Non-equilibrium effects on line-of-sight size estimates of QSO absorption systems

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Abstract

Estimates of the linear extent of heavy-element absorption systems along the line-of-sight to a QSO often assume that the cloud is photoionized and that the temperature takes the equilibrium value where photo-heating balances line cooling. We show that rather small deviations from this photoionization equilibrium temperature caused by additional heating processes will lead to an overestimate of the neutral hydrogen fraction and thus to an underestimate of the thickness of the absorber by about two orders of magnitude. Such temperature deviations are indicated both by observations and numerical simulations. This interpretation reconciles the discrepancy between the rather small extent of heavy-element-absorption systems parallel to the line-of-sight obtained from a standard photoionization analysis and the much larger transverse sizes estimates inferred from the observation of common absorption in the spectra of close quasar pairs.

1 Introduction

Recently new size estimates for QSO absorption systems have modified our view of the physical properties of low and intermediate column density QSO absorption systems. Dinshaw et al. (1994) and Bechthold et al. (1994) have observed coincident absorption lines in the spectra of the close quasar pair 1343+26 at redshift $z = 2.03$ with angular separation 9.5 arcmin (corresponding to a proper separation of $40h^{-1}kpc$ for $q_0 = 0.5$). Assuming a population of spherical absorbers of fixed size the authors of both studies inferred a typical absorber radius of $\sim 100h^{-1}$ kpc. Further observations of a few other quasar pairs confirmed the new size estimates which are at least an order of magnitude larger than assumed previously. Even so the assumption of spherical absorbers of fixed size is rather simplistic, more sophisticated modeling gives similar results with inferred sizes even larger by a factor $1.5 - 2$ (Charlton et al. 1996).

If the typical values measured for the transverse size were also characteristic for the extent parallel to the line-of-sight (LOS) then the usually assumed fiducial values for the total density and the neutral hydrogen fraction would have to be revised by factors $3 - 30$. However, Rauch & Haehnelt (1995) have argued that the absorbers are flattened structures in which case more moderate correction factors apply.

To further probe the nature of the absorption systems more detailed information on the physical properties and especially the absorber extent parallel to the LOS are necessary. Low-and intermediate column density absorption systems are known to be highly ionized and photoionization is generally assumed to be the ionizing mechanism (Bergeron & Stasińska 1986). If the absorbers were in full thermal photoionization equilibrium and strength and spectrum of the ionizing background radiation were known, a determination of the ionization parameter would be sufficient to determine the mean total density, the neutral fraction of the absorbing gas and thus its extent parallel to the the LOS (e.g. Giallongo & Petitjean 1994). The recent work by Cowie et al. (1995) used both the CII/CIV column density ratios of the associated metal absorption and the temperature of the clouds inferred from their Doppler parameter to determine the ionization parameter. Using standard photoionization models Cowie et al. inferred a thickness of 100 pc for the CIV absorbing gas clouds associated with low column density absorption systems. Considering the measured transverse sizes obtained for only slightly larger column density systems this result seems quite puzzling. It would imply axis ratios of $10^{-3} - 10^{-4}$ for a homogeneous distribution of

CIV absorbing gas. Such a configuration should be quite unstable. Problems of an alternative model where the CIV absorbing gas is highly inhomogeneous and consists of many small clumps with covering factor of order unity have been discussed by Mo (1994) and Mo & Miralda-Escudè (1996). We suggest here a different solution to reconcile the apparent large difference between the extent parallel and transverse to the LOS. In section 2 and 3 we will show that full thermal photoionization equilibrium is unlikely to be a valid assumption and will investigate non-equilibrium effects on the ionization state of the gas. In section 4 we discuss implications for the inferred thickness of the absorbers. Section 5 contains the conclusions.

