JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
29: S35 ~ S38, 1996

GALAXIES AND DUST AT HIGH REDSHIFT

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ABSTRACT

Much of our knowledge about the formation and evolution of high-redshift galaxies has come from studying the absorption signatures they impress on the spectra of background QSOs. The damped Lyman α (DLA) systems, in particular, have proved to be valuable probes of the metallicity and dust at redshifts $z \sim 2$–3 in what are the likely progenitors of galaxies like our own. At $z \sim 2$ we find that the typical metallicity of the universe was 1/15 solar. In addition, we find clear evidence for the existence of trace amounts of interstellar dust in DLA galaxies and show that this is consistent with recent high resolution spectra of DLAs with the Keck telescope, despite claims to the contrary.

Key Words : Galaxies; damped Lyman α; metallicity; dust

I. INTRODUCTION

Searches for the high-redshift counterparts of galaxies like our own have been largely unsuccessful until very recently, despite intense efforts and significant technical advances. Of course, we learned how to find high-z QSOs long ago and, more recently, we learned how to select high-z radio galaxies. For QSOs the techniques were based either on their prominent emission lines or non-thermal continua, while the radio-loud objects provided precisely located beacons for deep directed searches. However, in both cases it is believed that the presence of an active nucleus renders them of limited value in constructing a global picture of galaxy formation and evolution.

The most successful program for detecting 'normal' star-forming galaxies at redshifts $z > 3$ has been that of Steidel et al. (1996, and references therein), based on deep imaging and accurate photometry with a custom-built suite of broadband filters. The search technique rests on assumptions about the spectra of galaxies in the range $z = 3.0$–3.5 which are borne out by deep Keck telescope spectroscopy. The same basic assumptions are built into the analysis by Lanzetta et al. (1996) of the broadband colours of galaxies in the Deep Field images obtained by the Hubble Space Telescope in December 1995, yielding inferred redshifts extending to $z > 6$.

A long-standing and complementary method for studying normal high-z galaxies is through the absorption lines they produce in the spectra of background QSOs. This is a powerful technique which can lead to a wealth of information on parameters such as chemical composition, temperature, metallicity, dust content and star formation rates. In the following sections we introduce an important sub-class of QSO absorption line systems, the damped Lyman α galaxies, and discuss recent observational results pertaining to their chemical evolution and dust content.

II. DAMPED LYMAN α SYSTEMS

The damped Lyman α (DLA) absorption systems are characterised by neutral hydrogen column densities $N(\mathrm{HI}) > 2\times10^{20}$ cm^{-2}. Although relatively rare, it can be shown that the integrated mass of H I in these systems at redshifts $z \sim 2$–3 is directly comparable with the total mass of stars in galaxies today. For this reason they are believed to be the progenitors of present day luminous galaxies—or at least the neutral cores of such galaxies—observed at a time prior to the bulk of star formation, when the gas fraction was high. Further support for this picture comes from the redshift dependence of the H I mass density (Storrie-Lombardi et al. 1995), which appears to peak at $z \sim 3$ and fall steadily towards $z = 0$.

(a) Metallicity

A key property of the DLA systems is their chemical composition. As discussed by Pettini, Boksenberg & Hunstead (1990), in order to use interstellar absorption lines to chart the chemical evolution of high-z galaxies we need to consider both departures from solar relative abundances and selective depletion onto grains. Pettini et al. concluded that the elements best suited to measuring both metal enrichment and dust depletion in DLA galaxies were Zn and Cr. These elements track Fe over a wide range of metallicities but have very different dust depletion properties (Savage & Sembach 1996). Whereas Zn is at most lightly depleted in disk sightlines in the Milky Way, Cr is amongst the most depleted elements, with typically 90–99% in solid form. The Zn/H ratio is therefore a measure of the degree of metal enrichment, while a Cr/Zn ratio falling below the solar value is most naturally interpreted as being due to depletion of Cr onto grains and is therefore an indicator of the presence of interstellar dust.

Over the past six years we have obtained intermediate dispersion spectra for 25 DLA systems covering the

