Lyα Absorption Systems and the Intergalactic Medium

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The last few years have seen a dramatic improvement in our understanding of the origin of Lyman α absorption systems. Hydrodynamic numerical simulations of cold dark matter dominated universes have shown that the many properties of the Lyman α absorption systems can be explained by a photoionized, space-filling, intergalactic medium. Lyman α lines offer promising probes of the photoionizing background, the amplitude of the mass fluctuations at high redshift and the evolution of the equation of state of the intergalactic medium.

Keywords: Intergalactic medium, galaxy formation, dark matter

1. Introduction

The existence of a forest of absorption lines blueward of the Lyα emission line in quasar spectra has been known for over 30 years (Bahcall and Salpeter 1965; Lynds 1971). These lines arise from Lyα 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 the intergalactic medium (IGM), either pressure confined by a hot IGM (Sargent et al. 1980; Ostriker and Ikeuchi 1983) or confined by the gravity of dark matter ‘mini-halos’ (e.g. Rees 1986). Over the last few years our understanding of the Lyα 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 spectral resolution over the redshift range $2 \lesssim z \lesssim 4$. The exquisite quality of Keck spectra has allowed observers to resolve Lyα absorption lines at low column densities ($\sim 10^{12.5}$ cm$^{-2}$) and to study their 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 observed properties of the Lyα forest (Cen et al. 1994; Zhang, Anninos and Norman 1995, 1997; Miralda-Escudé et al. 1996; Hernquist et al. 1996, Theuns et al. 1998a). These simulations have shown that most of the Lyα lines at column densities $\lesssim 10^{14.5}$ cm$^{-2}$ arise from modest fluctuations in the baryon density in a space filling photoionized IGM, rather than from distinct clouds. The properties of the Lyα lines can therefore be used to probe the structure and thermal history of the diffuse IGM and of the background UV radiation that determines its ionization state. The key characteristics of the numerical simulations are described in the next Section. Section 3 summarizes
Figure 1. The figure to the left shows photoionization rates for hydrogen and helium computed in the model of Haardt and Madau (1996). The figure to the right shows 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 line.

a number of results from these simulations and describes how the Ly$\alpha$ lines can be used to study 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’s contribution to these proceedings. For a recent review of observations and theoretical models of Ly$\alpha$ absorption lines see Rauch (1998).

2. Numerical Simulations of the IGM

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:

- parameters defining the cosmological model and its matter content (e.g. $\Omega_m$, $\Omega_b$, $\Omega_\Lambda$, $H_0 = 100 h$ km s$^{-1}$ Mpc$^{-1}$);
- the amplitude and spectral shape of the mass fluctuations;
- 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 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 $\Omega_m = 1$, $\Omega_\Lambda = 0$, $h = 0.5$ 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 rms density fluctuations in spheres of radius $8 h^{-1}$ Mpc is $\sigma_8 = 0.7$. The photoionizing background radiation is assumed to originate from quasars according to the model of Haardt and Madau (1996, hereafter HM). The photoionization rates
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for hydrogen and helium in this model are plotted in the left hand panel of Figure 1 as a function of redshift. With these photoionization rates, and assuming a uniform IGM, hydrogen is reionized at a redshift of $z \approx 6$ and HeII is reionized at $z \approx 4.5$.

The right hand panel of Figure 1 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 plume of shock heated gas extending to temperatures $\gtrsim 10^5$K, but most of the gas has a low overdensity and follows a power law-like ‘equation of state’

$$T = T_0 \left( \frac{\rho_b}{\bar{\rho}_b} \right)^{\gamma^{-1}},$$  \hspace{1cm} (2.1)

(Hui and Gnedin 1997). 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

$$T \approx 3.2 \times 10^4 \text{K} \left[ \frac{\Omega_b h(1 + \delta)(1 + z)^3}{(2 + \alpha)E(z)} \right]^{1/1.76},$$  \hspace{1cm} (2.2)

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

where we have assumed a power-law photoionizing background

$$J_\nu = J_{\nu L} \left( \frac{\nu}{\nu_L} \right)^{-\alpha}. \hspace{1cm} (2.3)$$

In equation (2.2) $\Omega_k = 1 - \Omega_m - \Omega_\Lambda$ and the exponent 1/1.76 arise from the temperature dependence of the HII and HeIII recombination coefficients.

