Highly-ionized oxygen absorbers in the intergalactic medium

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ABSTRACT
Recent ultraviolet and X-ray observations of intergalactic O VI and O VII absorption systems along lines of sight to bright quasars have opened a new window on to the ‘warm–hot intergalactic medium’. These systems appear to provide a significant reservoir for baryons in the local Universe, and comparison to cosmological simulations suggests that their abundance roughly matches theoretical predictions. Here we use analytical arguments to elucidate the physical properties of the absorbers and their role in structure formation. We first show that if the absorbers result from structure-formation shocks, the observed column densities naturally follow from post-shock-cooling models, if we include fast-cooling shocks as well as those that cannot cool within a Hubble time. In this case, the known O VI absorbers should show stronger O VII absorption than expected from collisional-ionization equilibrium (and much more than expected for photoionized systems). We then argue that higher-temperature shocks will be spatially associated with more massive virialized objects even well outside the virial radius. Thus, the different oxygen ions will trace different structures; O VII absorbers are the most common because that ion dominates over a wide temperature range (corresponding to a large range in halo mass). If each dark matter halo is surrounded by a network of shocks with total cross-section a few times the size of the virialized systems, then we can reproduce the observed number densities of absorbers with plausible parameters. A simple comparison with simulations shows that these assumptions are reasonable, although the actual distribution of shocked gas is too complex for analytical models to describe fully. Our models suggest that these absorbers cannot be explained as a single-temperature phase.

Key words: intergalactic medium – quasars: absorption lines.

1 INTRODUCTION
The cosmic-web paradigm has had a great deal of success in explaining the distribution of matter in the intergalactic medium (IGM) at moderate redshifts $z \sim 3$, especially in the Ly$\alpha$ forest (e.g. Rauch 1998). In this picture, dark matter collapses through gravitational instability into sheets and filaments before accreting on to bound structures such as galaxies, groups and clusters (which appear at the intersections of filaments). The baryons also accrete on to these structures, but (in addition to gravitational forces) they are subject to fluid effects such as shock heating. At $z \sim 3$, the infall velocities are modest relative to the ambient sound speed, and shocks are relatively unimportant except in collapsed objects. However, at the present day, shocks have heated most of the filamentary gas to $T \gtrsim 10^5$ K (Cen & Ostriker 1999); this gas is now known as the ‘warm–hot IGM’ (WHIM). Simulations predict that this phase contains a substantial fraction of the baryons (Cen & Ostriker 1999; Davé et al. 2001). The characteristic temperature $T \sim 10^6$ K corresponds to the post-shock temperature that has collapsed over the non-linear mass scale in one Hubble time.

Unfortunately, most of the WHIM lies at a modest density ($\sim 10–100$ times the cosmic mean) and in a temperature regime with few observational signatures; the hydrogen column densities are small because of collisional ionization and the gas is not hot enough to emit substantial bremsstrahlung radiation. As such, the WHIM has thus far only been detected through absorption of highly ionized metals (specifically O VI, O VII, and possibly O VIII).

Space-based ultraviolet spectrographs – including the Space Telescope Imaging Spectrograph on the Hubble Space Telescope and the Far Ultraviolet Spectroscopic Explorer (FUSE) – have allowed relatively straightforward detections of the O VI $\lambda \lambda 1032, 1038$ doublet along lines of sight to nearby bright quasars (Oegerle et al. 2000; Tripp & Savage 2000; Tripp, Savage & Jenkins 2000; Sembach et al. 2001; Savage et al. 2002; Shull, Tumlinson & Giroux 2003; Prochaska et al. 2004; Richter et al. 2004; Danforth & Shull 2005; Tumlinson et al. 2005). The inferred number density of absorption systems is large ($dn/dz \sim 15$), suggesting that these systems constitute a significant baryon reservoir. However, in collisional-ionization equilibrium (CIE), O VI only exists near the lower end of
the WHIM temperature range. According to the simulations, most of the gas can only be probed through O VII or O VIII absorption, both of which require X-ray studies. The current generation of instruments does not have the sensitivity to measure the weak absorption expected from the IGM, and there are relatively few firm detections. A number of groups have found O VII and O VIII absorption at z = 0 which may be associated with the Local Group (Nicastro et al. 2002; Fang, Sembach & Canizares 2003; Rasmussen, Kahn & Paerels 2003). Nicastro et al. (2005) recently discovered two O VII absorbers along the line of sight to the blazar Mrk 421 during an outburst. Other detections have relatively low significance or lack confirmation from different instruments (e.g. Fang et al. 2002b). Nevertheless, the Mrk 421 line of sight suggests an even higher number density than O VI (dn/dz ∼ 60), albeit with large statistical uncertainties.

Comparison to lines of sight extracted from simulations suggests that these number densities are comparable to theoretical expectations (Hellsten, Gnedin & Miralda-Escudé 1998; Cen et al. 2001; Fang & Bryan 2001; Fang, Bryan & Canizares 2002a; Chen et al. 2003). Detailed quantitative tests are difficult because of the large uncertainties on both the observational and theoretical sides (with the latter depending primarily on the unknown distribution of metals in the IGM), but the overall consistency is a reassuring confirmation of the cosmic-web paradigm. However, the existing studies have not addressed many questions about their physical origin or characteristic environment. As a result, we lack a clear picture of their specific role in the structure-formation process. For example, do they probe outlying filamentary gas, gas more closely associated with galaxies, or something entirely different? Do the O VI and O VII absorbers probe distinct environments, and do the two ions have different physical origins? What sets the observed column densities?

In this paper, we provide an analytical framework to answer these questions. This is clearly a difficult proposition: the WHIM is non-linear and inherently asymmetric, so it is difficult to model analytically. Nevertheless, models describing the gross properties of the WHIM do exist (Nath & Silk 2001; Valageas, Schaeffer & Silk 2002; Furlanetto & Loeb 2004), and it is interesting to consider what these simple arguments reveal about the absorbers. Moreover, if shocks are ultimately responsible for heating gas to the WHIM temperatures, simple models of post-shock cooling can help to explain the properties of the absorbers (Heckman et al. 2002). We connect these two approaches in order to identify the key properties of the absorbers and how they may relate to collapsed objects.

The plan of this paper is as follows. In Section 2, we show how post-shock cooling predicts characteristic column densities for the absorbers. We then construct a simple analytical model to predict the abundance of IGM oxygen absorbers in Section 3. We highlight some of the strengths and weaknesses of this model by comparing to cosmological simulations in Section 4. In Section 5, we show that comparing the O VI and O VII columns can robustly distinguish shock-heated and photoionized O VI absorbers. Finally, we conclude in Section 6.