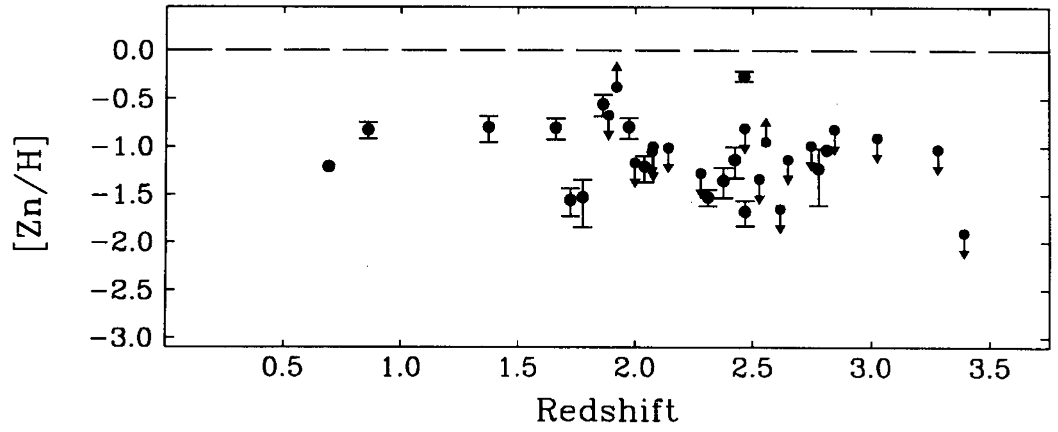

Fig. 1.— The abundance of Zn relative to solar (log scale) as a function of redshift for 30 DLA galaxies. 3σ upper limits, corresponding to non-detection of the Zn II doublet, are indicated by downward pointing arrows. The dashed line corresponds to the solar abundance of Zn.

Zn II $\lambda\lambda$2026,2062 and Cr II $\lambda\lambda$2056,2062,2066 resonance lines using the 4.2m William Herschel Telescope and 3.9m Anglo-Australian Telescope. Our original survey (Pettini et al. 1994) has now been augmented by a further 10 DLAs, together with eight from the literature. As can be seen from Fig. 1, the Zn abundances are generally well below solar, with a column-density-weighted mean metallicity of $\langle$[Zn/H]$\rangle = -1.15$ (1/15 solar) at $z \sim 2$ for the 33 DLA systems. Since the DLA systems dominate the mass density of neutral gas in the universe at this redshift, we can interpret this metallicity as being universal. The large scatter in Zn abundance evidently reflects different rates of chemical enrichment from galaxy to galaxy, combined with a protracted epoch for disk formation (Kauffmann 1996).

(b) Dust in DLA Systems

Turning now to Cr, we find that this element is generally less abundant than Zn by up to a factor of 5, relative to solar. In Fig. 2 we show [Cr/Zn] as a function of the metallicity [Zn/H] for 18 DLA systems, together with equivalent data for Galactic stars (Ryan et al. 1996) and for warm interstellar clouds in the Galactic disk and halo (Savage & Sembach 1996). There is a spread in [Cr/Zn] in DLA systems ranging from values consistent with stars to values comparable with local halo clouds. We interpret the mean $\langle$[Cr/Zn]$\rangle = -0.3$ as indicating that about half the Cr is locked up in grains or, putting it another way, that the dust-to-metals ratio in the DLAs is approximately half that in the Galaxy. The lower overall level of heavy element depletion in DLAs might be expected in view of (i) the low abundances of the grain constituents themselves, (ii) the more effective grain destruction at the higher temperatures accompanying the low metallicities, and (iii) more frequent grain processing as a result of higher supernova rates.

Combining the mean metallicity and the mean dust-to-metals ratio, we conclude that the 'typical' dust-to-gas ratio in DLA systems is $\approx$1/30 that in the Galactic interstellar medium. This value is a factor of 3 lower than our earlier estimate (Pettini et al. 1994), largely as a result of improved f-values for the Zn II and Cr II transitions. Given the large scatter in both [Zn/H] and [Cr/Zn], however, the concept of a 'typical' dust-to-gas ratio may be of limited use.

(c) Conflict with Keck Observations?

Recent analyses of HIRES Keck observations of DLA systems (Prochaska and Wolfe 1996, 1997: PW; Lu et al. 1997: LSB) have concluded that there is *no* evidence for dust depletion in these galaxies and have questioned the validity of the method outlined here as a test for the presence of dust at high redshift. It is important to note that these conclusions are *not* based on improved measures of Zn and Cr abundances—in all cases in common there is good agreement—but rather on significant differences in interpretation of the common body of data. We address these differences in the following section and show that the observations of Prochaska & Wolfe and Lu et al. are in fact completely consistent with the picture proposed here.

