ELEMENTAL ABUNDANCES IN QUASAR ABSORPTION LINE SYSTEMS

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Abstract. We discuss elemental abundances in quasar absorption line systems and their implications for galaxy formation and chemical evolution.

1. Introduction

Quasar absorption lines provide a means to probe the physical and chemical conditions in the gaseous component of the universe since the redshift of $z = 5$. The relevance of quasar absorption lines to the topic of this Joint Discussion, "Abundance Ratios in the Oldest Stars", is made clear by the following considerations: at $z = 2 - 5$, the lookback time is about 12-14 Gyrs (assuming 15 Gyrs for the present universe), which roughly corresponds to the time when the Galactic halo was formed. Consequently, studies of quasar absorption line systems at such redshifts may shed new light on the formation and early evolution of the Milky Way and of galaxies in general.

In this short article we will highlight some results concerning elemental abundances in high-redshift ($z > 2$) quasar absorption line systems and discuss their implications for galactic chemical evolution. The focus of the discussion will be on the Lyα forest absorption lines, which trace clouds in the intergalactic medium (IGM), and on the damped Lyα (DLA) absorption systems, which are widely accepted to be the high-redshift counterparts of present-day galaxies. Recent reviews of the general properties of Lyα forest clouds can be found in Weymann (1992), while that of DLA systems are given by Wolfe (1988, 1995).

2. Abundances in Lyα Forest Clouds: Evidence for Pop III Enrichment?

The IGM clouds were thought initially to have primordial compositions since early observations failed to detect any metal absorption lines at the redshifts of Lyα forest clouds. High resolution (FWHM$\sim$ 8 km/s), high S/N ($\sim$ 100) spectra taken recently with the 10m Keck telescopes (Cowie et al 1995; Tytler et al 1995; Songaila & Cowie 1996) clearly revealed the presence of weak C IV absorption at the redshifts of $\sim$ 70% of the Lyα forest clouds with neutral hydrogen column density N(H I)$\geq 3 \times 10^{14}$ cm^{-2} at $2.5 < z < 3.7$. The IGM clouds are known to be highly ionized (neutral fraction H I/H$\sim 10^{-4}$), probably through photoionization by the meta-galactic UV background. From modeling the ionization state of the clouds, Cowie et al (1995), Tytler et al (1995), and Songaila & Cowie (1996) deduced a mean metallicity of [C/H]~ -2 to -2.5, although the results are probably uncertain by as large as a factor of 10 owing to the large ionization corrections. There is also evidence for intrinsic variations in [C/H] from cloud to cloud (Rauch, Haehnelt, & Steinmetz 1997). A factor of 2-3 enhancement in the Si/C ratio seems to be indicated based on the Si IV/C IV ratios observed in some of the clouds (Songaila & Cowie 1996). Similar enhancement has been seen in Galactic halo stars (cf, Wheeler, Sneden, & Truran 1989), suggesting that the metals in the IGM clouds were probably produced by massive stars.

IGM clouds with N(H I)$\geq 3 \times 10^{14}$ cm^{-2} contain nearly half of the total baryon at $z = 2 - 4$ according to cosmological simulations (Miralda-Escude et al 1996; Bi & Davidsen 1997). Hence much

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of the universe was already enriched by $z > 4$. IGM clouds with lower N(H I) may also contain metals, but the corresponding C IV lines would be too weak to be detectable in existing observations. The metals could have been made locally (i.e., expelled from nearby star-forming regions at the same redshift), or by an earlier generation of stars (Population III). Theoretical considerations (eg, Ostriker & Snedin 1996) suggest that Pop III star formation is expected before "normal" galaxies were formed. Hence the Galaxy may have formed out of metal-enriched gas rather than primordial material. Recent observations of extremely metal poor halo stars (McWilliam et al 1995; Ryan, Norris, & Bessell 1996) revealed some very interesting abundance anomaly at [Fe/H]< -2.5, which may reflect the inhomogeneity resulting from the enrichment by only a few supernovae (Audouze & Silk 1995). These stars could be the survivors from the Pop III generation.

3. Abundances in DLA Galaxies: Implications for Galactic Chemical Evolution

Abundance determination for DLA systems began in the late 70's (Smith, Jura, & Margon 1979), but it was only recently that abundance estimates for a large number of systems became available. A summary of the DLA abundance measurements and discussions of their implications can be found in Lauroesch et al (1996). Results from two new surveys have since appeared in press, one by Lu et al (1996) who studied abundances for a large set of elements in a sample of DLA systems using the 10m Keck I telescope, and one by Pettini et al (1997a,b; 1994) who studied the Zn and Cr abundances in a sample of DLA systems. The new surveys represent a significant improvement over previous measurements in terms of both the quantity and quality of the measurements. We will therefore draw material primarily from these new surveys in the following discussion. It is important to point out that the exact nature of high-redshift DLA galaxies remains unclear at present.