We are primarily concerned with O VI, O VII and O VIII in this paper. For reference, we list details of their strongest transitions here. O VI has an ultraviolet doublet at λ = 1032, 1038 Å; the corresponding oscillator strengths are f _O VI _osc = 0.133, 0.0660. The most prominent O VII line is the HeII transition with λ = 21.602 Å and f _O VII _osc = 0.6945, while that for O VIII is the Lyα transition with λ = 18.97 Å and f _O VIII _osc = 0.416. To avoid any assumptions about the velocity widths of each line, we present all of our results in terms of column density N _ion. Observations are instead often presented in terms of equivalent width W (which is the fundamental observable). In the unsaturated limit, the two quantities are related (in cgs units) via W = 8.85 × 10⁻¹¹ N _ion f _osc λ² (e.g. Spitzer 1978). (For O VI, W is usually, although not universally, quoted for the stronger of the two doublet transitions.)

Throughout our discussion we assume a cosmology with Ω_m = 0.3, Ω_L = 0.7, Ω_b = 0.046, H_0 = 100 km s⁻¹ Mpc⁻¹ (with h = 0.7), n = 1, and σ_8 = 0.9, consistent with the most recent measurements (Spergel et al. 2003).

2 CHARACTERISTIC COLUMN DENSITIES

We begin with the simple question of whether shock heating can account for the observed column densities of O VI absorbers. A number of recent observations have found a large number of such systems in the local Universe, with typical column densities in the range N _O VI _P ≈ 2–20 × 10¹³ cm⁻² (e.g. Tripp et al. 2000; Sembach et al. 2001; Prochaska et al. 2004; Richter et al. 2004). While the lower limit may be an observational selection effect (but see Danforth & Shull 2005), the rapid decline in abundance as the column density approaches 10¹⁴ cm⁻² suggests that this is a characteristic maximum strength.

Heckman et al. (2002) provide a simple argument for why we should expect shocks to produce columns in this range. Consider a parcel of gas that is shocked to a temperature T_g. It will flow away from the shock with a velocity v_g (fixed by the jump conditions). After a time t _cool = 3 kT_g/n_g λ it will have radiated its thermal energy and no longer be highly ionized; here, n_g is the post-shock gas density and λ its normalized cooling rate in erg cm⁻³ s⁻¹. If we view the system along a plane perpendicular to the shock, and if the gas cools fully, we therefore expect to see highly ionized gas along a path-length l _cool ∝ v_g t _cool with a corresponding column density N ∝ n_g l _cool. Thus

N _O VI = f _O VI Z [O/H] n_g v_g t _cool (1)

where [O/H] = 10⁻³⁻⁰⁷ is the oxygen abundance by number in gas with solar metallicity (using the abundances of Sutherland & Dopita 1993). Z is the metallicity in solar units, and f _O VI is the fraction of oxygen atoms in the fifth ionized state. We note that the post-shock speed is directly related to the post-shock temperature via

v_g = \left( \frac{k T_g}{3 \mu m_p} \right) ^{1/2} \approx 50 \left( \frac{T_g}{10^4 K} \right) ^{1/2} \text{km s}^{-1}, \quad (2)

where we have assumed that the shock is strong (so that v_s = v_g/4, with v_s the speed of the shock) and μ m_p is the mean molecular mass. Heckman et al. (2002) emphasized that for moderately enriched gas, Λ ∝ Z (e.g. Sutherland & Dopita 1993). In this fully cooled case, we therefore expect the column density to be independent of the metallicity and physical density.

We note that there is some tentative observational evidence for such a picture. Shull et al. (2003) and Tumlinson et al. (2005) each found pairs of O VI absorbers displaced by v_s ≥ 200 km s⁻¹ from associated H I and/or low-ionization state metal absorbers. They suggested that the velocity difference may be characteristic of a shock.

Of course, equation (1) is only approximate because both t _cool and f _O VI depend on temperature. To properly compute the column density, we need to trace the (non-equilibrium) ionic abundances throughout the cooling (e.g. Dopita & Sutherland 1996). Fortunately, we can estimate the result reasonably well because f _O VI peaks sharply around a characteristic temperature, as we show in
Fig. 1. (a) Fractional abundance of O VI, O VII and O VIII (solid, dashed and dotted curves, respectively) if we assume CIE. (b) Ratio of the cooling time to the Hubble time, as a function of gas temperature. The solid, long-dashed, short-dashed, and dotted curves assume \( Z = 0.3, 0.1, 0.03 \) and 0.01 Z⊙, respectively. All curves assume that the gas element has density 10 times the mean (i.e. \( \Delta = 10 \Delta_{10}, \) with \( \Delta_{10} = 1 \)).

Fig. 1(a). We have computed the ionization fractions \( f_{\text{ion}} \) of the highly ionized states of oxygen using CLOUDY (version 94; Ferland 2001) for gas in CIE. We see that O VI is extremely sensitive to the gas temperature; \( f_{\text{OVI}} \sim 0.3 \) at \( T \approx 10^{4.5} \) K but drops steeply away from this value. The ionization fraction for O VII, on the other hand, rises rapidly to \( f_{\text{OVI}} \sim 1 \) in the same temperature range for which O VI rises, but it remains large for all \( 10^{5.5} < T < 10^{6.5} \) K. This is a simple consequence of the lone \( n = 2 \) electron in O VI, which is much easier to strip than the \( n = 1 \) electrons in O VII: the ionization potentials of O VI and O VII are 138.1 and 739.3 eV, respectively. The plateau in \( f_{\text{OVI}} \) at \( T \approx 10^{6} \) K and \( f_{\text{OVI}} \sim 0.003 \) occurs for the same reason. Clearly, O VI will come from gas in a narrow temperature range. Fig. 1(b) shows the ratio of the cooling time to \( H_{\odot}^{-1} \), also computed with CLOUDY, for a range of metallicities. In the plot we assume that \( \Delta = 10 \), where \( \Delta = n/n_{\odot} \) is the gas density relative to the cosmic mean; of course, \( t_{\text{cool}} \propto \Delta^{-1} \). The cooling time drops rapidly as we approach \( T \approx 10^{4.5} \) K from above (partly because of the strong O VI \( \lambda \lambda 1032, 1038 \) doublet) and then decreases further as O VI recombines. Heckman et al. (2002) pointed out that this allows us to substitute the values of \( f_{\text{OVI}} \) and \( t_{\text{cool}} \) at the O VI peak in equation (1), yielding

\[
N_{\text{OVI}} \approx 10^{44} \left( \frac{V}{50 \text{ km s}^{-1}} \right) \text{ cm}^{-2}
\]

for enriched gas; note that the result is independent of metallicity and physical density. The column density depends only on

\footnote{The CIE cooling models of Sutherland & Dopita (1993) are often used for this purpose. However, those tables modify the [O/Fe] ratio as a function of metallicity; because oxygen is particularly important for our purposes, we have chosen to keep its abundance fixed relative to other metals. For consistency with previous work, we use the solar-abundance ratios of Sutherland & Dopita (1993), with the exception of helium (which we set to its primordial value for a mass fraction \( Y = 0.24 \)).}
one important difference between our (time-limited) model and the fully cooled predictions of Heckman et al. (2002). Of course, O VI and O VIII can coexist in the same system.

