Mining for Metals in the Ly$\alpha$ Forest

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**Abstract.** In order to ascertain the extent of metal enrichment in the Ly$\alpha$ forest, we have analysed a very high S/N spectrum of the $z = 3.625$ QSO Q1422+231. We find that in high column density Ly$\alpha$ clouds, the power law column density distribution function of C IV continues down to log $N$(C IV) = 11.7. In addition, by analysing pixel-by-pixel optical depths we show that there are considerably more metals in the Ly$\alpha$ forest than are currently directly detectable.

1. Introduction

Our understanding of the Ly$\alpha$ forest and its connection with the Intergalactic Medium (IGM) have undergone radical revision in recent years. The paradigm in which the IGM consists of discrete, isolated clouds has been revolutionised by a generation of hydrodynamical simulations (e.g. Hernquist et al 1996). These simulations show that the ‘bottom-up’ hierarchy of structure formation knits a complex but smoothly fluctuating cosmic web, consisting of filaments, knots and extensive ‘voids’. Originally thought to be chemically pristine, it is now well-established that a large fraction of the strongest Ly$\alpha$ absorbers exhibit some metal enrichment, most notably C IV (e.g. Cowie et al 1995). Here, we address two specific questions. Firstly, are the C IV absorbers that have thus far been detected just the tip of the iceberg and can more sensitive spectra mine ever weaker systems? Secondly, to what H I column densities does the enrichment extend? This latter point has particularly poignant implications for the origin and transport mechanism of these metals. In-situ formation in a nearby galaxy could be responsible for the enrichment of its local IGM, explaining the presence of C IV in the relatively high column density Ly$\alpha$ clouds. However, low column density Ly$\alpha$ clouds (log $N$(H I) < 14.0), which are associated with physically less dense regions, are found further from the sites of star formation. The presence of C IV in these clouds could be indicative of widespread metal enrichment, possibly by an early epoch of Population III star formation. This is an overview of work described in more detail in Ellison et al (2000).
2. C IV in High Column Density Lyα clouds

With a S/N ratio in excess of 200 redward of Lyα, our Keck/HIRES spectrum of Q1422+231 is one of the most sensitive currently available to search for C IV associated with the Lyα forest. Although this target has been extensively studied in the past, our data reveal several C IV systems that had not been previously detected in spectra of lower S/N. We undertake the standard procedure of fitting Voigt profiles to determine column densities, b-values and redshifts of the 34 detected C IV systems associated mainly with Lyα clouds with log N(H I) > 14.5. Previous studies of C IV absorbers have established a power law column density distribution of the form $f(N)dN = B N^{-\alpha} dN$ and determined $\alpha \sim 1.5$, complete down to log N(C IV) ≃ 12.75 for $z > 3$ (Songaila 1997). Below this limit, there is an apparent departure from the power law which could be due to either incompleteness or a real turnover in the number density of C IV systems. We perform a maximum likelihood fit to our data points and determine a power law index $\alpha = 1.44 \pm 0.05$, in good agreement with previous estimates (see Figure 1). The column density limits at which previous studies have exhibited a departure from the power law are sketched and clearly our data establish that this was due to incompleteness. The C IV systems from this single high quality spectrum are sufficient to show that the power law continues down to at least log N(C IV) ∼ 12.3, below which the data points start to turn-over. Again, this could be due to the incompleteness caused, for example, by a bias against weak C IV lines with large b-values, or evidence of a real turn-over in column density distribution. By simulating C IV lines for the two lowest column density intervals in Figure 2 with b-values drawn at random from the observed distribution, we can estimate the incompleteness correction factor by determining the frequency with which these lines are recovered. Once this has been taken into account, there is no shortfall compared with the power law, showing that it continues at least down to log N(C IV) = 11.7, a factor of ten more sensitive than previous analyses.

3. Probing the Low Column Density Lyα Forest

Direct detection of the C IV systems associated with low column density Lyα clouds (log N(H I) < 14.0) is observationally very challenging due to the extreme weakness of the absorption. In the past, efforts have been made to overcome this problem by stacking together the regions where C IV absorption is expected in order to produce a high S/N composite spectrum (e.g Lu et al 1998). In Ellison et al (1999), we showed how a random redshift offset between the Lyα line and its associated C IV feature could ‘smear’ out the stacked feature and consequently underestimate the amount of metals present. Instead, we favour the optical depth method developed by Cowie & Songaila (1998) which we have found is more robust against redshift offset (see Ellison et al 2000 for a detailed discussion of this point). Briefly, the optical depth method consists of stepping through the spectrum and measuring the optical depth ($\tau$) of each Lyα pixel and its corresponding C IV. The results of this analysis are shown by the solid line in Figure 3 and are consistent with a constant level of C IV/H I (as shown by the dashed line) for optical depths down from $\tau$(Lyα) ∼ 100 over two orders
Figure 1. Column density distribution of C IV absorbers in Q1422+231. Points corrected for incompleteness are shown with open circles. The approximate turnovers seen in previous determinations of the $f(N)$ power law are shown as a grey solid line (Petitjean & Bergeron 1994) and black dashed line (Songaila 1997).

of magnitude, below which $\tau$(C IV) flattens off to an approximately constant value. In order to interpret these results, simulated spectra were reproduced using the Lyα forest taken directly from the data, adding C IV with a given enrichment recipe and then analysing the synthetic spectrum with the optical depth technique. A total of 3 simulated spectra were created, all of which include a random redshift offset of 17 kms$^{-1}$ between Lyα and C IV and assume $b$(C IV) = 1/2 $b$(Lyα). Spectrum ‘A’ includes only the directly detected C IV with no additional enrichment and the optical depth analysis reveals that it is clearly C IV deficient in comparison with the data at almost all optical depths. Clearly, there is more C IV in the data than is accounted for in the 34 directly identifiable systems. Adding C IV to the log $N$(C IV) $>$ 14.5 Lyα clouds at the detection limit of the spectrum (log $N$(C IV) = 12.0) can reproduce the results obtained for the data for $\tau$(Lyα) $>$ 3 but not at lower optical depths (spectrum ‘B’). The data are more consistent with spectrum ‘C’ in which a constant C IV/H I ratio of $-2.6$ was also included in log $N$(H I) $<$ 14.5.

We investigated the possible limitations of our analysis due to such effects as contamination by other metal lines, errors in the continuum fit and scatter in the C IV/H I ratio. We conclude that overall this is a robust technique and that the limiting factor is likely to be the accuracy of the continuum fit in the Lyα forest regions which could mimic the flattening of $\tau$(C IV) that we observe in the data at low H I optical depths. Nevertheless, we find that even in the high optical depth H I pixels (that will not be seriously affected by small continuum errors) the identified C IV systems are insufficient to account for the all the measured absorption and that there are clearly more metals in the IGM than we can currently detect.
Figure 2. The results from the optical depth analysis of Q1422+231 (solid points) are compared with three synthetic spectra. Top panel: open circles show the measured optical depths in a synthetic spectrum enriched solely with the detected C IV systems. Middle panel: In addition to the detected C IV systems, log $N$(C IV) = 12.0 is included in all Lyα clouds with log $N$(H I) > 14.5. Bottom panel: Supplementary C IV is now added in all weak (log $N$(H I)< 14.5) Lyα lines with log C IV/H I = −2.6.
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