3.1. THE DISTRIBUTION OF METALLICITY AS A FUNCTION OF REDSHIFT

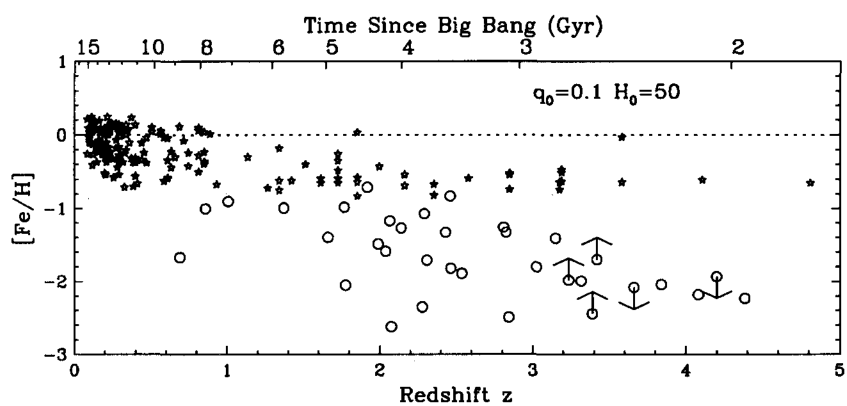

Figure 1. [Fe/H] vs z for damped Lyα systems (open circles) and for Galactic disk stars (star symbols; Edvardsson et al 1993), where [Fe/H]$\equiv$log(Fe/H)$_{DLA}$$-$log(Fe/H)$_\odot$. The stellar ages have been converted into redshifts for a $q_0 = 0.1$ and $H_0 = 50$ cosmology.

Firgure 1 shows the distribution of [Fe/H] vs z for DLA galaxies (open circles). The typical measurement uncertainty on [Fe/H] is ~ 0.1 dex assuming negligible ionization corrections. The sample comprises of the 23 DLA systems from Lu et al (1996), which includes some measurements from the literature, plus 14 new measurements from unpublished Keck observations, including 5 from Wolfe and Prochaska. Some of the new measurements are still preliminary and may be subject to change in the final analysis. However, the changes (if any) are expected to be small and should have no effect on any of the conclusions. The "$\star$" symbols in figure 1 map out the similar relation for a sample of Galactic disk stars in the solar neighborhood (Edvardsson et al 1993).

In general, the DLA galaxies have $-2.5 <$[Fe/H]< -1, corresponding to 1/300 to 1/10 solar metallicity. The N(H I)-weighted mean metallicity is $<$[Fe/H]$> \simeq -1.5$ at $\langle z \rangle = 2.5$. The low metallicities are consistent with them being young galaxies in the early stages of chemical enrichment. The N(H I)-weighted mean metallicity in term of Zn is about a factor of 2-3 (0.4 dex) higher (Pettini et al 1997b), possibility suggesting that some of the Fe atoms are locked up in dust grains in the DLA galaxies (Pettini et al 1997a; also section 3.2).

DLA galaxies appear significantly less metal-enriched than the Galactic disk in its past. Taken at face value, this argues against the suggestion that DLA galaxies are high-redshift (proto-) galactic disks (Wolfe 1988). Rather, the metallicities of the DLA systems are very similar to those of globular clusters and nearby dwarf galaxies. This result may be potentially in conflict with the evidence that DLA systems appear to show kinematics characteristic of fast-rotating ($v_{rot} \sim 250$ km/s) disks (Prochaska & Wolfe 1997). However, the rotating disk interpretation of the DLA kinematics may not be the only possible explanation (Haehnelt, Steinmetz, & Rauch 1997). In addition, the significance of the metallicity discrepancy between the DLA galaxies and the Milky Way disk may still be questioned for several reasons. (1) The ages of the stars in figure 1 at $z > 2$ are uncertain by 2-3 Gyrs from measurement errors alone, and there may also be systematic effects (Edvardsson et al 1993). (2) The true metallicities of DLAs may be higher than that indicated by [Fe/H] if significant dust depletion of Fe has occurred, although this effect alone cannot explain the discrepancy entirely because the inferred depletion of Fe is only $\sim$ 0.4 dex (section 3.2). (3) DLA systems may preferentially probe regions of disk galaxies (assuming they exist at the relevant redshifts) beyond the equivalent of the solar circle owing to their larger absorption cross sections. The metallicity gradient known to exist in local spiral disks (Vila-Costas & Edmunds 1992) may explain the discrepancy (Ferrini, Molla, & Diaz 1997).