The thin curves in Fig. 2 show the O VII column densities corresponding to each shock temperature. We see that O VII absorption should be significant over a much larger range of temperatures than O VI, but because the cooling times are long, the maximum $N_{\text{O VII}}$ is much more sensitive to the gas density and metallicity. We therefore cannot robustly predict a maximum that should be significant over a much larger range of temperatures than O VI.

Moreover, we do not expect every halo to host an absorber of a given type. As the depth of the potential well increases, the virial shock becomes stronger and the gas temperature increases. Thus, higher ionization states trace gas associated with larger objects, and we require some prescription to associate dark matter haloes with ion columns. We now consider two simple possibilities: virial shocks and infall shocks.

### 3 Abundance of Oxygen Absorbers

If the WHIM gas and the oxygen absorbers are a result of structure formation, it is natural to associate them with virialized dark matter haloes. We suppose that each halo has a cross-section to host an absorber that is proportional to the square of its virial radius $r_{\text{vir}}$, which we define as in Barkana & Loeb (2001). We can motivate such a scenario by noting that each halo is surrounded by a virial shock which we define as in Barkana & Loeb (2001).

With this picture, we can compute the differential number $dN/\Delta z$

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Column density of cooling material corresponding to a given shock temperature. The lower set of thick lines is for O VI, while the upper thin lines are for O VII. Solid, long-dashed and short-dashed curves have $\Delta = 10$ with $Z = 10^{-1}$, $10^{-1.5}$ and $10^{-2} Z_{\odot}$, respectively. Dotted and dashed curves have $\Delta = 100$ with $Z = 10^{-1.5}$ and $10^{-2} Z_{\odot}$.

The solid and dotted curves are for $z = 0$ and $z = 0.2$, respectively.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Number of virialized objects intersected per unit redshift as a function of halo mass. The top axis shows the corresponding virial temperature. The crucial result is that the number of systems intersected is small, of the order of a few per unit redshift. Thus, to reproduce the observed number density of O VI and O VII absorbers, we must have absorbers in the IGM outside virial objects; however, the virialized systems could still account for strong absorbers, so we cannot neglect them entirely.

Moreover, we do not expect every halo to host an absorber of a given type. As the depth of the potential well increases, the virial shock becomes stronger and the gas temperature increases. Thus, higher ionization states trace gas associated with larger objects, and we require some prescription to associate dark matter haloes with ion columns. We now consider two simple possibilities: virial shocks and infall shocks.

#### 3.1 Virialized haloes

Once gas falls through the virial shock, it is heated to $T_{\text{vir}}$ and begins to cool radiatively. If $t_{\text{cool}}$ is small, it accretes on to the central galaxy, passing through a range of ionization states along the way. If $t_{\text{cool}}$ is large, the gas remains in a diffuse halo (White & Frenk 1991). Virial shocks thus provide an obvious source for hot absorbing gas. The relevant halo masses can be read from the top axis of Fig. 3, which shows $T_{\text{vir}}$ as a function of halo mass; we see that massive galaxies and groups correspond to the temperature range of interest.

We note that both simulations and analytical arguments suggest that virial shocks do not form in many systems (Birnboim & Dekel 2003; Keres et al. 2004). However, for the halo masses and redshifts considered here, the ‘hot’ accretion phase dominates and virial shocks should be omnipresent.
To compute the absorber statistics, we follow the simple picture of White & Frenk (1991) and divide the gas into two components. First, if $t_{\text{cool}} < H_0^{-1}$, we assume that it cools fully. We evaluate the cooling time at a density $\Delta_{\text{cool}}$ (usually 200) reflecting the typical density within a halo. In this case, we can compute the column density of each system using the post-shock-cooling model described in Section 2: each halo mass then corresponds to a single column density independent of the impact parameter (at least if we neglect orientation effects). Equation (4) gives the number of absorbers per unit redshift provided that we include only those haloes hosting absorbers of the specified column. From Fig. 1(b), it is obvious that, at virial overdensities, cooling will be complete for haloes with $T_{\text{vir}} \lesssim 10^6$ K. This regime will thus be especially important for the O vi absorbers.

In the other regime, where $t_{\text{cool}} > H_0^{-1}$, the gas settles into a quasi-equilibrium hot halo with $T = T_{\text{vir}}$. We could again use the model of Section 2 to compute the corresponding columns. However, the density structure is likely to be important for virialized haloes, and reasonably well-motivated models for the profile do exist. We therefore use a simplified version of Perna & Loeb (1998), in which we integrate along a line of sight through the halo to find the column density; obviously the column density does depend on the impact parameter in this case. We assume that a fraction $f_h = 0.5$ of an object’s baryonic mass is contained in a diffuse gaseous halo within $r_{\text{vir}}$. We also assume that its density follows a beta-model $\rho \propto [1 + (r/r_c)^2]^{-1}$, where $r_c$ is the core radius. We take $r_c = r_{\text{vir}}/4 \equiv c_f r_{\text{vir}}$, which is approximately consistent with the profiles of luminous clusters (Jones & Forman 1999). We assume isothermal gas, so the column density $N_{\text{ion}}$ along a line of sight with impact parameter $b$ is

$$N_{\text{ion}} = f_{\text{ion}} Z [O/\text{H}] \int_0^b 2\Delta \tilde{H}(z) \frac{r_c}{3\Omega m g(c_f)} \frac{r_c}{\sqrt{1 + b^2/r_c^2}} \times \tan^{-1}\left(\frac{r_{\text{vir}}^2 + b^2}{r_c^2 + b^2}\right),$$

where the metallicity is in solar units, $\Delta$ is the virialization overdensity in units of the critical density (Bryan & Norman 1998), and $g(x) = x^2(1 - x \tan^{-1}x^{-1})$. In the slow-cooling limit, we have $N_{\text{ion}} \propto f_h Z$. The number of systems per unit redshift is then the analogue of equation (4)

$$\frac{dN(>N_{\text{ion}})}{dz} = \frac{dr}{dz} \int dm(m) \tau R^2(m, N_{\text{ion}}),$$

where $R(m, N_{\text{ion}})$ is the maximum impact parameter for a halo of mass $m$ within which the column exceeds $N_{\text{ion}}$.

Thus, to compute the total number of absorbers from virialized haloes, we begin by dividing haloes into fast-cooling and slow-cooling regimes (this amounts to finding the halo mass above which $t_{\text{cool}}$ exceeds the age of the Universe). For masses above this threshold, we approximate the halo as isothermal and use the halo mass profile of equation (5) to convert to column density as a function of impact parameter; the abundance is then given by equation (6). We need not specify a maximum halo mass, because $n(m)$ falls exponentially fast beyond the non-linear mass scale. For smaller masses, the column density is determined by the shock physics of equation (1) independent of impact parameter, and the corresponding cross-section is given by equation (4) if we integrate only over those haloes with sufficiently large columns. In this case, the integral converges because small haloes correspond to small virial temperatures for which highly ionized oxygen is vanishingly rare (see Fig. 2).