2 Non-equilibrium effects on the ionization state of carbon and hydrogen

Observations and numerical simulation indicate that the temperature of the absorbing gas does not take the equilibrium value where photo-heating balances line cooling (a situation which we will call *full* (=thermal photoionization) equilibrium in the following). This is already seen in the observed b-value distribution of Lyα lines. There is a broad range of b-values between 20 and 100 $\mathrm{km\,s^{-1}}$ (Hu et al. 1995). This corresponds to a temperature range between 1.5×10^4 K and 3×10^5 K if the line profiles are due to thermal broadening. High resolution studies of metal absorption lines do indeed indicate that a single temperature may not be a good approximation. Rauch et al. (1996) used a high resolution sample of CIV and SIV lines to show that the turbulent contribution to the Doppler broadening is small (considerably less than 10 $\mathrm{km\,s^{-1}}$) and that there is a range of gas temperatures between 2×10^4 K and 3×10^5 K with a mean temperature of 4×10^4 K. As discussed by Haehnelt, Steinmetz & Rauch (1996) and shown in Fig. 1 numerical simulations exhibit a similar range of gas temperatures. The deviations from full equilibrium are easy to explain as the equilibrium models neglect shock heating due to the collapse of structures. In the following we will discuss the effect of such deviations on the ionization state of the gas. The simulations also show a small turbulent contribution to the line width at the relevant column densities.

As pointed out by Cowie et al. (1995) the CIV $\lambda\lambda1548,1550$ and CII $\lambda1334$ seems the most promising line pair for a reliable determination of the ionization parameter of low and intermediate column density absorption systems. In the following we will therefore concentrate on hydrogen and carbon. As we are only interested in absorbers of moderate column density we will neglect self-shielding and radiative transfer effects. We have used the photoionization code CLOUDY (Ferland 1993) to calculate the ionization state for a grid of ionization parameter and temperatures dropping the assumption of full photoionization equilibrium. CLOUDY was used in its "Lyα absorber mode". The absorber is then assumed to be an infinite homogeneous slab of gas of low metallicity, optically thin to ionizing radiation and illuminated from both sides by a homogeneous UV field. $I_\nu \propto \nu^{-\alpha}$ was adopted for the spectrum of the ionizing photons. The ionization parameter

$$U = 4.2 \times 10^{-5}\ (I_{21}/n_H), \tag{1}$$

where I_{21} is the ionizing flux in units of $10^{-21}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}\,sr^{-1}}$, was defined as in Donahue & Shull (1991) with $\alpha = 1.5$.

In figure 2 the fraction of CIV, CII and HI is shown as function of ionization parameter. The solid curves assume full thermal photoionization equilibrium. While for large ionization parameter the temperature dependence of the CII and CIV fraction is weak, it is rather strong for small ionization parameter ($U \lesssim 0.01$). The temperature dependence of the HI fraction is generally strong with an increase towards low ionization parameter/high densities. The ion abundances derived from the equilibrium and non-equilibrium cases can differ by several orders of magnitude.

3 Ionization parameter and total density

Figure 3 shows how the ionization parameter inferred from the CII/CIV ratio changes if we drop the assumption of full equilibrium. The dependence on temperature is weak as long as the temperature does not exceed a critical value, beyond which CII/CIV becomes virtually independent of the ionizing parameter. For observed CII/CIV ratios this critical temperature is about $10^5 K$, somewhat above the temperature indicated by the Doppler parameter for most of the carbon lines (Rauch et al. 1996). The observed CII/CIV ratios will therefore give ionization parameter which are correct to a factor of about three if full equilibrium is assumed, although there are some additional uncertainties related to the unknown spectrum of the ionizing radiation. Hu et al. (1995) used the strong dependence of the ionization parameter on temperature in full equilibrium models as a second independent method to determine the ionization parameter. However, the typical temperature distribution of gas particles in a SPH simulation shown in Figure 1 (Steinmetz 1996, Haehnelt et al. 1996) indicates that a strong correlation between temperature and ionization parameter should not be expected. The temperature of full equilibrium models is therefore probably not a good indicator of the ionization parameter.

