Probing Galaxies through Quasar Absorption Lines
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Chemical history at $z \geqslant 2.0$: first results from the Magellan + Keck survey of Lyman limit systems

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Abstract. We present a measurement of [O/Fe] versus [Fe/H] in the $z > 2$ IGM derived from a sample of 23 Lyman Limit systems whose column density lies in the range $19.0 \leqslant \log N_{HI} \leqslant 20.2$ cm^{-2}. The systems span a metallicity range of $-2.70 \leqslant$ [Fe/H] $\leqslant -0.50$, allowing for a direct comparison with similar studies of stars within the Milky Way. Although the Lyman Limit systems can be highly ionised, the effects of ionisation on the determination of [O/Fe] is minor for most of the systems in the sample. The data appear to show a decrease in [O/Fe] with increasing metallicity with an approximate slope of $m \simeq -0.55$. We also determine a best fit power law slope of $\alpha = -1.86 \pm 0.2$ to the column density distribution $f_{HI}(N)$ for $19.0 \leqslant \log N_{HI} \leqslant 20.2$ cm^{-2}.

1. Introduction

Determinations of the relative abundances of O and Fe give clues to the stellar histories of the environments where these elements are measured. Fe is made primarily in Type I supernovae, whereas O is made primarily in supernovae of Type II. As such, measurements of [O/Fe] constrain chemical evolution and stellar mass histories. In the Milky Way, [O/Fe] can be measured in metal poor halo stars to probe early Galaxy time-scales. At high redshift, the damped Lyman alpha systems (DLAs) can provide a variety of elemental abundance ratios (e.g. Prochaska & Wolfe 2002). [O/Fe], however, is difficult to measure in DLAs since, for most metallicities, the O I transition is saturated, providing only a lower bound to its column density.

In this work, we present the measurement of [O/Fe] in Lyman limit systems, which are absorbers with H I column densities less than the DLAs, but still sufficient enough to show measurable metal line transitions. Unlike the DLAs, Lyman limit systems can be very highly ionised, making abundance measurements difficult. Fortunately for [O/Fe] however, when the $\log N_{HI} > 19.0$ cm^{-2}, the ionisation corrections to both O I and Fe II approach or fall below the measurement errors.

2. Observations

The data presented here come from ESI on Keck II and MIKE on the Clay telescope at Las Campanas. The data were scanned visually for the presence of large $N_{\rm HI}$ absorption systems, and candidate systems were fit in H I Lyman alpha with Voigt profiles to

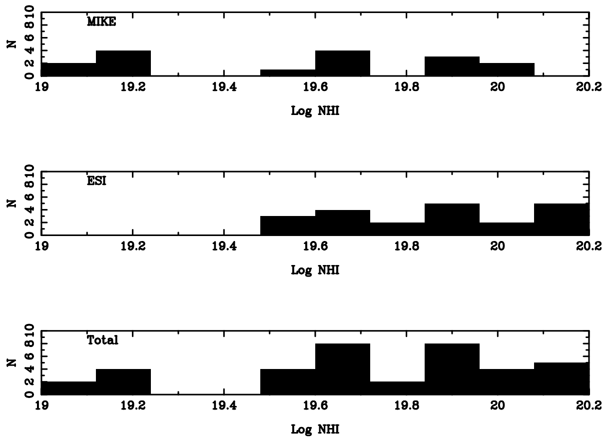

Figure 1. NHI distribution of the sample, including individual contributions from MIKE on Magellan (upper panel) and ESI on Keck II (middle panel)

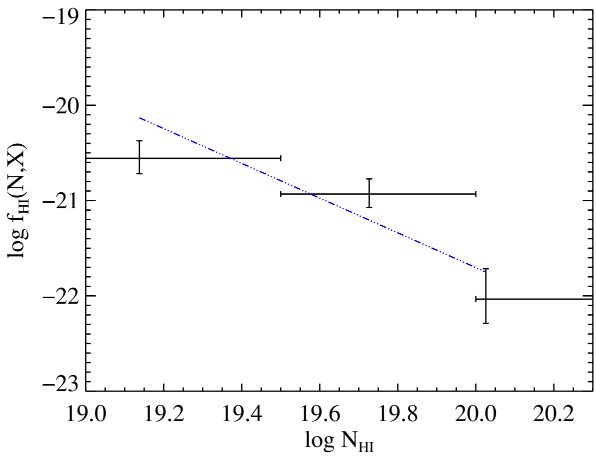

Figure 2. Best fit to the column density distribution $f_{HI}(N)$ for the MIKE data alone over the range 19.0 $\leqslant$log $N_{HI}\leqslant$ 20.2. The normalisation is arbitrary.

determine the H I column density. From the sample of $>$ 50 sight-lines, 38 systems were determined to have 19.0 $\leqslant$log N_{HI} $\leqslant$ 20.2 cm^{-2}.