We show our results for O vii and O viii in Fig. 4. The thick curves show the total $dN/dz$, while the thin curves show the contribution from systems with $t_{\text{cool}} < H_0^{-1}$. Long-dashed, solid and short-dashed curves assume $Z = 0.03, 0.1$ and $0.3 Z_{\odot}$ with $\Delta_{\text{cool}} = 200$. The dotted curves assume $Z = 0.1 Z_{\odot}$ and $\Delta_{\text{cool}} = 50$. As expected from Fig. 3, the number of virialized absorbers is a few per unit redshift, well below the total frequency found in observations (Nicastro et al. 2005) and simulations (Fang et al. 2002a) but consistent with other analytical treatments of virialized objects (Perna & Loeb 1998). Systems with $t_{\text{cool}} < H_0^{-1}$ can make a significant

**Figure 4.** Number of virialized absorption systems with column density larger than some threshold per unit redshift for the (a) O vii and (b) O viii ions at $z = 0$. Long-dashed, solid and short-dashed curves assume $Z = 0.03, 0.1$ and $0.3 Z_{\odot}$ with $\Delta_{\text{cool}} = 200$. The dotted curves assume $Z = 0.1 Z_{\odot}$ and $\Delta_{\text{cool}} = 50$. The thick curves show the total $dN/dz$, while the thin curves (plotted only for the solid and short-dashed cases) show the contribution from systems with $t_{\text{cool}} < H_0^{-1}$. In (b), the dotted curve is coincident with the long-dashed curve and the thin solid curve is zero everywhere.
contribution to the O\textsc{vii} absorbers but are unimportant for O\textsc{viii}. However, they are always relatively weak, with a characteristic \( N_{\text{O\textsc{vii}}} \sim 10^{15.5} \text{cm}^{-2} \) (which is relatively independent of metallicity). In contrast, hot haloes can contain quite large columns, because the path-lengths can be long. The abundance of O\textsc{vii} absorbers is larger than that of O\textsc{viii} because haloes near the non-linear mass scale have \( T \approx 10^6 \text{K} \), below the ionization threshold of O\textsc{viii}.

Note that the number of high-column-density absorbers increases if the metallicity decreases. As the metallicity declines, the cooling time increases and less-massive haloes retain their hot gas. This makes up for the decreased column in any one absorber because \( n(m) \) falls rapidly with mass. This is in many respects an artefact of our simplified treatment: for \( t_{\text{cool}} \sim H_0^{-1} \), we should include cooling to compute the detailed column densities.

Here and below, we present results for \( z = 0 \). The statistics evolve only modestly to \( z \sim 1 \) (e.g. compare the two curves in Fig. 3). Beyond that, the abundance falls rapidly because the non-linear mass scale falls below \( T_{\text{vir}} \sim 10^6 \text{K} \).

Fig. 5 shows analogous results for O\textsc{vi}. In this case, the rapidly cooling haloes are even more important, yielding a characteristic column density \( N_{\text{O\textsc{vi}}} \sim 10^{14.5} \text{cm}^{-2} \) (see Fig. 2). The high-\( N_{\text{O\textsc{vi}}} \) tail is composed of haloes just above the cooling threshold, which still have relatively large \( f_{\text{O\textsc{vi}}} \). Thus, it only appears if the cooling time is long (i.e. \( Z \) or \( \Delta_{\text{cool}} \) is small) and is subject to uncertainties in our simplified cooling model.

As required by Fig. 3, virial shocks underpredict \( dN_{\text{O\textsc{vi}}} / dz \) and \( dN_{\text{O\textsc{vii}}} / dz \) by factors of several. Clumping will further decrease the cross-section. If we place the shocked gas into \( n_b \) blobs of radius \( r < r_{\text{vir}} \), only a fraction \( f_{\text{cov}} \approx n_b (r/r_{\text{vir}})^2 \) of 1 of lines of sight through each halo would host absorbers. It could however increase the column densities. In the slow-cooling case, we would have \( N_{\text{cov}} \propto f_{\text{cov}}^{-1} \), increasing the amplitude of the strong-absorber tail. On the other hand, fast-cooling gas would be unaffected.

Finally, we note that we have allowed the gaseous haloes in groups to remain relatively dense and hot. It is well known that such models overpredict the soft X-ray background (Pen 1999; Wu, Fabian & Nulsen 2001). One solution is to introduce a feedback mechanism that decreases the density of the intragroup medium (Wu et al. 2001; Xue & Wu 2003). This would, of course, modify our column-density distribution. By slowing the cooling, the principal effect would be to increase the amount of absorption. It could also slightly increase the cross-section if the gas is spread over larger distances. However, simple geometry demands that such pre-heating scenarios will certainly not bring the abundance into agreement with observations; it is more likely to change the column densities by a modest amount. In principle, the distribution of strong IGM absorbers could then be used as a probe of feedback mechanisms, although the many other uncertainties (such as metallicity and non-equilibrium effects) make this a difficult endeavour.

3.2 Infalling gas

To reproduce the large number of absorbers found in simulations and observations, we must appeal to a population beyond virial shocks. This is of course not surprising, because simulations contain large networks of IGM shocks. To connect these shocks with collapsed objects, we postulate that the temperature \( T_{\text{sh}} \) of IGM shocks surrounding each dark matter halo depends (exclusively) on the halo mass. One way to motivate such a picture is if the shocks occur during infall on to existing structures. Furlanetto & Loeb (2004) used this ansatz, together with spherical symmetry, to estimate the distribution of IGM shocks. They argued that shocks could plausibly occur when an object breaks off from the cosmological expansion (at ‘turnaround’), because that is the point at which the flows begin to converge. Assuming strong shocks, the peculiar velocity at turnaround implies \( T_{\text{sh}} \approx T_{\text{vir}}/4 \). The model roughly matches simulation estimates of the mass fraction and characteristic temperature of the WHIM. Although clearly a simplification, this picture does describe many of the major features of the WHIM and provides a well-defined way to convert \( n(m) \) to the distribution of \( T_{\text{sh}} \). Furthermore, spherical infall occurs on quite large scales and could provide the cross-section we need. Turnaround occurs at \( r_{\text{ta}} \approx 3.5 r_{\text{vir}} \) for self-similar spherical infall (Bertschinger 1985) in an Einstein–de Sitter universe, so the shock networks could be quite large relative to collapsed objects. Simulations also show networks of shocks surrounding bound structures at a few times the virial radii (Keshet et al. 2003; Nagai & Kravtsov 2003). However, we leave the cross-section of each infall shock free, because it must depend on the asymmetric, filamentary nature of the infall. We parametrize it as \( \propto T_{\text{vir}}^{-1} \). For reference, the top axis of Fig. 2 shows \( T_{\text{sh}}(m) \) in this infall model.