4 Neutral hydrogen fraction and size estimation

Figure 2a shows that the neutral hydrogen fraction is strongly temperature dependent for fixed ionization parameter. Even if we determine the ionization parameter to about a factor of three a determination of the temperature is absolutely essential to fix the neutral hydrogen fraction $x = n_{HI}/n_H$. The extent of the absorber parallel to the LOS is given by

$$D = \frac{N_{HI}}{x\, n_H}. \tag{2}$$

Any error in the determination of the neutral fraction therefore directly propagates into an error in the determination of D. In the upper panel of Figure 4 the inferred extent parallel to the LOS is shown as a function of the CII/CIV ratio for $\alpha = 1.5$. The dashed curves are for different temperatures as indicated on the plot. The left axis is for a column density of $10^{14}\,\mathrm{cm}^{-2}$ and the right axis is for a column density of $10^{16}\,\mathrm{cm}^{-2}$. The dashed line assumes full equilibrium. The inferred size is extremely sensitive to the temperature. An increase in the assumed temperature by only a factor of 2.5 from $2\times10^4\,\mathrm{K}$ to $5\times10^4\,\mathrm{K}$ increases the inferred extent along the LOS by a factor of about 30.

5 Discussion and Conclusions

Cowie et al.(1995) used high resolution spectra obtained with the HIRES spectrograph of the Keck telescope to determine the CII/CIV column density ratio of low and intermediate column density absorbers. They derived an upper limit of $N_{CII}/N_{CIV} \le 0.1$ for absorption systems with neutral hydrogen column densities of $10^{14}\,\mathrm{cm}^{-2}$ and found $N_{CII}/N_{CIV} \sim 0.1 - 0.3$ for larger column densities. From this they inferred $U \gtrsim 10^{-2}$ and $U \sim 10^{-3} - 10^{-2.5}$, respectively, using the full equilibrium photoionization models of Donahue & Shull (1991). As discussed in section 2.3 these estimates do not change much if the assumption of full thermal photoionization equilibrium is dropped. However, numerical simulation indicate that typical ionization parameter of low column density systems are higher by at least an order of magnitude than the observed lower limits. This corresponds to $N_{CII}/N_{CIV} \sim 10^{-3} - 10^{-2}$ and it seems unlikely that CII will be actually detected in low-column density absorption systems.

Following Cowie et al. 1995 and assuming a full equilibrium model with $N_{CII}/N_{CIV} \sim 0.1$ we would infer an extent along the LOS of $\sim 100\,\mathrm{pc}$ for an absorber with $N_H = 10^{14}\,\mathrm{cm}^{-2}$ in good agreement with their result. Dropping the assumption that the temperature takes the equilibrium value and taking into account that we have only a upper limit for N_{CII}/N_{CIV}, the inferred extent is increased to at least $10 - 100\,\mathrm{kpc}$. For larger column densities ($N_{HI} \sim 10^{16}\,\mathrm{cm}^{-2}$) with actually observed $N_{CII}/N_{CIV} \sim 0.1 - 0.3$ the extent along the LOS changes less dramatically, from 1 to 10 kpc. The sizes inferred from our non-equilibrium calculations are in good agreement with the sizes of CIV absorbing regions which we found recently in numerical galaxy formation simulations (Haehnelt, Steinmetz & Rauch 1996).

If the ionizing spectrum were softer the size estimates would be even larger. This is shown in Figure 4b which assumes a spectral index $\alpha = 5$. For this very soft spectrum the inferred extent becomes unreasonable large. It reflects the well known fact that a stellar-like spectrum is not able to reproduce observed line ratios (e.g. Steidel 1990). Taking into account the presence of a He absorption edge at 4 Rydberg in the spectrum of the UV background has a more moderate effect on the size estimates, increasing them by a factor of about two for a depression of the spectrum by two orders of magnitude at 4 Rydberg.

Dropping the assumption of a homogeneous single-temperature absorbing medium would further increase the size estimates. If there were either a temperature and density gradient towards the centre of the absorber (as seen in the numerical simulations) or if the medium were clumpy, CII absorption would be biased towards the cooler and denser regions. The assumption of a homogeneous absorber then overestimates the HI absorption-weighted CII/CIV ratio of the gas.

