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G. Efstathiou, J. Schaye and T. Theuns

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$\frac{1}{\log 29}$ absorption systems and the intervalactic medium α absorption systems and
the intergalactic medium

the intergalactic medium
BY G. EFSTATHIOU¹, J. SCHAYE¹ AND T. THEUNS^{1,2}

 $1\,$ In *FSTATHIOU¹*, J. SCHAYE¹ AND T. THE
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 $\frac{\delta J}{4}$ Garening, Germany
The last few years have seen a dramatic improvement in our understanding of the
origin of Lyo absorption systems. Hydrodynamic numerical simulations of cold-dark-The last few years have seen a dramatic improvement in our understanding of the origin of Ly α absorption systems. Hydrodynamic numerical simulations of cold-dark-
matter-dominated universes have shown that the many pro origin of $Ly\alpha$ absorption systems. Hydrodynamic numerical simulations of cold-dark-
matter-dominated universes have shown that the many properties of the $Ly\alpha$ absorption systems can be explained by a photoionized, space-filling, intergalactic medium. matter-dominated universes have shown that the many properties of the $Ly\alpha$ absorption systems can be explained by a photoionized, space-filling, intergalactic medium.
Ly α lines offer promising probes of the photoioniz tion systems can be explained by a photoionized, space-filling, intergalactic medium.
Ly α lines offer promising probes of the photoionizing background, the amplitude of
the mass fluctuations at high redshift and the ev Ly α lines offer promising protein the mass fluctuations at higher the intergalactic medium. the intergalactic medium.
Keywords: intergalactic medium; galaxy formation; dark matter

1. Introduction

The existence of a forest of absorption lines blueward of the $Ly\alpha$ emission line in The existence of a forest of absorption lines blueward of the Ly α emission line in quasar spectra has been known for over 30 years (Bahcall & Salpeter 1965; Lynds 1971). These lines arise from Ly α absorption by neut The existence of a forest of absorption lines blueward of the Ly α emission line in quasar spectra has been known for over 30 years (Bahcall & Salpeter 1965; Lynds 1971). These lines arise from Ly α absorption by neut quasar spectra has been known for over 30 years (Bahcall & Salpeter 1965; Lynds 1971). These lines arise from Ly α absorption by neutral hydrogen from intervening structure along the line of sight. Early theoretical mod 1971). These lines arise from Ly α absorption by neutral hydrogen from intervening
structure along the line of sight. Early theoretical models interpreted this structure
as absorption caused by discrete gas clouds in th structure along the line of sight. Early theoretical models interpreted this structure
as absorption caused by discrete gas clouds in the intergalactic medium (IGM), either
pressure confined by a hot IGM (Sargent *et al.* as absorption caused by discrete gas clouds in the intergalactic medium (IGM), either
pressure confined by a hot IGM (Sargent *et al.* 1980; Ostriker & Ikeuchi 1983) or con-
fined by the gravity of dark matter 'mini-halos pressure confined by a hot IGM (Sargent *et al.* 1980; Ostriker & Ikeuchi 1983) or confined by the gravity of dark matter 'mini-halos' (see, for example, Rees 1986). Over the last few years our understanding of the Ly α fined by the gravity of dark matter 'mini-halos' (see, for example, Rees 1986). Over
the last few years our understanding of the Ly α forest has undergone a transformation
for at least two reasons. Firstly, observations the last few years our understanding of the $Ly\alpha$ forest has undergone a transformation for at least two reasons. Firstly, observations with the Keck telescope have produced almost noise-free spectra of quasars at high sp for at least two reasons. Firstly, observations with the Keck telescope have produced
almost noise-free spectra of quasars at high spectral resolution over the redshift range
 $2 \le z \le 4$. The exquisite quality of Keck spec almost noise-free spectra of quasars at high spectral resolution over the redshift range $2 \le z \le 4$. The exquisite quality of Keck spectra has allowed observers to resolve $Ly\alpha$ absorption lines at low column densities $(ca$ $2 \lesssim z \lesssim 4$. The exquisite quality of Keck spectra has allowed observers to resolve Ly α absorption lines at low column densities $(ca.10^{12.5} \text{ cm}^{-2})$ and to study their evolution. Secondly, hydrodynamic numerical si \succeq Ly α absorption lines at low column densities $(ca. 10^{12.5} \text{ cm}^{-2})$ and to study their evolution. Secondly, hydrodynamic numerical simulations of structure formation in \succeq cold-dark-matter (CDM) universes wit evolution. Secondly, hydrodynamic numerical simulations of structure formation in cold-dark-matter (CDM) universes with high spatial resolution are now possible and have proved remarkably successful in reproducing many ob cold-dark-matter (CDM) universes with high spatial resolution are now possible and
have proved remarkably successful in reproducing many observed properties of the
Ly α forest (Cen *et al.* 1994; Zhang *et al.* 1995, 199 have proved remarkably successful in reproducing many observed properties of the Ly α forest (Cen *et al.* 1994; Zhang *et al.* 1995, 1997; Miralda-Escudé *et al.* 1996; Hernquist *et al.* 1996; Theuns *et al.* 1998*a*) Ly α forest (Cen *et al.* 1994; Zhang *et al.* 1995, 1997; Miralda-Escudé *et al.* 1996;
Hernquist *et al.* 1996; Theuns *et al.* 1998*a*). These simulations have shown that most
of the Ly α lines at column densities Hernquist *et al.* 1996; Theuns *et al.* 1998*a*). These simulations have shown that most
of the Ly α lines at column densities $\leq 10^{14.5}$ cm⁻² arise from modest fluctuations
in the baryon density in a space-filli in the baryon density in a space-filling photoionized IGM, rather than from distinct clouds. The properties of the Ly α lines can, therefore, be used to probe the struc-
ture and thermal history of the diffuse IGM and o in the baryon density in a space-filling photoionized IGM, rather than from distinct clouds. The properties of the Ly α lines can, therefore, be used to probe the structure and thermal history of the diffuse IGM and of clouds. The properties of the $Ly\alpha$ lines can, therefore, be used to probe the structure and thermal history of the diffuse IGM and of the background ultraviolet (UV) radiation that determines its ionization state. The ke radiation that determines its ionization state. The key characteristics of the numeri-
cal simulations are described in the next section. Section 3 summarizes a number of

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Figure 1. (a) Photoionization rates for hydrogen and helium computed in the model of Haardt &
Madau (1996) (b) The mass-weighted distribution of fluid elements in the temperature-density Figure 1. (a) Photoionization rates for hydrogen and helium computed in the model of Haardt & Madau (1996). (b) The mass-weighted distribution of fluid elements in the temperature-density plane at $z = 3$ for our reference Madau (1996). (b) The mass-weighted distribution of fluid elements in the temperature-density plane at $z = 3$ for our reference CDM model. The number density of fluid elements increases by
an order of magnitude with each contour level. Most of the gas obeys a well-defined equation of
state, shown by the dashed lin an order of magnitude with each contour level. Most of the gas obeys a well-defined equation of

state, shown by the dashed line.
results from these simulations and describes how the Ly α lines can be used to study
the IGM. In this paper we discuss only the properties of the low-column-density the IGM. In this paper we discuss only the properties of the low-column-density the IGM. In this paper we discuss only the properties of the low-column-density Lvo lines. For a discussion of damped Lvo systems a the IGM. In this paper we discuss only the properties of the low-column-density $L_{\rm V}\alpha$ lines. For a discussion of damped $L_{\rm V}\alpha$ systems and metal lines see Pettini (this the IGM. In this paper we discuss only the properties of the low-column-density $Ly\alpha$ lines. For a discussion of damped $Ly\alpha$ systems and metal lines see Pettini (this issue). For a recent review of observations and theor Ly α lines. For a discussidissue). For a recent revier
lines see Rauch (1998). lines see Rauch (1998).

