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Probing the HeII reionization epoch with Damped Ly α systems

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Abstract. Interstellar studies indicate that the abundance of Ar is a good diagnostic tool of ionization conditions. We have used this property to probe the ionization state of the high redshift galaxies detected as Damped Ly α (DLA) absorbers in QSO spectra. From the analysis of Ar measurements in 15 DLA systems in the redshift range $2.4 \lesssim z \lesssim 3.4$ we find evidence for evolution of the abundance of Ar relative to other α-capture elements. The [Ar/α] ratio increases from ≈ -0.7 dex at $z \simeq 2.4$ to a nearly solar value at $z \simeq 3.4$. This evolutionary trend is consistent with the hardening of the intergalactic ionizing continuum expected during the epoch of HeII reionization. However, a dominant contribution of stellar type ionizing sources at $z > 3$ may be required to explain the data.

Key words. Diffuse radiation – Intergalactic medium – Ultraviolet: galaxies – Cosmology: observations – Quasars: absorption lines

1. Introduction

Observational evidence starts to accumulate suggesting that the HeII reionization epoch may have started at $z \approx 3.5$, well within the reach of QSO absorption spectroscopy (see Loeb 2001, for a recent review). In addition to the study of HeII absorption in QSO spectra, the observational evidence is based on three effects expected to occur as a consequence of HeII reionization: (1) heating of the intergalactic medium (IGM), (2) decrease of the effective optical depth of the IGM and (3) hardening of the UV ionizing background. We focus here on this last effect, which is induced by the increase of transparency of the IGM to photons with $h\nu > 54$ eV. Songaila (1998) claimed the detection of a jump of the median Si IV/C IV ratio in the IGM around $z \simeq 3$, attributed to a change of the slope of the ionizing continuum, in the sense expected by the onset of HeII reionization. This abrupt change of Si IV/C IV ratios has not been confirmed by subsequent studies (Kim 2002)BS03. However, evidence for a hardening of the IGM ionizing continuum with cosmic time, from $z \simeq 4$ to $z \simeq 2$, has been found from an extensive study of QSO metal absorbers (Boksenberg et al. 2003). Here we present a method to probe the IGM ionizing con-

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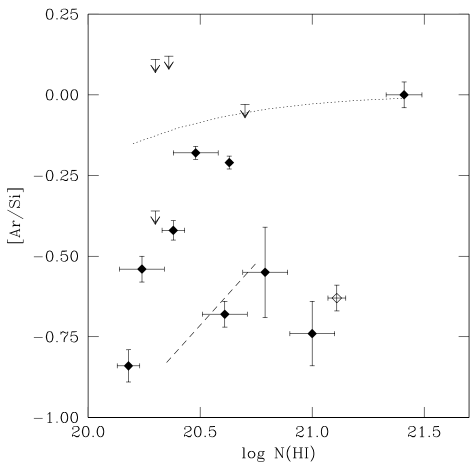

Fig. 1. [Ar/Si] ratios in DLA systems. Measurements and limits are indicated by diamonds and arrows, respectively. Curves: predictions of photoionization models with soft, stellar (dotted curve) and hard, quasar (dashed curve) ionizing continuum; see text.

tinuum at high z, based on the study of Ar abundances in Damped Lyman α (DLA) systems, the QSO absorbers with highest HI column density. Abundances in DLA systems are not traditionally used to probe ionization conditions since, in general, they are not sensitive to ionization effects (e.g. Prochaska & Wolfe 1996; Vladilo et al. 2001 and refs. therein). In addition, dust tend to deplete DLA abundances (Pettini et al. 1994; Prochaska & Wolfe 2002; Vladilo 2002), making harder to disentangle the effects of ionization. The abundance of Ar is an exception since interstellar studies indicate that this element is sensitive to ionization effects, but is probably not depleted into dust (Sofia & Jenkins 1998). Ar can be detected in DLA systems (Molaro et al. 2001) and we have used its properties to probe the ionization conditions at high z. We summarize here the results of our work which is treated in more detail in a separate paper (Vladilo et al. 2003; V&03).