Because of the lack of data pertaining to IGM shocks, a detailed comparison of this model with observations is difficult. However, Rines et al. (2003) have used galaxy redshifts to trace the infall regions of eight nearby clusters spanning about an order of magnitude in mass. Although the galaxies obviously will not be subject to shocks, their structure should reflect the underlying gas distribution at least qualitatively. Most importantly, Rines et al. (2003) found that \( r_{\text{ta}} \approx 3.5 r_{\text{vir}} \) in all of their clusters. The spherically averaged density profiles fall as \( r^{-3} \) at large radii, consistent with simulations (Hernquist 1990; Navarro, Frenk & White 1997). This implies that the average density falls by about a factor of 50 between the virial radius and turnaround radius. However, as we show in Section 4, the density field is highly inhomogeneous within this region. For simplicity, we assume a constant density behind these shocks. Finally, Rines et al. (2003) compute the velocity dispersion profiles. Between \( r_{\text{vir}} \) and \( r_{\text{ta}} \), the dispersion typically declines by a factor of 2 or so. This is nicely consistent with our assumption that \( T_{\text{sh}} \approx T_{\text{vir}}/4 \).
Given this prescription, we can compute the expected number of absorbers using the post-shock-cooling model of Section 2. Here we use this model for both fast-cooling and slow-cooling shocks, because (unlike for virialized haloes) we have no well-motivated model for the density profile of IGM filaments. However, we caution the reader that geometry (such as the thickness of filaments) could still ultimately determine the column densities. We also note that, for these modest densities \( \Delta \sim 10 \), the recombinations times can approach or even exceed the age of the Universe, so our assumption of local CIE in calculating the abundances may be problematic (see discussion in Section 2). To compute \( \frac{dn}{dz} \), we use equation (4), with the integration range set by the column density corresponding to each halo mass. Operationally, the calculation is similar to that described in Section 3.1, except that equation (1) applies to both fast-cooling and slow-cooling shocks.

Given the simplifications of our model, a detailed comparison to observations is unwarranted. However, we do wish to estimate the required \( \chi \) as well as to check whether the derived column densities are reasonable. As such, we begin with O\( \text{VI} \), which is by far the best studied ion. The filled squares in Fig. 6 show a distribution compiled from several lines of sight in the literature (Tripp et al. 2000; Sembach et al. 2001; Prochaska et al. 2004; Richter et al. 2004); these lines of sight have the best-defined samples. We have included all claimed detections (even those labelled 'tentative' by each survey’s authors). The error bars assume Poisson statistics. The open hexagons show the more systematic survey of Danforth & Shull (2005), who searched for O\( \text{VI} \) absorbers in 129 known Ly\( \alpha \) absorbers along 31 lines of sight studied with the *FUSE* satellite. We refer the reader to that paper for a detailed discussion of the errors.

Note that the two data sets are reasonably consistent, although the Danforth & Shull (2005) data do lie below our compilation by a small amount.

The curves in Fig. 6 show the results from our model assuming \( \chi = 8 \). The long-dashed, solid and short-dashed curves assume \( Z = 0.03, 0.1 \) and \( 0.3 Z_\odot \), respectively, with \( \Delta = 10 \). The dot-dashed curve assumes \( Z = 0.1 Z_\odot \) with \( \Delta = 100 \). The dotted curve is the same as the solid curve except that we take \( T_{\text{sh}} = T_{\text{vir}}/6 \). The two sets of points show observed results (the solid squares are described in the text; the open hexagons are from Danforth & Shull 2005). The thick solid curve adds the contribution from virialized systems.

3 However, we have not attempted to account for the different detection limits of each survey. As such, the statistics at \( N_{\text{OVI}} \sim 10^{13} \text{ cm}^{-2} \) may not be reliable.
well-studied line of sight (with secure detections of two absorbers); formally, this implies \( \frac{dn}{dz} (N_{\text{OVIII}} \gtrsim 7 \times 10^{14} \text{ cm}^{-2}) = \frac{67 \pm 88}{\Omega_1 / \Lambda_1} \) (Nicastro et al. 2005). Our model is well within this range. It is more interesting to note that the observed columns (\( 7 \times 10^{14} \) and \( 10^{15} \) cm\(^{-2} \)) are both near the cut-off and appear to require \( \Delta \gtrsim 30 \) or \( Z \sim 0.3 \, Z_\odot \), still well within reasonable bounds. Simulations suggest \( \frac{dn}{dz} (N_{\text{OVIII}} \gtrsim 7 \times 10^{14} \text{ cm}^{-2}) \sim 10-30 \), close to our model with \( \chi = 8 \) (Fang et al. 2002a; Chen et al. 2003). They do not show as severe a break as our model, probably because of scatter in the metallicity and geometric effects.

Fig. 7(b) shows that the expected number of \( \text{OVIII} \) absorbers is about half that of \( \text{OVII} \), although the column densities can be comparable. \( \text{OVIII} \) is rarer simply because the characteristic shock temperature is \( \lesssim 10^8 \text{ K} \) (Furlanetto & Loeb 2004), so there is not as much gas with large \( f_{\text{OVIII}} \). As a result, virialized systems make a larger relative contribution. Also, note that \( \text{OVIII} \) does not show a sharp cut-off; this is because \( f_{\text{OVIII}} \) varies rapidly with temperature.

4 COMPARISON TO SIMULATIONS

We have shown that the spherical-infall model described in the previous section can explain many of the key properties of the absorbers. However, it also makes a number of important assumptions and simplifications. Here we compare our model to simulations in order to highlight its strengths and weaknesses.

4.1 Cosmological simulation

We use the \( z = 0 \) dark matter, stellar-particle, gas-temperature and density outputs of a large-scale \( L = 25 \, h^{-1} \) Mpc cosmological hydrodynamical simulation, with \( 768^3 \) fluid elements and \( 384^3 \) dark matter particles (each with mass \( 2 \times 10^7 \, h^{-1} \) M\(_\odot\)). The code structure is similar to that in Cen & Ostriker (1992a,b) with some significant changes (Cen & Ostriker 2000). It is described in detail in Nagamine et al. (2001). The chosen cosmology is the ‘concordance model’ (Wang et al. 2000), a flat low-density (\( \Omega_m = 0.3 \) universe with a cosmological constant (\( \Omega_\Lambda = 0.7 \)) and \( h = 0.67 \). The baryon density (originally \( \Omega_b = 0.049 \)) has been scaled to \( \Omega_b = 0.046 \) to match the value used in our analytical model. The galaxy particles are formed through the recipe described in the appendix of Nagamine, Cen & Ostriker (2000). Each stellar particle is assigned a position, velocity, formation time, mass, and metallicity at birth. The stellar particle is placed at the centre of the cell with a velocity equal to the mean velocity of the gas in the cell. It is then followed by a particle-mesh code as a collisionless particle interacting gravitationally with the dark matter and the gas. We use the galaxy and group position information obtained from these stellar particles by Nagamine et al. (2001).