We conclude that equilibrium photoionization models considerably underestimate the size of the absorption systems parallel to the LOS if the temperature of the absorbing gas is higher than the equilibrium value where photo-heating balances line cooling. Such departures from equilibrium temperatures are indeed indicated both by observations and numerical simulations. The large discrepancy between the size estimates parallel and transverse to the LOS then disappears, reducing the need for models in which a population of numerous tiny clouds (R$\sim$ 100 pc) is kept in place by much larger halos.

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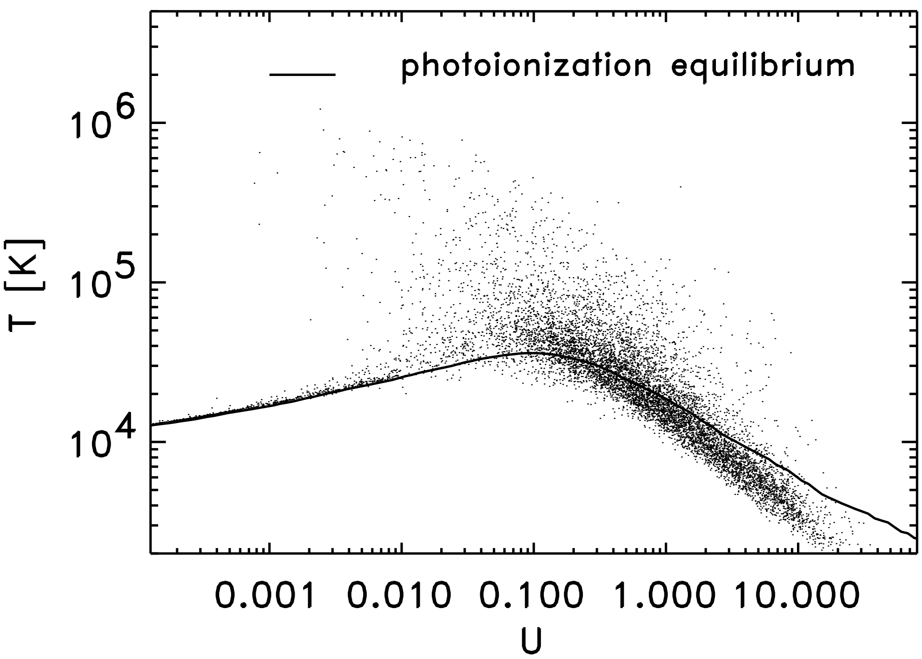

Figure 1: A typical temperature/ionization parameter distribution of gas particles in a SPH simulation at redshift $z = 3$ is shown. The ionizing background ($I_\nu \propto \nu^{-\alpha}$, $\alpha = 1.5$, $I_{21}(z = 3) = 0.3$) is fixed, while the density varies. The effects of Compton cooling due to the cosmic microwave background, adiabatic cooling and shock heating are included (see also Haehnelt, Steinmetz & Rauch 1996). The solid curve shows the corresponding relation assuming full thermal photoionization equilibrium.

