen column densities ($N(\text{HI}) \sim 10^{20} - 10^{22} \text{cm}^{-2}$), most of the absorbing gas should be neutral so ionization corrections should be minimal (cf. Viegas 1995); (3) the damped Lyα galaxies should be relatively representative of galaxies at high redshifts since they are selected simply because they happen to lie in front of background quasars.

The first systematic investigation of the chemical evolution of damped Lyα galaxies was conducted by Pettini and collaborators (Pettini et al. 1994; 1995), who studied the Zn and Cr abundances in $\sim 20$ damped Lyα galaxies. The advent of the 10-m Keck telescope allows us to carry out similar investigations in a much more detailed fashion. In this short contribution, we present some preliminary results from such a program. Detailed analysis and discussion may be found in Lu, Sargent, & Barlow (1996; hereafter LSB96).

2. Results

Figure 1 shows the abundance results so far obtained from our Keck program, with the addition of selected measurements from published papers where we believe the effect of line saturation has been treated properly. We also correct (when applicable) the abundance measurements from previous papers for the set of new oscillator strengths compiled by Tripp, Lu, & Savage (1995) so that all the measurements will be on the same footing. References to the data used in constructing figure 1 may be found in LSB96.
2.1. Age-Metallicity Relation

Figure 1(a) shows the age-metallicity relation for our sample of damped Lyα galaxies (filled circles). The solid curve roughly indicates the age-metallicity relation for disk stars in the Galactic solar neighborhood determined by Eddvardsen et al. (1993). We note the following:

1. The damped Lyα galaxies have Fe-metallicities ([Fe/H]) in the range of 1/10 to 1/300 solar, thus representing a population of very young galaxies at least in terms of the degree of chemical enrichment.

2. The mean metallicity appears to increase with age, providing direct evidence for the buildup of heavy elements in galaxies. It may be significant that all the four galaxies with $z > 3$ have $[\text{Fe/H}] < -1.7$, while at $2 < z < 3$ at least some galaxies have achieved much higher metallicities. This may signal
an epoch of rapid star formation in galaxies. We also note that the intrinsic trend of increasing metallicity with age would be stronger if Fe is somewhat depleted by dust in these galaxies because the depletion should be the least for the highest redshift galaxies (see section 2.2, however).

(3) Clearly the damped Lyα galaxies have much lower metallicities than the Milky Way disk at any given time in the past. This may bear significantly on the nature of the damped Lyα galaxies. It was suggested initially (cf. Wolfe 1988) that the damped Lyα absorbers may trace disks or proto-disks of high-redshift spirals. But the low metallicities of damped Lyα galaxies cast some doubts on this interpretation. Timmes, Lauroesch, & Truran (1995; also see Timmes 1995, this volume) suggested that the abundance measurements of damped Lyα galaxies are consistent with the chemical enrichment history of the Milky Way disk if the enrichment process in damped Lyα galaxies is delayed by \( \sim 3 \) Gyrs for some reason; this seems to place the Milky Way at a privileged position. On the other hand, the metallicities found for our sample of damped Lyα galaxies are very similar to those found for Galactic halo stars and globular clusters, suggesting the possibility that damped Lyα absorbers may represent a spheroidal component of high-redshift galaxies. This possibility has in fact already been suggested by Lanzetta, Wolfe, & Turnshek (1995) based on considerations of gas consumptions in these galaxies.

2.2. Abundance Ratios and Nucleosynthesis

Panels (b)-(f) of figure 1 show the abundance ratios of various elements in damped Lyα galaxies relative to their corresponding solar ratios. Elemental abundance ratios, in principle, allow one to gain insight of what kind of nucleosynthetic processes may be responsible for the enrichment of the interstellar medium. For example, the well-documented overabundance of even-Z (\( Z = \text{atomic number} \) \( \alpha \)-group elements relative to the Fe-peak elements in Galactic halo stars is believed to reflect the nucleosynthetic products of massive stars through SN II explosions (cf. Wheeler, Sneden, & Truran 1989). It is interesting that the observed abundance patterns of N/O, Si/Fe, Cr/Fe and Mn/Fe in damped Lyα galaxies are all consistent with measurements in Galactic halo stars (cf. Wheeler et al. 1989). In particular, we note that the observed N/O ratios are not easily explained with dust depletions because N and O are largely unaffected by dust in the Galactic ISM. The observed Mn/Fe ratios are also difficult to explain with dust depletions because in the Galactic ISM dust depletions cause the gas-phase Mn/Fe ratio to be higher than the solar ratio, opposite to what is observed in damped Lyα galaxies. On the other hand, these ratios are easily understood in terms of the odd-even effect (ie, the odd-Z elements generally show underabundances relative to the even-Z elements of same nucleosynthetic origin at low Fe metallicities) and the different nucleosynthetic origins of these elements (cf. Wheeler et al. 1989). These results strongly indicate that we have observed these galaxies during the epoch when SN II are largely responsible for the enrichment of the interstellar medium in these galaxies, while low mass stars have not had enough time to evolve and to dump their nucleosynthetic products into the interstellar medium through mass loss and SN Ia. Thus the chemical enrichment process in these galaxies should not have proceeded more than 1 Gyr when they were observed.
However, the observed Zn/Fe ratio in damped Ly\(\alpha\) galaxies is inconsistent with the above nucleosynthesis interpretation. In Galactic stars, Zn/Fe is found to be solar at all metallicities (cf. Wheeler et al. 1989 and references therein). This difference may suggest that, while the observed relative abundance patterns in damped Ly\(\alpha\) galaxies are dominated by the effects of nucleosynthesis, there is some dust depletion effect on top of that. The presence of a small amount of dust in damped Ly\(\alpha\) galaxies has been claimed from the reddening of the background quasars (cf. Pei, Fall, & Bechtold 1991). On the other hand, recent theoretical studies indicate that Zn can be produced in large quantities in the neutrino driven winds during SN II explosions (Hoffman et al. 1995; see also Woosley 1995, this volume). Since SN II makes little Fe, a Zn/Fe overabundance may be possible in the ejecta of SN II. The puzzle is then why Zn is observed to track Fe abundance in Galactic stars. If indeed the observed Zn/Fe overabundance in damped Ly\(\alpha\) galaxies is caused by depletion of Fe onto dust grains, the [Fe/H] measurements in figure 1(a) will underestimate the true Fe-metallicities by \(\sim 0.5\) dex (on average).

3. Concluding Remarks

Damped Ly\(\alpha\) galaxies provide the unprecedented opportunity to directly probe the chemical enrichment history of galaxies over a large fraction of the Hubble time. Some intriguing results have already emerged from the current study. However, many questions remain, eg, why do the damped Ly\(\alpha\) galaxies have so low metallicities compared to the past history of the Milky Way disk, and what are the implications? What is the significance of the large scatter in the measured [Fe/H] at any give redshift? How big a role does dust play in modifying the observed abundances and their interpretations? Some of these issues will be addressed in more details in LSB96.

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