III. DISCUSSION

Before introducing the evidence put forward by Prochaska & Wolfe and Lu et al., we need to consider if it really matters whether the high-z dust-to-gas ratio is $\approx$1/30 of today's or zero. The qualitative difference between these two possibilities has important consequences:

1. If DLA galaxies are dust-free this constitutes a major difference between galaxies then and now;

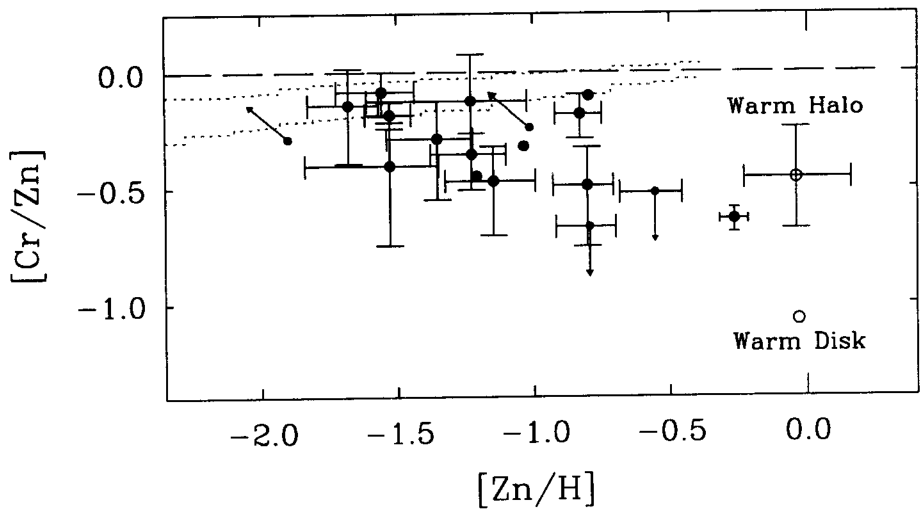

Fig. 2.— Cr abundance relative to Zn (log scale relative to solar) in 18 DLA systems (filled circles) and in warm interstellar clouds in the disk and halo of the Galaxy (open circles; from Savage & Sembach 1996). The dotted lines indicate the upper and lower quartiles of [Cr/Fe] for a large sample of Galactic stars in this metallicity regime (Ryan et al. 1996).

2. Even small amounts of dust have profound effects on the transfer of Lyman α radiation, long before reddening effects become noticeable; and
3. Small amounts of dust can affect relative abundances by factors comparable with nucleosynthetic effects.

The assertion by PW and LSB that the abundance patterns seen in high-z DLA systems are ***inconsistent*** with dust depletions is based on two main lines of evidence: (i) there is no obvious correlation between the degree of depletion of an element and its condensation temperature, as there is in the local interstellar medium, and (ii) departures from solar relative abundances are consistent with nucleosynthesis by Type II supernovae alone, with no room for additional contribution from selective grain depletion. We now examine each point in turn.

(a) Depletion and Condensation Temperature

The local pattern of element depletions is normally defined by the sightline to ζ Oph. The cool cloud in front of this star does indeed show a trend of decreasing gas-phase abundance with increasing condensation temperature; for example, Ti is more depleted than Fe and Cr which in turn are more depleted than Mn. The measured gas-phase abundances imply that $\approx$99.9% of the Ti, $\approx$99% of the Fe and Cr, and $\approx$96% of the Mn are in solid form.

However, at the reduced dust depletions prevailing in DLA systems, such a pattern would be largely washed out. If half the interstellar grains are destroyed, correponding to our 'typical' DLA, then all four elements would have gas-phase abundances of $\sim$50%, similar to the pattern of relative depletions seen in warm interstellar clouds and, indeed, in the Keck DLA data. The mistake is in assuming that the element depletion pattern seen when only tiny fractions remain in gaseous form is maintained when the degree of depletion is reduced to only 1/2. Of course, we may then find small differences superimposed on this uniform degree of depletion, depending on the nucleosynthetic origin of particular elements.

(b) Departures from Solar Element Ratios

LSB argue that the [N/O] and [S/Fe] ratios in DLAs are inconsistent with dust depletions because they exhibit the same values in Galactic metal-poor stars. However, Pettini, Lipman & Hunstead (1995) have shown that the [N/O] ratio is very sensitive to the past history of star formation in a galaxy and is therefore not a useful tracer of dust. Interpretation of the [S/Fe] result is complicated by the fact that S has been measured in only three DLAs in total, two of which are among the most metal-deficient known and may indeed be dust-free. Extrapolation of this result to *all* other DLA systems is therefore not justified.

Finally, in coming to terms with 'anomalous' abundance ratios it is important to recognise that star-formation histories of the high-z galaxies giving rise to the DLA systems may be different from that of the Milky Way, just as galaxies in the Local Group have experienced widely different star-formation histories.

IV. CONCLUSIONS

The damped Lyman α systems provide us with a direct view of the early stages of the evolution of galaxies. The generally low abundances found for [Zn/H]—an average of 1/15 solar at $z \sim 2$—suggest that the DLA systems trace an early stage in the formation of galaxies. The range of values we have measured for [Zn/Cr] has led us to conclude that dust is present in at least some high-z galaxies, albeit at concentrations well below those in the Milky Way interstellar medium. We find no conflict between this result and recently published Keck observations.

RWH gratefully acknowledges financial assistance from the Australian Research Council.

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