The mean metallicity of DLA systems increases gradually from $z > 4$ to $z \sim 2$ as expected. However, there is a factor of $\sim$30 scatter in [Fe/H] at $2 < z < 3$, presumably reflecting differences in the formation epoch/star formation history of the galaxies and/or a mixture of morphological types. The metallicity distribution appears to reach a "plateau" value of [Fe/H]~ -2 to -2.5 at $z > 4$. Coincidentally, this "plateau" metallicity is identical (within the measurement uncertainties) to that found for the IGM clouds at similar redshifts (section 2). This coincidence suggests that the metals in DLA galaxies with [Fe/H]~ -2 to -2.5 may simply reflect those in the IGM, possibly produced by Pop III stars. If this interpretation is correct, then significant star formation did not start in DLA galaxies until $z \sim 3 - 4$. Such an inference is consistent with the decline in the neutral gas content of DLA systems at $z > 3$ (Storrie-Lombardi, McMahon, Irwin 1996), presumably because DLA galaxies are still being formed at such high redshifts; and with the rapid decline in the space density of quasars at $z > 3$ (Schmidt, Schneider, & Gunn 1995). It will be important to study more DLA systems at the highest redshift possible to confirm the reality of the "plateau" metallicity, and to improve the accuracy of the metallicity determination for IGM clouds.

3.2. RELATIVE ABUNDANCES

The abundance ratios of selected elements are plotted against the [Fe/H] of the DLA systems in figure 2, which represents an updated version of a similar figure in Lu et al (1996) but incorporating our new unpublished observations. In principle, abundance ratios of elements can be used to diagnose the nature of the nucleosynthesis (Wheeler et al 1989): were the heavy elements made by Type II supernovae, Type Ia supernovae, AGB stars, or some combination of these processes? However, abundances derived from interstellar absorption lines may not reflect the total abundance of the elements since many elements (e.g., Si, Fe, Cr, Mn) are prone to condensation onto dust grains (Jenkins 1987). Keeping this in mind, the relative abundance patterns shown in figure 2 are very similar to those seen in metal-poor halo stars (cf, Wheeler et al 1989), showing a low N/Fe ratio, an overabundance of Si and S relative to Fe (i.e., enhancement of α-process elements over iron-peak elements), and an underabundance of Mn relative to Fe (i.e., the odd-even effect). The implication is that metal productions in most of the DLA systems under study were probably dominated by massive stars via Type II supernova. However, the observed Zn/Fe ratios in DLA systems, $<$[Zn/Fe]$>\simeq 0.4$ dex, are inconsistent with the abundance pattern seen in halo stars, where [Zn/Fe]$\simeq 0$ for all stars with [Fe/H]> -3. Since Zn is relatively unaffected by dust, while 80-99% of the Fe atoms are usually removed from the gas phase by condensation onto dust grains (Jenkins 1987), the super-solar Zn/Fe ratios found in DLAs suggest that the [Fe/H] values may underestimate the true metallicities of the DLA galaxies by $\sim$ 0.4 dex owing to dust depletion.

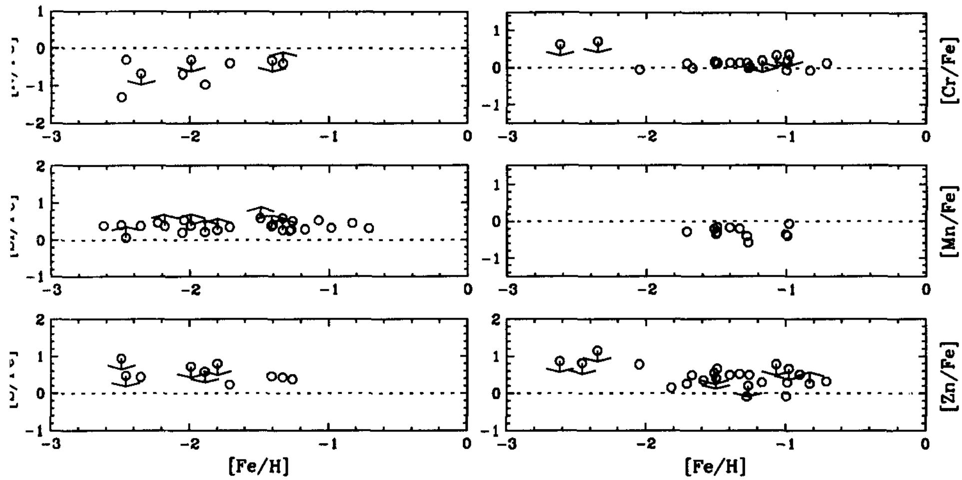

Figure 2. Relative abundance patterns of damped Lyα systems.

Consequently, a full understanding of the DLA abundance patterns must take into account the effect of dust depletion. This issue is discussed in detail elsewhere (cf, Lu et al 1997).

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