2. Numerical simulations of the IGM

The simplest cosmological hydrodynamical simulations follow the evolution of (opti-The simplest cosmological hydrodynamical simulations follow the evolution of (optically thin) gas and dark matter assuming a uniform photoionizing background. The simulation is therefore specified by The simplest cosmological hydrodynamically thin) gas and dark matter assumir
simulation is, therefore, specified by (i) parameters defining the cosmological model and its matter content (e.g. $\Omega_{\rm m}$, $\Omega_{\rm m}$)

- $\Omega_{\rm b}$, Ω_{Λ} , $H_0 \equiv 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$);
- (ii) the amplitude and spectral shape of the mass fluctuations; and
- %) (ii) the amplitude and spectral shape of the mass fluctuations; and (iii) a model for the background UV flux as a function of redshift.

ii) a model for the background UV flux as a function of redshift.
Here we will review the evolution of CDM universes with initially scale-invariant
jabatic fluctuations. The linear power spectrum for these models (in the l Here we will review the evolution of CDM universes with initially scale-invariant adiabatic fluctuations. The linear power spectrum for these models (in the limit of small baryon content) is given by Bardeen *et al*. (1986). We adopt a reference model adiabatic fluctuations. The linear power spectrum for these models (in the limit of small baryon content) is given by Bardeen *et al.* (1986). We adopt a reference model (model S) with parameters $\Omega_m = 1$, $\Omega_A = 0$, $h = 0$ small baryon content) is given by Bardeen *et al.* (1986). We adopt a reference model (model S) with parameters $\Omega_{\rm m} = 1$, $\Omega_{\Lambda} = 0$, $h = 0.5$ and $\Omega_{\rm b} = 0.05$. The physical density in baryons in this model is ω (model S) with parameters $\Omega_m = 1$, $\Omega_A = 0$, $h = 0.5$ and $\Omega_b = 0.05$. The physical density in baryons in this model is $\omega_b \equiv \Omega_b h^2 = 0.0125$. The model is normalized so that the root mean square density fluctuations in density in baryons in this model is $\omega_{\rm b} \equiv \Omega_{\rm b} h^2 = 0.0125$. The model is normalized
so that the root mean square density fluctuations in spheres of radius $8h^{-1}$ Mpc
is $\sigma_8 = 0.7$. The photoionizing background ra so that the root mean square density fluctuations in spheres of radius $8h^{-1}$ Mpc
is $\sigma_8 = 0.7$. The photoionizing background radiation is assumed to originate from
quasars according to the model of Haardt & Madau (1996 is $\sigma_8 = 0.7$. The photoionizing background radiation is assumed to originate from
quasars according to the model of Haardt & Madau (1996, hereafter HM). The
photoionization rates for hydrogen and helium in this model ar quasars according to the model of Haardt & Madau (1996, hereafter HM). The photoionization rates for hydrogen and helium in this model are plotted in figure 1a as a function of redshift. With these photoionization rates, photoionization rates for hydrogen and helium in this model are plotted in figure 1a as a function of redshift. With these photoionization rates, and assuming a uniform IGM, hydrogen is reionized at a redshift of $z \approx 6$

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in a numerical simulation of our reference model S at a redshift of $z = 3$. There is a
plume of shock-heated gas extending to temperatures Figure 1b shows the distribution of gas elements in the temperature-density plane in a numerical simulation of our reference model S at a redshift of $z = 3$. There is a in a numerical simulation of our reference model S at a redshift of $z = 3$. There is a plume of shock-heated gas extending to temperatures $\geq 10^5$ K, but most of the gas has a low overdensity and follows a power-law-li 1997):

$$
T = T_0(\rho_b/\bar{\rho}_b)^{\gamma - 1}.
$$
\n(2.1)

 $T = T_0(\rho_b/\bar{\rho}_b)^{\gamma-1}$. (2.1)
At times long after reionization, the diffuse IGM will settle into a state in which
adiabatic cooling is balanced by photoheating. The temperature of the IGM will. $I = I_0(\rho_b/\rho_b)$. (2.1)
At times long after reionization, the diffuse IGM will settle into a state in which
adiabatic cooling is balanced by photoheating. The temperature of the IGM will,
therefore tend towards At times long after reioni
adiabatic cooling is balan
therefore, tend towards \mathbf{v}

$$
T \approx 3.2 \times 10^4 \text{ K} \left[\frac{\Omega_{\text{b}} h (1 + \delta)(1 + z)^3}{(2 + \alpha) E(z)} \right]^{1/1.76},
$$

\n
$$
E(z) = \frac{H_0}{H(z)} = \left[\Omega_{\text{m}} (1 + z)^3 + \Omega_k (1 + z)^2 + \Omega_\Lambda \right]^{1/2},
$$

\nwhere we have assumed a power-law photoionizing background

-law photoionizing background
\n
$$
J_{\nu} = J_{\nu_{\rm L}} (\nu/\nu_{\rm L})^{-\alpha}.
$$
\n(2.3)

 $J_{\nu} = J_{\nu_{\rm L}} (\nu/\nu_{\rm L})^{-\alpha}$. (2.3)
In equation (2.2) $\Omega_k = 1 - \Omega_{\rm m} - \Omega_{\Lambda}$, and the exponent 1/1.76 arises from the
temperature dependence of the HII and HeIII recombination coefficients. $J_{\nu} = J_{\nu_{\rm L}}(\nu/\nu_{\rm L})$.
In equation (2.2) $\Omega_k = 1 - \Omega_{\rm m} - \Omega_{\Lambda}$, and the exponent 1/1.76 arises temperature dependence of the HII and HeIII recombination coefficients.
Figure 2 shows the spatial distribution of the equation (2.2) $\Omega_k = 1 - \Omega_m - \Omega_A$, and the exponent 1/1.76 arises from the mperature dependence of the HII and HeIII recombination coefficients.
Figure 2 shows the spatial distribution of the gas in the simulation at $z = 3$

temperature dependence of the HII and HeIII recombination coefficients.
Figure 2 shows the spatial distribution of the gas in the simulation at $z = 3$. Figure 2b shows the gas with temperature $T > 10^5$ K. This hot gas fi Figure 2 shows the spatial distribution of the gas in the simulation at $z = 3$. Figure 2b shows the gas with temperature $T > 10^5$ K. This hot gas fills a small fraction of the volume and is located in the dense knots and ure 2b shows the gas with temperature $T > 10^5$ K. This hot gas fills a small fraction
of the volume and is located in the dense knots and filaments corresponding to col-
lapsed structures. In contrast, the cool gas with of the volume and is located in the dense knots and filaments corresponding to collapsed structures. In contrast, the cool gas with $T < 10^5$ K (shown in figure 2b) fills most of the computational volume. It is this diffu lapsed structures. In contrast, the cool gas with $T < 10^5$ K (shown in figure 2b) fills most of the computational volume. It is this diffuse low-density gas that we believe accounts for the vast majority of the observed most of the computational volume. It is this diffuse low-density gas that we believe accounts for the vast majority of the observed $Ly\alpha$ lines. Furthermore, because most accounts for the vast majority of the observed Ly α lines. Furthermore, because most
of this gas is at low overdensities, $\delta \lesssim 10$, it is relatively easy to model numerically.
By investigating the Ly α forest we ca of this gas is at low overdensities, $\delta \lesssim 10$, it is relatively easy to model numerically.
By investigating the Ly α forest we can, therefore, hope to learn about the properties
of the diffuse IGM, which at typical q By investigating the Ly α forest we can, therefore, hope to learn about the properties of the diffuse IGM, which at typical quasar redshifts of $z \sim 2-4$ contains most of the baryonic matter in the Universe. In particul

- The optical depth of HI and HeII absorption can set constraints on the baryonic
(i) the optical depth of HI and HeII absorption can set constraints on the baryonic
density of the Universe and on the evolution, amplitude a nce matter in the Universe. In particular:
the optical depth of HI and HeII absorption can set constraints on the baryonic
density of the Universe and on the evolution, amplitude and spectrum of the
photoionizing backgroun the optical depth of HI and H
density of the Universe and
photoionizing background;
- (ii) the fluctuating optical depth of HI absorption can be used to construct the nower spectrum of the matter fluctuations at redshifts $z \approx 2-4$ and photolomizing background,
the fluctuating optical depth of HI absorption can be used to construe
power spectrum of the matter fluctuations at redshifts $z \sim 2-4$; and
- (ii) the interdating optical depth of HI absorption can be used to construct the
power spectrum of the matter fluctuations at redshifts $z \sim 2-4$; and
(iii) the Ly α absorption linewidths can be used to infer the temper the Ly α absorption linewidths can be used to infer
tion of state of the diffuse IGM and its evolution.