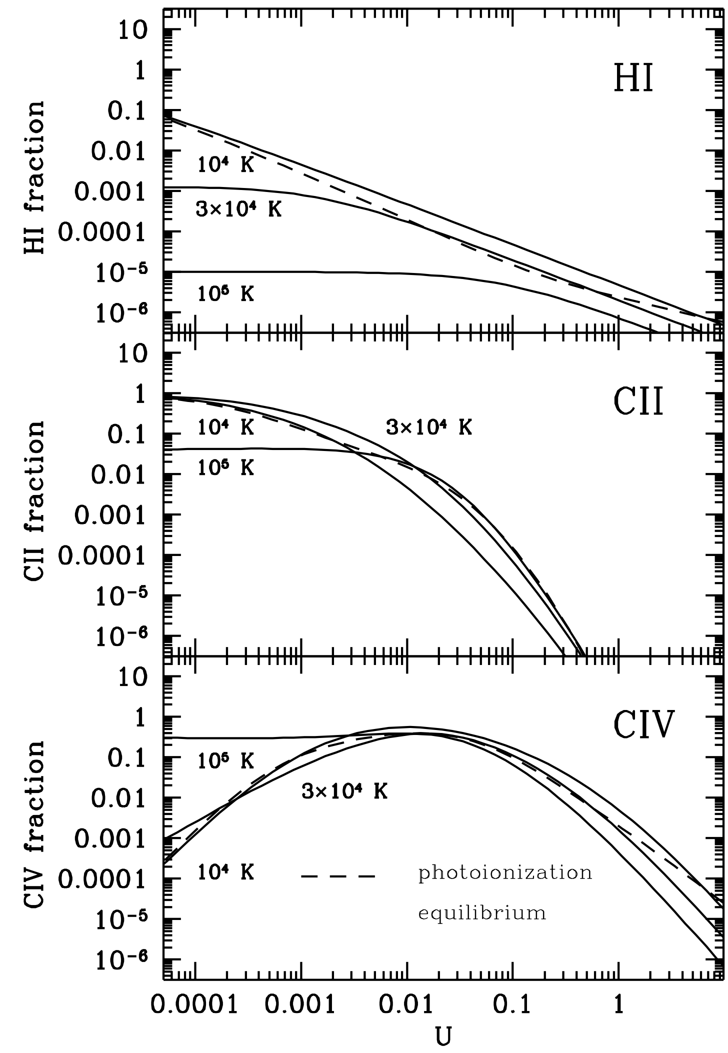

Figure 2: The three panels show the fraction of hydrogen and carbon in the form of HI, CII, and CIV as a function of the ionization parameter U for three different temperatures as indicated on the plot ($I_\nu \propto \nu^{-\alpha}$, $\alpha = 1.5$). The dashed curve assumes that the temperature takes the equilibrium value where photo-heating balances line cooling.

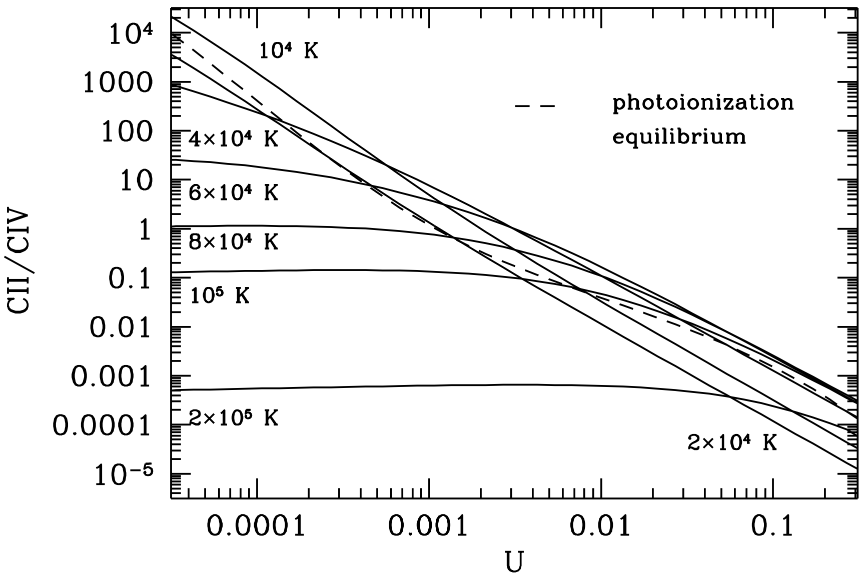

Figure 3: The solid curves show the CII/CIV ratio as a function of the ionization parameter U for different temperatures as indicated on the plot ($I_\nu \propto \nu^{-\alpha}$, $\alpha = 1.5$). The dashed curve assumes that the temperature takes the equilibrium value where photo-heating balances line cooling