We are primarily concerned with the IGM around bound objects. We use the dark matter halo parameters for this simulation obtained by Nagamine et al. (2001) with the HOP grouping algorithm of Eisenstein & Hu (1998). We then search for the haloes that are most closely coincident (\( \Delta L \lesssim 68 \, h^{-1} \text{ kpc} \)) with the galaxy-particle groups, and we use the properties of these dark matter haloes. The virial radius is obtained from halo mass using equation (24) of Barkana & Loeb (2001). Around the centre of each halo, we obtain the volume-averaged radial distributions of matter, temperature and metals in the inner regions abutting the galaxy-particle locations in the \( z = 0 \) output

\[
\frac{\int d^3x \rho(x) Q(x)}{\int d^3x \rho(x)},
\]

where \( Q(x) \) is the parameter value (\( \Delta, T, f_{\text{ion}}, \) etc.) in the volume element \( d^3x \). For the sake of transparency, we do not directly use the metallicities reported by the simulation. Instead we consider two metallicity prescriptions. The first scales metallicity with density as described by Croft et al. (2001), \( Z = (0.005 \, Z_\odot)\sqrt{\bar{n}/n} \), with a maximum metallicity of \( Z = 0.33 \, Z_\odot \). The second prescription simply uses a constant metallicity \( Z = 0.1 \, Z_\odot \). In order to study the \( \text{OV}, \text{OVII} \) and \( \text{OVIII} \) abundance distributions, we compute the ionization fraction as a function of temperature, as illustrated in Fig. 1(a). With \( f_{\text{ion}} \) for each cell, plus the density and metallicity, we compute the total ionic abundance relative to hydrogen. We scale the distributions by the virial radius corresponding to each halo and follow them out to five virial radii. We obtain the volume-averaged distributions for several virial-radius bins, \( r_{\text{vir}} = 240-300, 360-480 \) and \( 600-720 \) kpc; these correspond to roughly (1–2), (3–7) and (14–24) \( \times 10^{12} \, M_\odot \).
4.2 Absorbers around virialized haloes

The key ansatz in our infall-shock model is that the characteristic IGM temperature surrounding a collapsed object increases with its mass, even on scales much larger than \( r_{\text{vir}} \). Fig. 8 shows spherically averaged temperature profiles around haloes in the simulation (normalized by \( r_{\text{vir}} \)). We see that isolated galaxies tend to lie in cooler regions of the IGM than massive groups, even at several times \( r_{\text{vir}} \). The trend appears to break down at \( r \gtrsim 3 r_{\text{vir}} \) for the smallest objects. This is in a temperature range where cooling can be significant, which may affect the results. Also note that there is no characteristic radius at which the temperature increases, as would be expected for pure spherical infall. Thus, the shocks appear to be complex and distributed, with a range of temperatures. The typical temperature is however a few times smaller than \( T_{\text{vir}} \), consistent with our model.

Fig. 9 shows that it may be more accurate to associate different oxygen ions with different halo masses. The three panels show the spherically averaged ionization fractions for each of our ions as a function of normalized radius. The curves correspond to the same mass ranges shown in Fig. 8. We see that O\textsc{vi} tends to be associated with the smallest-mass objects, although even these haloes are too hot to sustain a large \( f_{\text{O\textsc{vi}}} \) inside \( r_{\text{vir}} \). On the other hand, O\textsc{viii} is most prevalent around the highest-mass objects (although not within the virialized regions, again because the gas is too hot) and is extremely rare around the low-mass objects. Finally, O\textsc{vii} appears in all systems because it dominates over such a wide temperature regime; only the virialized gas in extremely massive objects is hot enough to destroy O\textsc{vii}.

Thus, we can be confident in expecting highly ionized absorbers to lie near massive collapsed objects. However, the simulations also show that a simplified spherical model is not accurate. In Fig. 10 we have computed \( \frac{dn}{dz} \) for each ionic absorber using our spherical profiles. We have used equation (6) with the column densities determined by integrating through the average profiles. In each case we truncate the profile at \( 5 r_{\text{vir}} \). The dotted, dashed and solid curves show the expected statistics for O\textsc{vi}, O\textsc{vii} and O\textsc{viii}, respectively. First consider the thin curves, which assume a constant \( Z = 0.1 Z_{\odot} \) metallicity (as in our fiducial analytic model). We see \( \frac{dn}{dz} \sim 65 \) for each ion at sufficiently small column densities. This is an artefact of truncating the integration at \( 5 r_{\text{vir}} \). The profiles in Fig. 9 tend to approach nearly constant values at large radii, so for large impact parameters the column density is essentially proportional to the maximum radius; only well above this turnover can the column densities be trusted.
In that range, O VII and O VIII do not present dramatically different pictures from the analytical model. Because $f_{\text{O VII}}$ is nearly temperature-independent over a broad range, we might expect spherical averages to do a passable job with that ion. Indeed, the number density does agree roughly with our model and with more detailed simulation analyses (Fang et al. 2002a; Chen et al. 2003). However, it is certainly not so good that we can claim support for our model. O VIII is considerably worse, and the O VI results do not appear to have converged and disagree strongly with our model. This is also not surprising, because O VI is often in a fast-cooling regime and is so temperature sensitive that averaging over large volumes artificially suppresses its importance. Ray tracing appears vital to predict the O VI absorber abundance, as would be expected in a shock-cooling model.

The thick curves in Fig. 10 assume the density-dependent metallicity distribution described above. The number of absorbers declines sharply in this scenario: at large radii, the mean physical densities are near the cosmic mean, so the overall metallicity is small. As a result, high column densities require small impact parameters. One fortunate consequence is that the curves converge better. However, much more significantly, the number of absorbers is far below the result of more complete simulation analyses (Cen et al. 2001; Fang & Bryan 2001; Fang et al. 2002a; Chen et al. 2003). Thus, the spherical averages do not accurately describe the absorbers in simulations. Of course, this is the clumpiness of the IGM.