tion of state of the diffuse IGM and its evolution.
These topics will be discussed in more detail in the next section.

be discussed in more detail in the next section.
3. The $Ly\alpha$ forest as a probe of the IGM **3.** The $Ly\alpha$ forest as a probe of the IGM (*a*) *Mean optical depth of* HI *and* HeII *absorption*

(a) Mean optical depth of HI and HeII absorption
The optical depth for HI Ly α absorption from an IGM in ionization equilibrium with
density ρ_k is given by The optical depth for HI I
density ρ_b is given by density $\rho_{\rm b}$ is given by

$$
\tau(z) = 6.5 \times 10^{-4} \left(\frac{\omega_{\rm b}}{0.019}\right)^2 \left(\frac{h}{0.65}\right)^{-1} \frac{(1+z)^6}{E(z)} \frac{T_4^{-0.76}}{(T_{\rm HI}/10^{-12} \text{ s}^{-1})} \left(\frac{\rho_{\rm b}(z)}{\bar{\rho}_{\rm b}(z)}\right)^2, \quad (3.1)
$$

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Figure 2. The distribution of gas in a CDM simulation at $z = 3$. (a) Shocked gas with a Figure 2. The distribution of gas in a CDM simulation at $z = 3$. (*a*) Shocked gas with a temperature greater than 10⁵ K, which is located in dense clusters and filaments. (*b*) Gas with a temperature of less than 10⁵ Figure 2. The distribution of gas
temperature greater than 10^5 K, w
a temperature of less than 10^5 K.

a temperature of less than 10⁵ K.
(see, for example, Peebles 1993, §23), where $\Gamma_{\rm HI}$ is the photoionization rate for (see, for example, Peebles 1993, §23), where Γ_{HI} is the photoionization rate for HI and T_4 is the temperature of the IGM in units of 10^4 K. Variations in $\rho_{\text{b}}(z)$ along the line of sight will produce a ' (see, for example, Peebles 1993, §23), where Γ_{HI} is the photoionization rate for HI and T_4 is the temperature of the IGM in units of 10^4 K. Variations in $\rho_{\text{b}}(z)$ along the line of sight will produce a ' along the line of sight will produce a 'fluctuating Gunn-Peterson' effect. An observed
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Figure 3. The mean optical depth as a function of redshift for HI and HeII absorption. Our
reference model S (using half the amplitude of the HM photoionizing background) is plotted as Figure 3. The mean optical depth as a function of redshift for HI and HeII absorption. Our reference model S (using half the amplitude of the HM photoionizing background) is plotted as the open squares joined by the solid reference model S (using half the amplitude of the HM photoionizing background) is plotted as
the open squares joined by the solid line. This matches the observed HI optical depth but fails to reference model S (using half the amplitude of the HM photoionizing background) is plotted as
the open squares joined by the solid line. This matches the observed HI optical depth but fails to
match observations of the He the open squares joined by the solid line. This matches the observed HI optical depth but fails to
match observations of the HeII optical depth. The observational data plotted in the figure are as
follows: Rauch *et al.* (match observations of the HeII optical depth. The observational data plotted in the figure are as
follows: Rauch *et al.* (1997); Fardal *et al.* (1998) (FGS); Davidsen *et al.* (1996) (DKZ); Jakobsen
et al. (1994) (JBDG follows: Rauch *et al.* (1997); Fardal *et al.* (1998) (FGS); Davidsen *et al.* (1996) (DKZ); Jakobsen *et al.* (1994) (JBDGJP); Reimers *et al.* (1997) (RKWGRW); Tytler *et al.* (1995) (TFB); Heap *et al.* (2000).

z

absorption line spectrum can, therefore, be inverted to infer the clustering of the baryon distribution as pioneered by Croft *et al.* (1998; see also $8.3c$ below) absorption line spectrum can, therefore, be inverted to infer the clustering
baryon distribution as pioneered by Croft *et al.* (1998; see also $\S 3 c$ below).
The mean HI and HeII optical depths as a function of redshift sorption line spectrum can, therefore, be inverted to infer the clustering of the ryon distribution as pioneered by Croft *et al.* (1998; see also $\S 3 c$ below).
The mean HI and HeII optical depths as a function of redshi

baryon distribution as pioneered by Croft *et al.* (1998; see also $\S 3 c$ below).
The mean HI and HeII optical depths as a function of redshift are plotted in figure 3 for our fiducial model S. The open squares show the o The mean HI and HeII optical depths as a function of redshift are plotted in figure 3 for our fiducial model S. The open squares show the optical depths derived using half the amplitude of the HM UV background. With this c ure 3 for our fiducial model S. The open squares show the optical depths derived
using half the amplitude of the HM UV background. With this choice of photoioniz-
ing background, the mean HI optical depth of the simulation using half the amplitude of the HM UV background. With this choice of photoionizing background, the mean HI optical depth of the simulation matches observations quite well over the redshift range 2–4. Evidently, the amplit ing background, the mean HI optical depth of the simulation matches observations
quite well over the redshift range $2-4$. Evidently, the amplitude of the photoion-
izing background can be balanced by variations in other quite well over the redshift range $2-4$. Evidently, the amplitude of the photoion-
izing background can be balanced by variations in other cosmological parameters
according to equation (3.1) to preserve the match to obse according to equation (3.1) to preserve the match to observations. The simulations therefore imply that

$$
\left(\frac{\omega_{\rm b}}{0.0125}\right)^2 \left(\frac{h}{0.5}\right)^{-1} \Omega_{\rm m}^{1/2} \left(\frac{0.5\Gamma_{\rm HM}}{\Gamma_{\rm HI}}\right) \left(\frac{6 \times 10^3}{T}\right)^{0.76} \approx 1. \tag{3.2}
$$

This type of criterion has been used by Weinberg *et al.* (1997) to set a crude lower limit to the baryon density. At redshifts of 2–3 one can be reasonably confident of

This type of criterion has been used by Weinberg *et al.* (1997) to set a crude lower
limit to the baryon density. At redshifts of 2-3 one can be reasonably confident of
the HM model of the photoionizing background around This type of criterion has been used by Weinberg *et al.* (1997) to set a crude lower
limit to the baryon density. At redshifts of 2–3 one can be reasonably confident of
the HM model of the photoionizing background around limit to the baryon density. At redshifts of 2–3 one can be reasonably confident of
the HM model of the photoionizing background around the Lyman edge, because
the quasar luminosity function is quite well determined at th the HM model of the photoionizing background around the Lyman edge, because
the quasar luminosity function is quite well determined at these redshifts (see $\S 3$
of Madau, this issue). The HM model provides a lower limit the quasar luminosity function is quite well determined at these redshifts (see $\S 3$
of Madau, this issue). The HM model provides a lower limit to the photoioniz-
ing flux because it ignores additional photoionizing radi of Madau, this issue). The HM model provides a lower limit to the photoionizing flux because it ignores additional photoionizing radiation from star formation. The temperature of a photoionized IGM cannot exceed a few tim

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its precise value depends on the past thermal and ionization history of the IGM .[†] Uncertainties in the temperature of the IGM lead to an additional source of uncertainty in using equation (3.2) to derive a bound on the baryon density. Nevertheless, its precise value depends on the past thermal and ionization history of the IGM.[†]
Uncertainties in the temperature of the IGM lead to an additional source of uncer-
tainty in using equation (3.2) to derive a bound on th Uncertainties in the temperature of the
tainty in using equation (3.2) to derive a
equation (3.2) implies $\omega_{\rm b} \gtrsim 0.02 \Omega_{\rm m}^{1/2}$, $\omega_{\rm b} = 0.019$ inferred from primordial nual $1/2$; f the IGM lead to an additional source of uncer-
rive a bound on the baryon density. Nevertheless,
 $\frac{1/2}{m}$, interestingly close to the baryon density of
al nucleosynthesis and the deuterium abundances tainty in using equation (3.2) to derive a bound on the baryon density. Nevertheless,
equation (3.2) implies $\omega_{\rm b} \gtrsim 0.02 \Omega_{\rm m}^{1/2}$, interestingly close to the baryon density of
 $\omega_{\rm b} = 0.019$ inferred from prim equation (3.2) implies $\omega_{\rm b} \gtrsim 0.02 \Omega_{\rm m}^{1/2}$, interestingly close to the baryon density of $\omega_{\rm b} = 0.019$ inferred from primordial nucleosynthesis and the deuterium abundances measured in quasar spectra (Burles $\omega_{\rm b} = 0.019$ inferred from primordial nucleosynthesis and the deuterium abundances measured in quasar spectra (Burles & Tytler 1998; Burles *et al.* 1999). The observed HI optical depth, therefore, leads to a consiste in the Universe at $z \sim 2{-}4$ belong to the diffuse photoionized IGM.