At the redshift of each absorber, column densities of the ions C II, O I, Mg II, Al II, Al III, Si II, and Fe II were determined, where possible, by using the apparent optical depth (AODM) method. In some cases, these ionic transitions were either heavily blended with the Lyα forest or fell outside the wavelength range of the data, and column densities could not be measured.

3. Analysis

The distribution of $N_{\rm HI}$ values in the sample is shown in Fig. 1. For the MIKE data alone, we determine a value of the best fit single power-law slope to the column density distribution $f_{HI}(N)$ of $\alpha = -1.86 \pm 0.2$, as shown in Fig. 2.

Fig. 3 shows the measurement of (O/Fe) vs. [Fe/H] in 24 Lyman limit systems. The points indicate the MIKE and ESI data. To explore the effects on [O/Fe] of ionisation, we

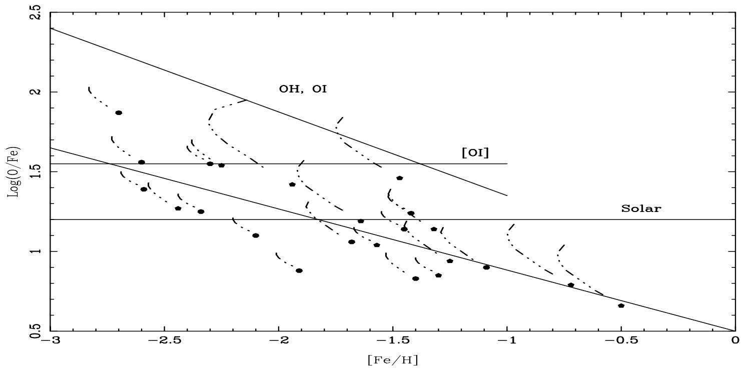

Figure 3. Log(O/Fe) observed in 24 Lyman Limit systems from MIKE and ESI

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performed a number of Cloudy (Ferland, 1991) simulations assuming a Haardt & Madau (1999) ionising spectrum at $z = 3$, a J_ν of $10^{-21.2}$ erg $s^{-1}cm^{-2}$ at 1 Ryd, and a range of hydrogen densities from 10^{-3} to 1 cm^{-3}. For each system, we summarise the range that ionisation can alter the observed (O I/Fe II) with the dot-dashed tracks. Photoionisation has the net effect of raising the (O/Fe), but in most cases the change is maximally 0.2 dex or less from the observed (O I/Fe II). For convenience, we over-plot an approximate Solar value of (O/Fe)= 1.2.

To compare with measurements of [O/Fe] in metal poor giants in the Milky Way, we over-plot the results cited in Fulbright & Johnson (2003) and references therein. The solid line with slope $m = -0.35$ shows the trend of the measurements of [O/Fe] when the O abundance is derived from OH and O I transitions, while the flat solid line shows the [O/Fe] when the O abundance comes from measurements of the [OI] forbidden transition. To guide the eye, we also over-plot a thick line with slope $m = -0.55$ to show the trend of the Lyman limit system data. This line is not a fit, since the ionisation corrections for the individual systems is not known. The slope is similar to that of the [O/Fe] as derived from OH and O I in the Milky Way, but is lower in magnitude by nearly a full dex. At low metallicities, the data are consistent with [O/Fe] as derived from [OI] but are nearly a full dex too low at higher metallicity.

4. Discussion

The data in Fig. 3 is potentially troubling, since at the higher metallicity end ([Fe/H] > -1.4), the (O/Fe) drops below the Solar value beyond even the point where ionisation corrections can drive it upward. One likely explanation is the effect of O I line saturation which would increase (O/Fe). Without correction, the trend in (O/Fe) is difficult to explain, since we expect (O/Fe) to be greater than the Solar value at early times (i.e. high z) as the number of Type Ia supernovae is decreasing with increasing redshift. Dust depletion can not explain the data, since Fe depletes more strongly than O. Clearly, a proper determination of the O I and Fe II column densities needs to be made before we can view the trend as secure.

References

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