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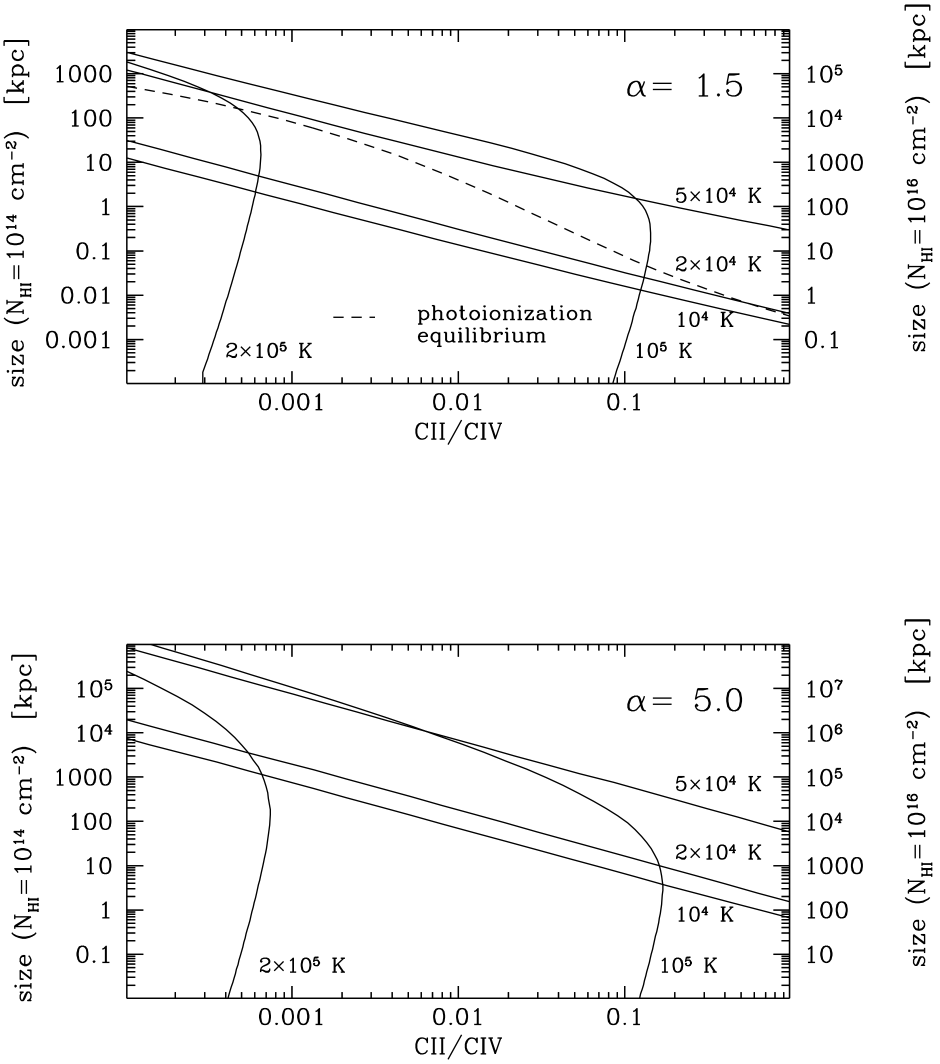

Figure 4: The inferred extent parallel to the line-of-sight is shown for an absorption system with neutral hydrogen column densities of $10^{14}\,\mathrm{cm}^{-2}$ (left axis) and $10^{16}\,\mathrm{cm}^{-2}$ (right axis) as a function of the CII/CIV ratio. The solid curves assume the absorber to be photo-ionized ($I_\nu \propto \nu^{-\alpha}$) and to have a temperature and spectral index α as indicated on the plot. The dashed curve assumes that the temperature takes the equilibrium value where photo-heating balances line cooling. The upper panel is for $\alpha = 1.5$, the lower panel is for $\alpha = 5.0$.