The HeII optical depth is shown in figure 3b. The open squares show $\tau_{\rm HeII}$ computed from the simulation using the same amplitude for the photoionizing background that provides a good match to $\tau_{\rm HI}$. The results from the simulation lie below puted from the simulation using the same amplitude for the photoionizing background that provides a good match to τ_{HI} . The results from the simulation lie below the observations at all redshifts, suggesting that th ground that provides a good match to τ_{HI} . The results from the simulation lie below
the observations at all redshifts, suggesting that the photoionizing background has
a softer spectrum than that computed by Haardt a softer spectrum than that computed by Haardt $\&$ Madau (1996). In photoion-
ization equilibrium, the optical depth in HeII is related to the optical depth in HI a softer spectrum than that computed by Haardt & Madau (1996). In photoion-
ization equilibrium, the optical depth in HeII is related to the optical depth in HI
by $\tau_{\rm HeII}/\tau_{\rm HI} \propto \Gamma_{\rm HI}/\Gamma_{\rm HeII} \propto J_{\rm HI}/J_{\rm HeII}$, and ization equilibrium, the optical depth in HeII is related to the optical depth in HI
by $\tau_{\rm HeII}/\tau_{\rm HI} \propto \Gamma_{\rm HI}/\Gamma_{\rm HeII} \propto J_{\rm HI}/J_{\rm HeII}$, and so $\tau_{\rm HeII}$ can be raised by softening the
photoionizing spectrum appropri by $\tau_{\text{HeII}}/\tau_{\text{HI}} \propto \Gamma_{\text{HI}}/\Gamma_{\text{HeII}} \propto J_{\text{HI}}/J_{\text{HeII}}$, and so τ_{HeII} can be raised by softening the photoionizing spectrum appropriately. By lowering $\Gamma_{\text{HeII}}/\Gamma_{\text{HI}}$ by a factor of two compared with the H photoionizing spectrum appropriately. By lowering $\Gamma_{\rm HeII}/\Gamma_{\rm HI}$ by a factor of two compared with the HM model of figure 1, model S can match the observations at $z \leq 2.8$, but cannot match the high HeII optical depth pared with the HM model of figure 1, model S can match the observations at $z \leq 2.8$, but cannot match the high HeII optical depths at $z \geq 2.9$ found in the recent observations by the Hubble Space Telescope (HST) and t but cannot match the high HeII optical depths at $z \gtrsim 2.9$ found in the vations by the Hubble Space Telescope (HST) and the Space Telescope Spectrograph (STIS) of the quasar Q0302-003 by Heap *et al.* (2000). One possib

One possible interpretation of these results is that the typical quasar spectrum Spectrograph (STIS) of the quasar Q0302-003 by Heap *et al.* (2000).
One possible interpretation of these results is that the typical quasar spectrum
adopted by Haardt & Madau (1996) is too hard and that HeII reionization One possible interpretation of these results is that the typical quasar spectrum
adopted by Haardt & Madau (1996) is too hard and that HeII reionization is delayed
until a redshift of $z \approx 3$, corresponding to the abrupt adopted by Haardt $\&$ Madau (1996) is too hard and that HeII reionization is delayed
until a redshift of $z \approx 3$, corresponding to the abrupt change in HeII opacity observed
by Heap *et al.* (2000). Additional arguments until a redshift of $z \approx 3$, corresponding to the abrupt change in HeII opacity observed
by Heap *et al.* (2000). Additional arguments to support this picture are discussed in
§ 3 d. If this interpretation is correct, the by Heap *et al.* (2000). Additional arguments to support this picture are discussed in § 3 d. If this interpretation is correct, then active galactic nuclei (AGN) and 'miniquasars' cannot produce much photoionizing radiat § 3 d. If this interpretation is correct, then active galactic nuclei (AGN) and 'miniquasars' cannot produce much photoionizing radiation capable of doubly ionizing helium at redshifts of $z \geq 3$ (see Rees, this issue).

(*b*) *Evolution of the column density distribution*

(b) Evolution of the column density distribution
It has been known for many years that a Ly α forest shows strong cosmological
olution (see for example Sargent *et al.* 1980). Over a narrow range in redshift the (b) Evolution of the column density distribution
It has been known for many years that a Ly α forest shows strong cosmological
evolution (see, for example, Sargent *et al.* 1980). Over a narrow range in redshift the
evo It has been known for many years that a Lya evolution (see, for example, Sargent *et al.* 1980). Convolution can be approximated by a power law,

$$
\frac{\mathrm{d}N}{\mathrm{d}z} \propto (1+z)^{\epsilon},\tag{3.3}
$$

where N is the number of lines above a threshold rest-frame equivalent width (typi-
cally $W > 0.32 \text{ Å}$). From high-resolution Keck observations. Kim *et al.* (1997) found where N is the number of lines above a threshold rest-frame equivalent width (typically $W > 0.32 \text{ Å}$). From high-resolution Keck observations, Kim *et al.* (1997) found $\epsilon = 2.78 + 0.71$ in the redshift range $2 < z < 3.5$ where N is the number of lines above a threshold rest-frame equivalent width (typically $W > 0.32 \text{ Å}$). From high-resolution Keck observations, Kim *et al.* (1997) found $\epsilon = 2.78 \pm 0.71$ in the redshift range $2 < z < 3.5$ cally $W > 0.32$ Å). From high-resolution Keck observations, Kim *et al.* (1997) found $\epsilon = 2.78 \pm 0.71$ in the redshift range $2 < z < 3.5$. Williger *et al.* (1994) found that the evolution is still stronger at higher redsh μ ϵ = 2.78 \pm 0.71 in the redshift range 2 < z < 3.5. Williger *et al.* (1994) found that the evolution is still stronger at higher redshifts with $\epsilon > 4$ at $z > 4$. In contrast, observations with the HST indicate much weaker evolution at low redshifts with $\epsilon = 0.48 \pm 0.62$ for $z < 1$ (Morris *et al.* 1991; B = 0.48 ± 0.62 for $z < 1$ (Morris *et al.* 1991; Bahcall *et al.* 1991, 1993; Impey *et al.* 96).
The evolution of the Ly α forest, including the low rates of evolution at redshifts $z < 2$ can be reproduced quite simply

1996).
The evolution of the Ly α forest, including the low rates of evolution at redshifts of $z \leq 2$ can be reproduced quite simply in CDM models (Theuns *et al.* 1998*b*; Davé *et al.* 1999). This is illustrated in figure 4, which shows the evolution of the number

al. 1999). This is illustrated in figure 4, which shows the evolution of the number
† Although a highly ionized IGM is in ionization equilibrium, it is not in thermal equilibrium and so
ains a 'memory' of the way in which \dagger Although a highly ionized IGM is in ionization equations a 'memory' of the way in which it was heated. *Phil. Trans. R. Soc. Lond.* A (2000)

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 $Ly\alpha$ absorption 2055
of Ly α lines within a given range of column density for our reference model S. (The
lines are identified by fitting Voigt profiles to simulated Keck spectra using the lineof Ly α lines within a given range of column density for our reference model S. (The line-
lines are identified by fitting Voigt profiles to simulated Keck spectra using the line-
fitting program VPFIT (Webb 1987)) As i of Ly α lines within a given range of column density for our reference model S. (The
lines are identified by fitting Voigt profiles to simulated Keck spectra using the line-
fitting program VPFIT (Webb 1987).) As in \S lines are identified by fitting Voigt profiles to simulated Keck spectra using the line-
fitting program VPFIT (Webb 1987).) As in $\S 3a$, we adopt the HM model of the
photoionizing background with an amplitude divided by photoionizing background with an amplitude divided by a factor of 2 to match the observed optical depth in HI absorption. This model reproduces the observed column density distribution accurately over the column density r photoionizing background with an amplitude divided by a factor of 2 to match the observed optical depth in HI absorption. This model reproduces the observed column density distribution accurately over the column density r 10^{15} cm⁻² (see fig. 2 in Theuns *et al.* (1998b)), and, as figure 4 shows, also reproduces ptical depth in HI absorption. This model reproduces the observed column
tribution accurately over the column density range $10^{12.5}$ cm⁻² $\lesssim N_{\text{HI}} \lesssim$
(see fig. 2 in Theuns *et al.* (1998*b*)), and, as figure 4 s the observed rates of evolution as a function of column density. In particular, the 10^{15} cm⁻² (see fig. 2 in Theuns *et al.* (1998*b*)), and, as figure 4 shows, also reproduces the observed rates of evolution as a function of column density. In particular, the decrease in the rate of evolution of t the observed rates of evolution as a function of column density. In particular, the decrease in the rate of evolution of the Ly α lines found from HST observations arises from the steep decline in the photoionizing back from the steep decline in the photoionizing background at $z \lesssim 2$ caused by the rapid \Box drop in quasar numbers at low redshift.