Fig. 11 shows phase diagrams of the IGM gas surrounding haloes with $M = 3–7 \times 10^{12} \, M_{\odot}$ in four radial slices. The $n_{\text{OVII}}$, $n_{\text{OVI}}$, and $n_{\text{OVIII}}$ averaged contours were obtained using the Croft et al. (2001) prescription for the metallicity. Hotter gas tends to sit at higher densities (and hence occupy a small volume). This correlation holds even at $\Delta \sim 1–10$, well below virial overdensities. Moreover, the mean temperature and density decrease and the scatter in the relation increases as one moves away from the central galaxy. However, regardless of radius there is a non-negligible fraction of gas at high temperatures comparable to $T_{\text{vir}}$. This gas (which also has a relatively large density) is presumably responsible for most of the oxygen absorption. Thus, as can be seen from Fig. 11(d), the higher-ionization states will tend to probe the densest filaments (and the most enriched gas, on average) around each structure, in addition to the largest structures. Meanwhile, most of the volume is filled with cooler, low-density gas that has a small metallicity given our prescription. The averaging procedure smooths the high-density gas, boosting the column density along all lines of sight under a constant metallicity. However, when the metallicity is density-dependent, the tenuous gas is so metal-poor that the dense clumps essentially disappear during averaging. These clumps are reflected in the fragmentary nature of the density-averaged contours at higher $\Delta$. As one moves outward, they represent an ever-decreasing fraction of the volume but continue to contribute significantly to $n_{\text{OVII}}$, $n_{\text{OVIII}}$, and even $n_{\text{OVI}}$. The distribution is highly complex: there is a wide range of temperatures for any given density (spanning about a decade for $\Delta \sim 10$), which reflects the non-uniformity of the infall process.

How can we reconcile the apparent success of our analytical treatment with the clear failure of spherical averaging in simulations? The key reason is that, with the exception of hot virialized haloes, we did not use spherical geometry in the calculation; instead we used only the infall velocities and a cooling time (capped at $H_{\odot}^{-1}$). The physics of shock cooling then predicted the column densities without recourse to the gas distribution. Thus, we only need modify our picture to describe a network of inhomogeneous shocks with total cross-section $\pi T_{\text{vir}}^{-2/3}$ rather than a single coherent structure. Of course, it is still an open question whether our model provides an accurate description of these networks even on a mean level (specifically the shock temperature). In the future, quantitative treatments must also consider the importance of the scatter seen in Fig. 11.
5 PHOTOIONIZED GAS

To this point, we have focused on systems that are cooling after being collisionally ionized by a shock. In simulations, such systems make up only about half of the O VI absorbers (Fang & Bryan 2001; Cen et al. 2001). The others are photoionized; such systems are rare for the strong absorbers but dominate at \( N_{\text{OVI}} \simeq 10^{13} \text{ cm}^{-2} \). In the simulations, these absorbers are typically cooler and lower-density than collisionally ionized systems. Modelling of the observed O VI systems also suggests that about half are photoionized (e.g. Prochaska et al. 2004). However, this interpretation is subject to uncertainties in the relative metal abundances, the ionizing background, and whether the medium is multiphase. Reliably separating this population is crucial because it typically has \( T \sim 10^4 \text{ K} \), which means that these systems are not part of the canonical WHIM. We have shown in Section 2 (see Fig. 2) that post-shock cooling predicts that individual O VI absorbers should have O VII columns about an order of magnitude larger than \( N_{\text{OVI}} \). This is larger than \( f_{\text{OVI}}/f_{\text{OVI}} \) in CIE at the O VI peak because most shocks begin at higher temperatures and cool into the O VI range, so O VII probes a longer path-length through the post-shock region. We now calculate the associated O VI columns if photoionization dominates.

We have again used CLOUDY (version 94; Ferland 2001) to compute \( f_{\text{OVI}} \) and \( f_{\text{OVI}} \) assuming ionization equilibrium with an input radiation background. We have constructed a grid in density and temperature with spacings \( \Delta \log n_H = 0.5 \) for \( -7 < \log n_H < -3 \) (in units of \( \text{cm}^{-3} \)) and \( \Delta \log T = 0.1 \) for \( 3 < \log T < 7 \) (in K). We use the \( z = 0 \) Haardt & Madau (2001) ionizing background normalized to a total ionizing rate \( \Gamma_{-12} = 0.084 \) (in units of \( 10^{-15} \text{ s}^{-1} \)). This roughly matches the observational estimate of Davé & Tripp (2001).

Fig. 12 summarizes our results. Fig. 12(a) shows the logarithm of the ratio \( f_{\text{OVI}}/f_{\text{OVI}} \). Dashed (solid) contours indicate \( f_{\text{OVI}}/f_{\text{OVI}} > 1 \) (\( < 1 \)). To delineate those regions of phase space where we could expect O VI absorbers in the IGM, Fig. 12(b) shows the logarithm of the path-length (in kpc) that would be required to produce an absorber with \( N_{\text{OVI}} = 10^{15} \text{ cm}^{-2} \) if \( Z = 0.1 Z_{\odot} \). Systems with \( \Delta \lesssim 100 \text{ kpc} \) are confined to gas with \( T \lesssim 10^5 \text{ K} \) and \( n_H \sim 10^{-6} - 10^{-5} \text{ cm}^{-3} \) or to relatively dense gas lying close to the ionization temperature of O VI. In the former case, we find that \( f_{\text{OVI}}/f_{\text{OVI}} \gtrsim 1 \), unless the gas has \( T \sim 10^{6.5} \text{ K} \) (in which case collisional processes dominate and it is part of the WHIM) or is extremely tenuous and spatially large. Thus, photoionized absorbers have smaller associated X-ray absorption than in the post-shock-cooling model and comparison of \( f_{\text{OVI}}/f_{\text{OVI}} \) offers a powerful test of the nature of the absorbing gas. Upper limits of \( N_{\text{OVI}} \sim 3 N_{\text{OVI}} \) can robustly identify those absorbers with \( T < 10^5 \text{ K} \) and separate WHIM systems from cooler photoionized gas.

This conclusion holds even if the ionizing background has a different amplitude or shape. The ratio \( f_{\text{OVI}}/f_{\text{OVI}} \) is nearly independent of \( \Gamma_{-12} \). The required path-length for low-density cool gas increases slightly as \( \Gamma_{-12} \) increases, making tenuous absorbers more unlikely. The shape of the metagalactic background matters little because the ionization potentials of Ov and O VI are so closely spaced (114.2 and 138.1 eV, respectively). We would have to introduce a (physically unmotivated) sharp feature to the background in this energy range to substantially change the ion ratios. We have verified this with the Haardt & Madau (1996) ionizing background, which includes only quasars and is significantly harder than the Haardt & Madau (2001) background (which also includes galaxies). The corresponding Fig. 12 looks identical.

It is worth emphasizing that \( f_{\text{OVI}}/f_{\text{OVI}} \) is less subject to modelling uncertainties than constraints that use only ultraviolet lines (e.g. Prochaska et al. 2004) because it depends only on a single atomic species. We also note that other ionization states could be useful. For example, shocks that produce O VIII have \( T_{\text{cool}} \gg H_0^{-1} \) and should not contain substantial O VI. Thus, a large measured \( f_{\text{OVI}}/f_{\text{OVI}} \) would help to identify photoionized systems. Note that Heckman et al. (2002) imply that large columns of O VI and O VIII can coexist in the same absorber. This is because they implicitly assume that the material cools fully; while reasonable for Galactic systems, this limit is not relevant for IGM absorbers.

Finally, Heckman et al. (2002) also pointed out that the linewidth-column-density relation offers another way to discriminate between photoionization and post-shock cooling.