2. Ar abundances in DLA systems

Our sample includes all available Ar abundances in DLA systems (10 measurements and 5 limits). Most of the measurements, including ours, were derived from UVES/VLT observations. The remaining data were obtained with HIRES/Keck. The full list is given in Table 1 of V&03.

In order to disentangle the effects of ionization from those of chemical evolution we have normalized the Ar abundances to those of other α capture elements measured in DLA systems. The Ar/α ratio should not change in the course of chemical evolution if Ar production tracks that of the other α elements. The reference α elements adopted — i.e. O, Si and S — are essentially unaffected by ionization (Vladilo et al. 2001) and dust (Vladilo 2002) effects. Therefore, given the particular properties of Ar, the Ar/α ratio is expected to be a good indicator of the ionization conditions, not affected by chemical evolution or dust depletion.

In Fig. 1 we plot the [Ar/Si] data versus log N(HI). The ratios are underabundant in most cases, down to $\simeq -0.8$ dex relative to solar, only a few ratios showing nearly solar values. To interpret these results, we have plotted in the same figure the predictions of photoionization models tuned to reproduce the Al III/Al II ratios measured in DLA systems (Vladilo et al. 2001). The dashed line represents a model with hard ionizing continuum dominated by quasars. The dotted line a model with soft continuum dominated by stellar sources. In order to reproduce the Al III/Al II data, this latter model requires a ionization parameter (flux of ionizing photons per hydrogen particle) about two orders of magnitude higher than the hard continuum model. Analysis of Fig. 1 suggests that the strong underabundances of the Ar/Si ratio are induced by a hard ionizing background. The few cases with nearly solar values are instead suggestive of a softer ionizing continuum, albeit with a higher ionization parameter. We derive the same results from the analysis of Ar/O and Ar/S ratios (V&03).

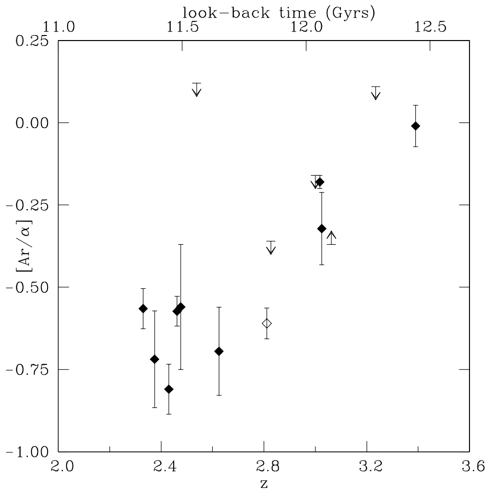

Fig. 2. The [Ar/α] ratios in DLAs plotted versus redshift (bottom axis) and look-back time (top axis), for $H_0 = 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

3. Redshift evolution

In Fig. 2 we plot [Ar/α] versus absorption redshift in DLA systems. The [Ar/α] ratios have been estimated as the mean value of available [Ar/O], [Ar/S], and [Ar/Si] measurements. For the limits we adopt the most stringent one.

The data show a trend of increasing [Ar/α] with redshift, even though more data are required to confirm the result at $z > 3$. This trend is unique among abundance studies of DLA systems. For instance, the metallicity evolution of DLAs is quite mild, with a decrease of $\simeq 0.3$ dex per unit redshift interval (Vladilo et al. 2000; Prochaska et al. 2003). The chemical evolution of α/Fe ratios, such as S/Zn or Si/Fe, is even milder (Centurión et al. 2000; Vladilo 2002). Therefore, we consider extremely unlikely the possibility that the large variation of the Ar/α ratio ($\simeq 0.75$ dex per unit redshift interval) might be due to chemical evolution.