(*c*) *Reconstruction of the matter power spectrum*

(c) Reconstruction of the matter power spectrum
Equations (2.1) and (3.1) can be combined to write the observed transmitted flux
terms of fluctuations in the baryon density: Equations (2.1) and (3.1) can be combined to in terms of fluctuations in the baryon density: in terms of fluctuations in the baryon density:

$$
F = \exp[-A(\rho_b/\bar{\rho}_b)^{\beta}], \qquad \beta \approx (2.76 - 0.76\gamma).
$$
 (3.4)

 $F = \exp[-A(\rho_b/\bar{\rho}_b)^{\beta}], \qquad \beta \approx (2.76 - 0.76\gamma).$ (3.4)
Croft *et al.* (1998) have used this relation to infer the one-dimensional power spec-
trum $P_{\text{FD}}(k)$ of the baryon fluctuations from which the three-dimensional power Croft *et al.* (1998) have used this relation to infer the one-dimensional power spectrum $P_{1D}(k)$ of the baryon fluctuations, from which the three-dimensional power spectrum can be recovered by differentiation: Croft *et al.* (1998) have used this relation to in
trum $P_{1D}(k)$ of the baryon fluctuations, from
spectrum can be recovered by differentiation: spectrum can be recovered by differentiation:

$$
P(k) = -\frac{2\pi}{k} \frac{d}{dk} P_{1D}(k).
$$
 (3.5)

 $P(k) = -\frac{2\pi}{k} \frac{d}{dk} P_{1D}(k).$ (3.5)
Croft *et al.* (1998) calibrate the amplitude of the matter power spectrum by compar-
ing it with numerical simulations. The procedure is not completely straightforward Croft *et al.* (1998) calibrate the amplitude of the matter power spectrum by comparing it with numerical simulations. The procedure is not completely straightforward and we refer the reader to Croft *et al.* (1998) for d **IYSICAL**
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IENCES ing it with numerical simulations. The procedure is not completely straightforward and we refer the reader to Croft *et al.* (1998) for details. By testing their inversion ing it with numerical simulations. The procedure is not completely straightforward
and we refer the reader to Croft *et al.* (1998) for details. By testing their inversion
algorithm against numerical simulations these aut and we refer the reader to Croft *et al.* (1998) for details. By testing their inversion algorithm against numerical simulations these authors find that the amplitude and shape of the underlying matter power spectrum can shape of the underlying matter power spectrum can be recovered accurately and that the recovery is insensitive to uncertainties in the equation of state. A variant of this technique, which incorporates a correction for the distortion of the clustering pattern

by peculiar velocities, is described by Nusser & Haehnelt (1999).
Croft *et al.* (1999*b*) describe an application of their method to a sample of 19 quasar

by peculiar velocities, is described by Nusser & Haehnelt (1999).
Croft *et al.* (1999*b*) describe an application of their method to a sample of 19 quasar
spectra spanning the redshift range 2.08-3.23. They recover $P(k)$ Croft *et al.* (1999*b*) describe an application of their method to a sample of 19 quasar spectra spanning the redshift range 2.08–3.23. They recover $P(k)$ at $z \approx 2.5$ over the (comoving) wavenumber range $2\pi/k \sim 2{\text -}12$ spectra spanning the redshift range 2.08–3.23. They recover $P(k)$ at $z \approx 2.5$ over the (comoving) wavenumber range $2\pi/k \sim 2{\text -}12h^{-1}$ Mpc and find that it is well fitted by a power law $P(k) \propto k^n$ with $n = -2.25 \pm 0.28$, (comoving) wavenumber range $2\pi/k \sim 2{\text -}12h^{-1}$ Mpc and find that it is well fitted
by a power law $P(k) \propto k^n$ with $n = -2.25 \pm 0.28$, consistent with what is expected
from CDM models. This important result is the first at by a power law $P(k) \propto k^n$ with $n = -2.25 \pm 0.28$, consistent with what is expected
from CDM models. This important result is the first attempted determination of
the matter power spectrum at high redshift. The amplitude of from CDM models. This important result is the first attempted determination of
the matter power spectrum at high redshift. The amplitude of the inferred power
spectrum is high compared with that expected for spatially fla the matter power spectrum at high redshift. The amplitude of the inferred power
spectrum is high compared with that expected for spatially flat CDM models with
 $\Omega_{\rm m} = 1$ normalized to reproduce the abundance of rich cl spectrum is high compared with that expected for spatially flat CDM models with $\Omega_{\rm m} = 1$ normalized to reproduce the abundance of rich clusters at the present day.
The best-fitting CDM models have $\Omega_{\rm m} + 0.2\Omega_A \approx 0$ $\overline{\Omega}_{\rm m} = 1$ normalized to reproduce the abundance of rich clusters at the present day.
The best-fitting CDM models have $\Omega_{\rm m} + 0.2\Omega_A \approx 0.46$ (Weinberg *et al.* 1999; Phillips *et al.* 2000), in agreement with the The best-fitting CDM models have $\Omega_{\rm m} + 0.2\Omega_A \approx 0.46$ (Weinberg *et al.* 1999; Phillips *et al.* 2000), in agreement with the parameters $\Omega_{\rm m} \approx 0.3$, $\Omega_A \approx 0.7$ derived from combining observations of anisotropies et al. 2000), in agreement with the parameters $\Omega_{\rm m} \approx 0.3$, $\Omega_A \approx 0.7$ derived from
combining observations of anisotropies in the cosmic microwave background radiation
and distant Type Ia supernovae (see, for example combining observations of anisotropies in the cosmic microwave background radiation
and distant Type Ia supernovae (see, for example, Efstathiou *et al.* (1999), and
references therein). Constraints on neutrino masses fro and distant Type Ia supernovae (see, for example references therein). Constraints on neutrino materials redshift are discussed by Croft *et al.* (1999*a*). redshift are discussed by Croft *et al.* (1999*a*).
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²⁰⁵⁶ *G. Efstathiou,J.SchayeandT. Theuns*

Figure 4. Evolution of the number of lines within a given range of column density from numerical Figure 4. Evolution of the number of lines within a given range of column density from numerical
simulations of Theuns *et al.* (1998b) compared with observations. Open and filled circles show
simulation results for the re Figure 4. Evolution of the number of lines within a given range of column density from numerical
simulations of Theuns *et al.* (1998b) compared with observations. Open and filled circles show
simulation results for the r simulation results for the reference model S (described in the text) run at different numerical resolutions. The large open pentagon shows a re-analysis of the simulation at $z = 0.5$ but simulation results for the reference model S (described in the text) run at different numerical
resolutions. The large open pentagon shows a re-analysis of the simulation at $z = 0.5$ but
imposing the photoionizing backgro resolutions. The large open pentagon shows a re-analysis of the simulation at $z = 0.5$ but
imposing the photoionizing background appropriate to $z = 2$. The observational data points are
as follows: Kim *et al.* (1997) (op imposing the photoionizing background appropriate to $z = 2$. The observational data points are
as follows: Kim *et al.* (1997) (open and filled triangles); Bahcall *et al.* (1993) (filled squares);
Impey *et al.* (1996) (as follows: Kim *et al.* (1997) (open and filled triangles); Bahcall *et al.* (1993) (filled squares); Impey *et al.* (1996) (open squares); Lu *et al.* (1996) (filled pentagon); Williger *et al.* (1994) (long-dashed line