6 DISCUSSION

In this paper, we have attempted to elucidate the physical origin and properties of IGM oxygen absorbers (O VI, O VII and O VIII) with a set of simple analytical arguments. While simulations appear to predict approximately the correct number of absorbers (Cen et al. 2001; Fang & Bryan 2001; Fang et al. 2002a; Chen et al. 2003), such studies have only examined the physical origin of the absorbing gas in a cursory fashion. We first argued that the typical maximum column density of O VI absorbers \( N_{\text{OVI}} \sim 10^{15} \text{ cm}^{-2} \) follows naturally from post-shock cooling (Heckman et al. 2002), suggesting that at least some absorbers are generated by structure-formation shocks. We then argued that, if these shocks are associated with bound structures, we must have a (more numerous) population of significantly hotter shocks around larger objects. These shocks can be traced by O VII and O VIII; the former is more useful because it dominates over such a broad temperature range. Moreover, shocked O VI systems must all have strong O VII absorption. This contrasts with photoionized O VI absorbers, which should have O VII columns not much larger than the O VI columns.

We have shown that a simple picture with virial shocks and ‘infall’ shocks can account for the observed number density of absorbers if each bound halo has a total cross-section several times larger than \( \pi r_s^2 \). The inferred cross-section depends on the fraction of observed...
O VI systems that are photoionized; if it is negligible, we find $\chi \approx 8$. If about half of the weak absorbers are photoionized (as suggested by some recent data; Prochaska et al. 2004), $\chi \approx 4$; however, this does not necessarily affect the predicted abundance of strong absorbers, which mostly arise from virial shocks. In our picture, the temperature of the infall shock increases with the central object's mass (Furlanetto & Loeb 2004). Comparison to numerical simulations shows that these shocks are complex, with dense clumps of metal-enriched shocked gas embedded in a tenuous weakly absorbing medium. They do confirm our key assumption, the association of hotter shocks with more massive systems (albeit with substantial scatter). In the future, we hope that more detailed comparisons to simulations will test other elements of our picture.

One of our most interesting results is that, while O VII and O VI can be associated with the same shocked system (even neglecting multiphase media from thermal instabilities), they do not necessarily sample the same physical volume. As the gas flows away from the shock, it cools over a range of temperatures. O VII is presumably associated with gas closer to the shock, while O VI probes more distant gas. This calls into question modelling of the absorbers with single-temperature CIE gas. Fig. 2 shows that gas with a more or less constant $N_{\text{OVIII}}$ can correspond to a wide range of $N_{\text{OVII}}$ because of the range of temperatures through which the gas element cools, even if it remains near equilibrium at any single temperature (which may not be a valid assumption; Dopita & Sutherland 1996). The crucial point is that gas with $\Delta \sim 100$ and $T \sim 10^{5}–10^{7}$ K has a cooling time comparable to (although often a few times larger than) the Hubble time, so the temperature varies across the system.

The association of oxygen absorbers with virialization and infall shocks obviously implies that these systems must be spatially correlated with galaxy groups and clusters. This is not unique to our picture; any model that associates absorbers with large-scale shocks in the cosmic web must show a similar correlation. There appears to be a relatively strong correlation between O VI absorbers and galaxy groups: most lines of sight show galaxy overdensities coincident with the absorber locations (Tripp & Savage 2000; Savage et al. 2002; Richter et al. 2004), although it has not been statistically quantified and the correspondence is by no means perfect. Typical separations are $\lesssim 1$ Mpc, suggesting that the correlation must extend significantly beyond the virial radius. Perhaps the clearest example lies along the line of sight toward PKS 2155–304, which has a pair of intergalactic O VI absorbers (Shull et al. 2003) offset by $\pm 400$ km s$^{-1}$ from a galaxy group. Using Chandra, Fang et al. (2002b) also found an O VII absorber coincident with the galaxy group, although subsequent observations with XMM failed to confirm this detection. Because the line of sight passes near the barycentre of the group, the O VII could correspond to virialized gas while the O VI systems probe gas that has not yet reached the virial radius but has nevertheless been shocked during infall. This is somewhat similar to the interpretation of Shull et al. (2003), who argued that O VI and O VII could trace multiphase infalling gas, although in their case they placed the gas in a single shocked region. However, we note that the O VII absorbers discovered by Nichastro et al. (2005) appear to show no correlation with galaxy systems. A more detailed study of the relation between galaxies and the known absorbers should shed light on the physical origin and significance of these systems. For example, photoionized O VI absorbers need not correlate with galaxies because they are not part of the filamentary structure.

Our model may also apply to the Local Group absorber. Nichastro et al. (2002) noted that all three ionization states appear along the line of sight to PKS 2155–304 with $N_{\text{OVIII}} \sim 10^{14}$ cm$^{-2}$, $N_{\text{OVII}} \sim 4 \times 10^{15}$ cm$^{-2}$, and $N_{\text{OVIII}} \sim 5 \times 10^{15}$ cm$^{-2}$. They modelled the absorber as a single phase and favoured a model with low-density photoionized gas. The comparable abundance of O VII and O VII contrasted with the relatively large O VI column ruled out CIE. As a result, the absorber was forced to have a physical size $\sim 5$ Mpc.

In our picture, the transitions sample different spatial locations and shocks. We can easily accommodate $N_{\text{OVIII}}/N_{\text{OVII}}$ at infall shocks associated with halo masses $M \sim 10^{13}$ M$_{\odot}$. The column density $N_{\text{OVIII}}$ would be too small in such a shock; however, our privileged position near the centre of the Milky Way and Local Group implies that this transition could be sampling a second, nearby shocked component at $T_{\text{vir}} \sim 2 \times 10^{6}$ K. Thus, the X-ray absorbers could be cosmological but no more than a few hundred kpc in extent. This is reassuring because, if every dark matter halo comparable to the Local Group had a 5-Mpc hot gaseous halo, we would expect to find several times as many high-column-density O VII and O VIII absorbers as we see or as appear in simulations (Fang et al. 2002a). In that case, the PKS 2155–304 line of sight would have to be unusual; however, comparable absorption columns appear along many other lines of sight through the Local Group (Rasmussen et al. 2003).

Our simple model is clearly not sophisticated enough for detailed predictions of the absorber statistics. For those purposes, cosmological simulations are much more appropriate (Cen et al. 2001; Fang & Bryan 2001; Fang et al. 2002a). Chen et al. (2003) have presented the most detailed treatment to date. They have shown that modern simulations do reproduce the observed number densities, at least to the (admittedly limited) accuracy of the current measurements and given an ad hoc (although reasonable) metallicity distribution. We have taken a complementary approach using analytical arguments to estimate the typical column densities and to parametrize the number densities in terms of the known abundance of collapsed objects. We believe that a combination of the two approaches should yield a much deeper physical understanding of the substantial baryon reservoir probed by these observations.

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