On the basis of our previous discussion of Fig. 1, the Ar/α evolution appears to be governed by a change of the ionizing continuum from $z \simeq 3.4$ to $z \simeq 2.4$: during the corresponding interval of cosmic time the continuum would become harder, albeit with a $\simeq 2$ dex decrease of the ionization parameter. This change would occur on a billion-year time scale (top axis of Fig. 2). Unless DLA systems are a very homogeneous class of objects, all formed exactly at the same redshift, it is hard to imagine why they should change their *internal* ionization properties in lockstep. It is more likely that the observed change results from a gradual evolution of the *external* ionizing background.

The occurrence of HeII reionization offers a natural explanation to the hardening of the external ionizing background suggested by our analysis: the hardening is expected as a result of the IGM becoming transparent to high energy photons in the course of the HeII reionization. In support of this explanation, we note that the redshift interval of the data in Fig. 2 matches perfectly well the interval where a decrease of the optical depth of the IGM, also expected in the course of HeII reionization, has been detected (Theuns et al. 2002).

The HeII reionization, however, does not provide a straightforward explanation for the decrease with time of the ionization parameter, apparently suggested by our analysis. A significant increase of the contribution of stars relative to QSOs as ionizing sources at $z > 3$ might explain this effect. This possibility seems in line with the results of the extensive study of IGM ionic ratios performed by Boksenberg et al. (2003): modeling the full set of ionic ratios at $3.4 < z < 4.4$ in terms of photoionization may require that stars overcome the QSO contribution by about two orders of magnitude at the HI ionization threshold; such stellar contribution is not necessary at $1.9 < z < 2.65$.

A better understanding of the comoving density of ionizing sources at $z \gtrsim 3$ is required to model the evolution of the ionizing continuum concomitant with the occurrence of the HeII reionization.

4. Conclusions

We have presented a method for probing the ionization conditions at high redshift from the study of Ar abundances in DLA systems. The method relies on the properties of the Ar/α ratio, which is a good discriminator of the ionizing continuum.

From the analysis of Ar data in 15 DLA systems we have found that the Ar/α ratio increases with redshift in the interval $2.4 \lesssim z \lesssim 3.4$, from $[\mathrm{Ar}/\alpha] \simeq -0.75$ up to $[\mathrm{Ar}/\alpha] \simeq 0$. This trend suggests that the ionizing continuum in DLAs becomes harder with cosmic time on a billion-year time scale. Unless DLA galaxies are very similar and all formed at the same redshift, the existence of this regular trend suggests that the change is dominated by external, rather than internal ionizing sources. More data at $z > 3$ are required to confirm the regularity of the trend at high redshift.

The hardening of the ionizing continuum suggested by our analysis is consistent with the onset of the HeII reionization at $z \approx 3.4$, as a consequence of which the IGM becomes transparent to energetic photons. The inferred epoch for the onset of the HeII reionization matches very well the one found from the study of evolution of the effective optical depth of the IGM (Theuns et al. 2002). However, our analysis also suggests that a significant increase of the contribution of stellar ionizing sources may take place at z>3. This possibility is also suggested by the recent study of ionic ratios in the IGM performed by Boksenberg et al. (2003).

The results of our analysis argue for an external origin of the ionizing continuum in DLAs. The evidence comes not only from the regular variation of ionization properties with cosmic time, but also from the strong underabundances of Ar at $z \simeq 2.4$, which are difficult to explain without invoking a QSO dominated continuum. These severe underabundances are not observed in HI regions of the local universe (Sofia & Jenkins 1998; Aloisi et al. 2003; see more refs. in V&03). An external origin of the ionizing continuum in DLAs suggests that the internal stars must give a little contribution, i.e. that the star formation rate in DLA galaxies must be mild, consistent with the weak signal of chemical evolution, typical of low mass galaxies or external regions of disk galaxies, detected so far in these objects (Calura et al. 2003).

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