(*d*) *Widths of the Ly*[¬] *lines*

The widths of the $Ly\alpha$ lines are usually characterized by the broadening param-The widths of the Ly α lines are usually characterized by the broadening parameter b determined by fitting Voigt profiles. If the linewidth is caused by thermal broadening the parameter b is related to the temperature o The widths of the Ly α lines are usually characterized by the broadening eter b determined by fitting Voigt profiles. If the linewidth is caused by broadening, the parameter b is related to the temperature of the gas by

er *b* is related to the temperature of the gas by
\n
$$
b = \left(\frac{2kT}{m_p}\right)^{1/2} = 12.8T_4^{1/2} \text{ km s}^{-1}.
$$
\n(3.6)

 $b = \left(\frac{2m}{m_p}\right)^{-1} = 12.8T_4^{1/2} \text{ km s}^{-1}.$ (3.6)
In reality, a number of mechanisms in addition to thermal broadening contribute to
the widths of the lines e g the differential Hubble flow across the absorbing region In reality, a number of mechanisms in addition to thermal broadening contribute to
the widths of the lines, e.g. the differential Hubble flow across the absorbing region
and the smoothing of small-scale fluctuations by ga In reality, a number of mechanisms in addition to thermal broadening contribute to the widths of the lines, e.g. the differential Hubble flow across the absorbing region and the smoothing of small-scale fluctuations by gas the widths of the lines
and the smoothing of
Theuns *et al.* 2000).
The first sets of sim d the smoothing of small-scale fluctuations by gas pressure (Bryan *et al.* 1999;
neuns *et al.* 2000).
The first sets of simulations of the Ly α forest in CDM models appeared to show
od agreement with the observed *b*-

The first sets of simulations of the Ly α forest in CDM models appeared to show good agreement with the observed b-parameter distributions. However, subsequent The first sets of simulations of the Ly α forest in CDM models appeared to show
good agreement with the observed b-parameter distributions. However, subsequent
simulations with higher spatial resolution produced a large good agreement with the observed *b*-parameter distributions. However, subsequent simulations with higher spatial resolution produced a larger fraction of narrower lines than observed (Theuns *et al.* 1998*a*; Bryan *et a* simulations with higher spatial resolution produced a larger fraction of narrower lines
than observed (Theuns *et al.* 1998*a*; Bryan *et al.* 1999). This is illustrated in figure 5,
which shows observations of the *b* di which shows observations of the *b* distribution at $z \approx 3$ compared with the results *Phil. Trans. R. Soc. Lond.* A (2000)

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 b (km s⁻¹)
Figure 5. (a) The distribution of linewidths at $z = 3$ derived from simulations of the reference
model S and for a spatially flat. A-dominated universe (model L) with $Q_4 = 0.7$ and identical Figure 5. (a) The distribution of linewidths at $z = 3$ derived from simulations of the reference model S and for a spatially flat A-dominated universe (model L) with $\Omega_A = 0.7$ and identical photoionizing background. Both 6 model S and for a spatially flat A-dominated universe (model L) with $\Omega_A = 0.7$ and identical
photoionizing background. Both of these models have a baryon density of $\omega_b = 0.0125$. (b) Mod-
els with $\omega_b = 0.025$ and wit photoionizing background. Both of these models have a baryon density of $\omega_{\rm b} = 0.0125$. (b) Modphotoionizing background. Both of these models have a baryon density of $\omega_b = 0.0125$. (b) Models with $\omega_b = 0.025$ and with double the amplitude of the photoionizing background so that the optical depth of HI absorption els with $\omega_{\rm b} = 0.025$ and
optical depth of HI abso
from Hu *et al.* (1995).

from Hu *et al.* (1995).
from numerical simulations. Figure 5*a* shows the distribution derived by fitting Voigt
profiles to simulated spectra from reference model S (solid line). The lines in this from numerical simulations. Figure 5a shows the distribution derived by fitting Voigt
profiles to simulated spectra from reference model S (solid line). The lines in this
model are clearly too narrow, suggesting that the from numerical simulations. Figure 5a shows the distribution derived by fitting Voigt
profiles to simulated spectra from reference model S (solid line). The lines in this
model are clearly too narrow, suggesting that the profiles to simulated spectra from reference model S (solid line). The lines in this
model are clearly too narrow, suggesting that the temperature of the IGM is too low.
From the asymptotic relation (2.2) one can see that model are clearly too narrow, suggesting that the temperature of the IGM is too low.
From the asymptotic relation (2.2) one can see that the temperature of the IGM can
be raised by increasing the baryon density and by low be raised by increasing the baryon density and by lowering $\Omega_{\rm m}$ (the asymptotic tem-
perature is extremely insensitive to the amplitude of the photoionizing background
long after reionization). Figure 5b shows the ef perature is extremely insensitive to the amplitude of the photoionizing background perature is extremely insensitive to the amplitude of the photoionizing background
long after reionization). Figure 5b shows the effect of increasing the baryon density
to $\omega_{\rm b} = 0.025$. The dashed lines in both parts long after reionization). Figure 5b shows the effect of increasing the baryon density
to $\omega_{\rm b} = 0.025$. The dashed lines in both parts of figure 5 show the effect of lowering
 $\Omega_{\rm m}$ and introducing a cosmological co to $\omega_{\rm b} = 0.025$. The dashed lines in both parts of figure 5 show the effect of lowering $\Omega_{\rm m}$ and introducing a cosmological constant so that the Universe remains spatially flat. These variations in cosmological p $\Omega_{\rm m}$ and introducing a cosmological constant so that the Universe remains spatially flat. These variations in cosmological parameters can go some way to resolving the conflict with observations (Theuns *et al.* 1999) flat. These variations in cosmological parameters can go some way to resolving the conflict with observations (Theuns *et al.* 1999), but cannot provide an exact match unless the baryon density is much higher than the val conflict with observations (Theuns *et al.* 1999), but cannot provide an exact match
unless the baryon density is much higher than the value favoured from primordial
nucleosynthesis. This suggests that we are missing a si unless the baryon density is much higher than the value favoured from primordial nucleosynthesis. This suggests that we are missing a significant heating source of the IGM. A number of mechanisms have been suggested that m

nucleosynthesis. This suggests that we are missing a significant heating source of the IGM. A number of mechanisms have been suggested that might boost the temperature of the IGM, e.g. photoelectric heating of dust grains IGM. A number of mechanisms have been suggested that might boost the temperature of the IGM, e.g. photoelectric heating of dust grains (Nath *et al.* 1999) and Compton heating by the hard X-ray background (Madau & Efstath ature of the IGM, e.g. photoelectric heating of dust grains (Nath *et al.* 1999) and
Compton heating by the hard X-ray background (Madau & Efstathiou 1999). How-
ever, the most plausible explanation (Abel & Haehnelt 1999) Compton heating by the hard X-ray background (Madau & Efstathiou 1999). How-
ever, the most plausible explanation (Abel & Haehnelt 1999) is that the simulations
underestimate the temperature at $z \sim 3$ because they assume ever, the most plausible explanation (Abel & Haehnelt 1999) is that the simulations underestimate the temperature at $z \sim 3$ because they assume an optically thin IGM (and also a uniform photoionizing background that has underestimate the temperature at $z \sim 3$ because they assume an optically thin IGM
(and also a uniform photoionizing background that has *already* been reprocessed
by Ly α absorbing clouds; see Haardt & Madau (1996)). T by Ly α absorbing clouds; see Haardt & Madau (1996)). This is inconsistent and by Ly α absorbing clouds; see Haardt & Madau (1996)). This is inconsistent and
the simulations should properly include the effects of radiative transfer while the
medium is still optically thick prior to complete reioni the simulations should properly include the effects of radiative transfer while the medium is still optically thick prior to complete reionization, because in this regime every photoionizing photon is absorbed and contrib medium is still optically thick prior to complete reionization, because in this regime
every photoionizing photon is absorbed and contributes to heating the IGM. Abel
& Haehnelt (1999) estimate that correct inclusion of ra every photoionizing photon is absorbed and contributes to heating the IGM. Abel & Haehnelt (1999) estimate that correct inclusion of radiative transfer during the epoch of HeII reionization might increase the temperature o & Haehnelt (1999) estimate that correct inclusion of radiative transfer during the epoch of HeII reionization might increase the temperature of the IGM by a factor of approximately 2, perhaps enough to resolve the discrepa epoch of HeII reionization might increase the temperature of the IGM by a factor
of approximately 2, perhaps enough to resolve the discrepancy with the observed
b-parameter distributions illustrated in figure 5. The idea of approximately 2, perhaps enough to resolve the discrepancy with the observed b -parameter distributions illustrated in figure 5. The idea that the temperature of the IGM at $z \sim 3$ is boosted by HeII reionization is s b-parameter distributions illustrated in figure 5. The idea that
the IGM at $z \sim 3$ is boosted by HeII reionization is supported by
equation of state of the IGM described in the next subsection. *Phil. Trans. R. Soc. Lond.* A (2000)

 $\log N_{\rm HI}$ (cm⁻²) log $N_{\rm HI}$ (cm⁻²)
Figure 6. The $b(N)$ distributions derived by applying the Voigt profile-fitting program VPFIT
to 800 random lines of sight through two cosmological simulations at $z = 3$ (a) The r Figure 6. The $b(N)$ distributions derived by applying the Voigt profile-fitting program VPFIT to 800 random lines of sight through two cosmological simulations at $z = 3$. (a) The results for a model with a hot IGM (see te to 800 random lines of sight through two cosmological simulations at $z=3$. (a) The results for a model with a hot IGM (see text). Only lines with VPFIT errors $\Delta b/b < 0.5$ and $\Delta N_{\text{H}}/N_{\text{H}} < 0.5$ are plotted. The dashed line shows the best fit to the lower envelope of the $b(N)$ distribution over model with a hot IGM (see text). Only lines with VPFT errors $\Delta b/b < 0.5$ and $\Delta N_{\rm H1}/N_{\rm H1} < 0.5$
are plotted. The dashed line shows the best fit to the lower envelope of the $b(N)$ distribution over
the column density are plotted. The dashed line shows the best fit to the lower envelope of the $b(N)$ distribution over
the column density range $10^{12.5}$ cm⁻² $\leq N_{\text{H I}} \leq 10^{14.5}$ cm⁻² determined using the algorithm
of Schaye *et* of Schaye *et al.* (1999). This dashed line is reproduced in part (b) together with the $b(N)$ distribution for the colder reference model S.

(*e*) *Constraining the equation of state of the IGM*

As we have mentioned, a number of physical mechanisms contribute to the breadth As we have mentioned, a number of physical mechanisms contribute to the breadth
of the b distribution. However, the minimum linewidth is set by the temperature of
the gas which in turn depends on the density (cf figure 1) As we have mentioned, a number of physical mechanisms contribute to the breadth
of the b distribution. However, the minimum linewidth is set by the temperature of
the gas, which in turn depends on the density (cf. figure of the b distribution. However, the minimum linewidth is set by the temperature of
the gas, which in turn depends on the density (cf. figure 1). By fitting the cut-off in
the b distribution as a function of column density the gas, which in turn depends on the density (cf. figure 1). By fitting the cut-off in
the *b* distribution as a function of column density (the ' $b(N)$ ' distribution), one can
reconstruct the effective equation of state the *b* distribution as a function of column density (the ' $b(N)$ ' distribution), one can reconstruct the effective equation of state of the IGM (Schaye *et al.* 1999; Ricotti *et al.* 2000; Bryan & Machacek 2000). construct the effective equation of state of the IGM (Schaye *et al.* 1999; Ricotti *et*
2000; Bryan & Machacek 2000).
The method is illustrated in figure 6, which shows the $b(N)$ distributions derived
applying the VPFIT

al. 2000; Bryan & Machacek 2000).
The method is illustrated in figure 6, which shows the $b(N)$ distributions derived
by applying the VPFIT line-fitting program to two cosmological simulations. Results
for the standard ref The method is illustrated in figure 6, which shows the $b(N)$ distributions derived
by applying the VPFIT line-fitting program to two cosmological simulations. Results
for the standard reference model S are plotted in figu by applying the VPFIT line-fitting program to two cosmological simulations. Results
for the standard reference model S are plotted in figure 6*b*. Figure 6*a* shows a hotter
model, which has the same parameters as model Lb for the standard reference model S are plotted in figure 6*b*. Figure 6*a* shows a hotter model, which has the same parameters as model Lb plotted in figure 5 but with the HeI and HeII photoheating rates doubled over thos model, which has the same parameters as model Lb plotted in figure 5 but with
the HeI and HeII photoheating rates doubled over those of the HM model (crudely
representing 'radiative transfer' effects during the reionizati the HeI and HeII photoheating rates doubled over those of the HM model (crudely representing 'radiative transfer' effects during the reionization of helium). The dashed line in the figure shows the best fit to the lower e representing 'radiative transfer' effects during the reionization of helium). The dashed
line in the figure shows the best fit to the lower envelope of the $b(N)$ distribution
of figure 6a, determined by applying the itera of figure 6a, determined by applying the iterative fitting algorithm of Schaye *et al.*
(1999). The same line is plotted in figure 6b and it passes almost through the middle of
the $b(N)$ distribution of the colder model. (1999). The same line is plotted in figure 6b and it passes almost through the middle of
the $b(N)$ distribution of the colder model. The lower envelope of the $b(N)$ distribution
is clearly a sensitive indicator of the cha the $b(N)$ distribution of the colder model. The lower envelope of the $b(N)$ distribution is clearly a sensitive indicator of the characteristic temperature of the Ly α clearly and can be accurately determined from fits is clearly a sensitive indicator of the characteristic temperature of the Ly α clouds
and can be accurately determined from fits to high-resolution quasar spectra.
What is more difficult is to convert the fit to the low

and can be accurately determined from fits to high-resolution quasar spectra.
What is more difficult is to convert the fit to the lower envelope of the $b(N)$
distribution, $b = b_0(N/N_0)^{T-1}$, into the parameters T_0 and What is more difficult is to convert the fit to the lower envelope of the $b(N)$
distribution, $b = b_0 (N/N_0)^{T-1}$, into the parameters T_0 and γ of the effective equation
of state of the IGM (equation (2.1)). This is distribution, $b = b_0(N/N_0)^{T-1}$, into the parameters T_0 and γ of the effective equation
of state of the IGM (equation (2.1)). This is done by calibrating b_0 and Γ against
 T_0 and γ using numerical simulat of state of the IGM (eq
 T_0 and γ using numerica
al. (1999) for details).
The results of applying T_0 and γ using numerical simulations with different equations of state (see Schaye *et al.* (1999) for details).
The results of applying this technique to nine high-quality quasar spectra spanning

al. (1999) for details).
The results of applying this technique to nine high-quality quasar spectra spanning
the redshift range $2.0 < z < 4.5$ are shown in figure 7 (Schaye *et al.* 2000). Except
for the two lowest redshift The results of applying this technique to nine high-quality quasar spectra spanning
the redshift range $2.0 < z < 4.5$ are shown in figure 7 (Schaye *et al.* 2000). Except
for the two lowest redshift quasars, the $Ly\alpha$ fores the redshift range $2.0 < z < 4.5$ are shown in figure 7 (Schaye *et al.* 2000). Except
for the two lowest redshift quasars, the Ly α forest spectra were divided in two to
reduce the effects of redshift evolution and signa for the two lowest redshift quasars, the Ly α forest spectra were divided in two to reduce the effects of redshift evolution and signal-to-noise variations across a single spectrum. From $z \sim 3.5$ to $z \sim 3$, the inferr

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Figure 7. (a) The temperature at the mean density as a function of (decreasing) redshift inferred Figure 7. (a) The temperature at the mean density as a function of (decreasing) redshift inferred
from the lower envelope in the $b(N)$ distribution determined from nine high-resolution spectra
(Schave et al. 2000) (b) The Figure 7. (a) The temperature at the mean density as a function of (decreasing) redshift inferred
from the lower envelope in the $b(N)$ distribution determined from nine high-resolution spectra
(Schaye *et al.* 2000). (b) from the lower envelope in the $b(N)$ distribution determined from nine high-resolution spectra (Schaye *et al.* 2000). (*b*) The inferred slope of the equation of state as a function of redshift. The horizontal error bars (Schaye *et al.* 2000). (*b*) The inferred slope of the equation of state as a function of redshift.
The horizontal error bars indicate the redshift interval spanned by the absorption lines, and the vertical error bars sh vertical error bars show estimates of 1σ errors. The lines show the evolution of the equation of state in two numerical simulations as described in the text. Different symbols correspond to different quasars. of state in two numerical simulations as described in the text. Different symbols correspond to

the IGM, T_0 , increases and the gas is close to isothermal $(\gamma \sim 1)$. This behaviour the IGM, T_0 , increases and the gas is close to isothermal $(\gamma \sim 1)$. This behaviour differs markedly from that expected if helium were fully reionized at higher redshift.
For example, the solid lines show the evolution the IGM, T_0 , increases and the gas is close to isothermal $(\gamma \sim 1)$. This behaviour differs markedly from that expected if helium were fully reionized at higher redshift.
For example, the solid lines show the evolution differs markedly from that expected if helium were fully reionized at higher redshift.
For example, the solid lines show the evolution of the equation of state in a simulation with the HM background. In this simulation, b For example, the solid lines show the evolution of the equation of state in a simulation with the HM background. In this simulation, both hydrogen and helium are fully ionized by $z \approx 4.5$ and the temperature of the IGM d lation with the HM background. In this simulation, both hydrogen and helium are fully ionized by $z \approx 4.5$ and the temperature of the IGM declines slowly as the Universe expands, tending to the asymptotic form of equation fully ionized by $z \approx 4.5$ and the temperature of the IGM declines slowly as the Universe expands, tending to the asymptotic form of equation (2.2). This model cannot account for the peak in the temperature at $z \sim 3$ inf verse expands, tending to the asymptotic form of equation (2.2). This model cannot account for the peak in the temperature at $z \sim 3$ inferred from the observations.
Instead, we associate the peak in T_0 , and the low va account for the peak in the temperature at $z \sim 3$ inferred from the observations.
Instead, we associate the peak in T_0 , and the low value of γ , with reheating caused
by the second reionization of helium (HeII \rightarrow Instead, we associate the peak in T_0 , and the low value of γ , with reheating caused by the second reionization of helium (HeII \rightarrow HeIII). This interpretation is supported
by the abrupt change in HeII opacity at $z \sim 3$ from the measurements of Heap *et*
al. (2000) discussed in § 3 *a*. It is also con by the abrupt change in HeII opacity at $z \sim 3$ from the measurements of Heap *et al.* (2000) discussed in § 3 *a*. It is also consistent with evidence from the SiIV/CIV ratio that the spectrum of the photoionizing backgr al. (2000) discussed in $\S 3a$. It is also consistant chat the spectrum of the photoionizing (Songaila $\&$ Cowie 1996; Songaila 1998).[†]
The dashed lines in figure 7 show a 'designeer' ratio that the spectrum of the photoionizing background hardens abruptly at $z \sim 3$
(Songaila & Cowie 1996; Songaila 1998).[†]
The dashed lines in figure 7 show a 'designer model' with parameters tuned to fit

(Songaila & Cowie 1996; Songaila 1998).[†]
The dashed lines in figure 7 show a 'designer model' with parameters tuned to fit
the observations. This simulation has a much softer UV background at high redshift
than the mode The dashed lines in figure 7 show a 'designer model' with parameters tuned to fit
the observations. This simulation has a much softer UV background at high redshift
than the model shown by the solid line, and, consequentl the observations. This simulation has a much softer UV background at high redshift
than the model shown by the solid line, and, consequently, HeII reionizes at $z \sim 3.2$.
In addition, the photoheating rates have been enha than the model shown by the solid line, and, consequently, HeII reionizes at $z \sim 3.2$.
In addition, the photoheating rates have been enhanced during reionization to boost the temperature of the IGM (again, crudely modell In addition, the photoheating rates have been enhanced during reionization to boost the temperature of the IGM (again, crudely modelling the heating of optically thick gas). This model suggests that the jump in temperature at $z \sim 3$ may be associated with HeII reionization, but, clearly, more-realistic gas). This model suggests that the jump in temperature at $z \sim 3$ may be associated
with HeII reionization, but, clearly, more-realistic simulations that include radiative
transfer are required to determine the evolution with HeII reionization, but, clearly, more-realistic simulations that include radiative
transfer are required to determine the evolution of the equation of state during the
reionization phase more accurately. Further obse transfer are required to determine the evolution of the equation of state duri
reionization phase more accurately. Further observations would also be use
assess how steeply the IGM temperature changes between $z = 4$ and μ temperature changes between $z =$
4. Summary and outlook

4. Summary and outlook
The work reviewed in this paper provides a powerful argument that the Ly α forest The work reviewed in this paper provides a powerful argument that the $Ly\alpha$ forest arises from a space-filling, highly photoionized, diffuse IGM that contains most of the

ises from a space-filling, highly photoionized, diffuse IGM that contains most of the
† Note, however, that Boksenberg *et al.* (1998) found a more gradual change of the SiIV/CIV ratio
th redshift \dagger Note, however, that Boksenberg $et~al.$ (1998) found a more gradual change of the SiIV/CIV ratio with redshift.

²⁰⁶⁰ *G. Efstathiou,J.SchayeandT. Theuns* Downloaded from rsta.royalsocietypublishing.org

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Baryonic material in the Universe at high redshift. This model is a natural outcome of
CDM theories of structure formation and can account for many observed properties baryonic material in the Universe at high redshift. This model is a natural outcome of CDM theories of structure formation and can account for many observed properties of the Ly α forest in quantitative detail. The gene baryonic material in the Universe at high redshift. This model is a natural outcome of CDM theories of structure formation and can account for many observed properties of the Ly α forest in quantitative detail. The gene CDM theories of structure form
of the Ly α forest in quantitative
to us to be reasonably secure.
However, a more detailed are However, a more detailed analysis of the thermal history of the IGM requires

simulations that incorporate radiative transfer, and a model for the spatial distribution of ionizing sources. Such calculations are now being done (Abel *et al*. 1999; simulations that incorporate radiative transfer, and a model for the spatial distribution of ionizing sources. Such calculations are now being done (Abel *et al.* 1999; Gnedin 2000; Madau, this issue), but the computation bution of ionizing sources. Such calculations are now being done (Abel *et al* Gnedin 2000; Madau, this issue), but the computational problems are form Some outstanding problems that deserve further attention are listed be % one outstanding problems that deserve further attention are listed below.
(i) Detailed simulations of the inhomogeneous reionization of H and He.

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- (i) Detailed simulations of the inhomogeneous reionization of H and He.
(ii) Extending the analysis of Ly α linewidths to redshifts ≥ 4 , perhaps leading to constraints on the epoch of reionization of hydrogen. (ii) Extending the analysis of $Ly\alpha$ linewidths to redshifts ≥ 4 , perhaps leading to constraints on the epoch of reionization of hydrogen.
- (iii) Analysis of inhomogeneities in the temperature of the IGM. Are there, for
example, regions in the spectra of quasars in which Lvo linewidths are system-Analysis of inhomogeneities in the temperature of the IGM. Are there, for example, regions in the spectra of quasars in which $Ly\alpha$ linewidths are system-
atically broader or narrower than in other regions? Analysis of inhomogeneities in the temperature of the example, regions in the spectra of quasars in which Lyder atically broader or narrower than in other regions? example, regions in the spectra of quasars in which $Ly\alpha$ linewidths are system-
atically broader or narrower than in other regions?
(iv) Further observations of absorption gaps in HeII $Ly\alpha$ absorption (reported by
- Further observations of absorption gaps in HeII Ly α absorption (reported by Heap *et al.* (2000) and others) and the development of a model to understand their sizes. Further obse
Heap *et al.* (
their sizes. % their sizes.
(v) Searching for signatures of outflows around protogalaxies in the Ly α forest.
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- (v) Searching for signatures of outflows around protogalaxies in the $Ly\alpha$ forest.
(vi) Determining the mean metallicity of the IGM and understanding how the met-
als were transported from protogalaxies. (vi) Determining the mean metallicity of the IGM and understanding how the metals were transported from protogalaxies.

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contributions to this work J.S. thanks the Isaac Newto
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contributions to this work.

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