Figure 2 shows the spatial distribution of the gas in the simulation at $z = 3$. The upper figure 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 collapsed structures. In contrast, the cool gas with $T < 10^5$K (shown in the lower figure) fills most of the computational volume. It is this diffuse low density gas which we believe accounts for the vast majority of the observed Ly\alpha 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\alpha 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 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 background;
- the fluctuating optical depth of HI absorption can be used to construct the power spectrum of the matter fluctuations at redshifts $z \sim 2 - 4$;
- the Ly\alpha absorption line-widths can be used to infer the temperature and equation of state of the diffuse IGM and its evolution.

These topics will be discussed in more detail in the next section.
3. The Ly $\alpha$ forest as a probe of the IGM

(a) Mean optical depth of HI and HeII absorption

The optical depth for HI Ly$\alpha$ absorption from an IGM in ionization equilibrium with density $\rho_b$ is given by

\[
\tau(z) = 6.5 \times 10^{-4} \left( \frac{\omega_b}{0.019} \right)^2 \left( \frac{h}{0.65} \right)^{-1} \left( \frac{1+z}{E(z)} \right)^{0.76} \frac{T_4^{-0.76}}{\Gamma_{HI}/10^{-12}s^{-1}} \left( \frac{\rho_b(z)}{\bar{\rho}_b(z)} \right)^2, \tag{3.1}
\]

(e.g. Peebles 1993 §23), where $\Gamma_{HI}$ is the photoionization rate for HI and $T_4$ is the temperature of the IGM in units of $10^4$ K. Variations in $\rho_b(z)$ along the line-of-sight will produce a ‘fluctuating Gunn-Peterson’ effect. An observed absorption line spectrum can therefore be inverted to infer the clustering of the baryon distribution as pioneered by Croft et al. (1998, see Section 3c 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 optical depths derived 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 amplitude of the photoionizing background can be balanced by variations in other cosmological parameters according to equation (3.1) to preserve the match to observations. The
Ly α absorption

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 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. 1997; Fardal et al. 1998 (FGS); Davidsen et al. 1996 (DKZ); Jakobsen et al. 1997 (JBDGJP); Reimers et al. 1997 (RKWGRW); Tytler, Fan and Burles 1995 (TFB); Heap et al. 2000.

Simulations therefore imply that

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

This type of criterion has been used by Weinberg et al. (1997) to set a crude lower limit to the baryon density. At redshifts 2–3 one can be reasonably confident of the HM model of the photoionizing background at around the Lyman edge, because the quasar luminosity function is quite well determined at these redshifts (see Section 3 of Madau’s article in these proceedings). 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 times \(10^4 K\), but 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

Although a highly ionized IGM is in ionization equilibrium, it is not in thermal equilibrium and so retains a memory of the way in which it was heated.
Nevertheless, equation (3.2) implies \( \omega_b \gtrsim 0.02 \Omega_m^{1/2} \), interestingly close to the baryon density of \( \omega_b = 0.019 \) inferred from primordial nucleosynthesis and the deuterium abundances measured in quasar spectra (Burles and Tytler 1998, Burles, Kirkman and Tytler 1999). The observed HI optical depth therefore leads to a consistent picture in which most of the baryons in the Universe at \( z \sim 2-4 \) belong to the diffuse photoionized IGM.

The HeII optical depth is shown in the lower panel of Figure 3. The open squares show \( \tau_{\text{HeII}} \) computed from the simulation using the same amplitude for the photoionizing background that provides a good match to \( \tau_{\text{HI}} \). The results from the simulation lie below the observations at all redshifts, suggesting that the photoionizing background has a softer spectrum than computed by HM. In photoionization equilibrium, the optical depth in HeII is related to the optical depth in HI by \( \tau_{\text{HeII}} / \tau_{\text{HI}} \propto J_{\text{HI}} / J_{\text{HeII}} \), and so \( \tau_{\text{HeII}} \) can be raised by softening the photoionizing spectrum appropriately. By lowering \( \Gamma_{\text{HeII}} / \Gamma_{\text{HI}} \) by a factor of two compared to the HM model of Figure 1, model S can match the observations at \( z \lesssim 2.8 \), but cannot match the high HeII optical depths at \( z \gtrsim 2.9 \) found in the recent HST-STIS observations of the quasar Q0302-003 by Heap et al. (2000).

One possible interpretation of these results is that the typical quasar spectrum adopted by HM is too hard and that HeII reionization is delayed until a redshift \( z \approx 3 \), corresponding to the abrupt change in HeII opacity observed by Heap et al. (2000). Additional arguments to support this picture are discussed in Section (3d). If this interpretation is correct, then AGN and ‘mini-quasars’ cannot produce much photoionizing radiation capable of doubly-ionizing helium at redshifts \( z \gtrsim 3 \) (see the article by Rees in this volume).

(b) Evolution of the column density distribution

It has been known for many years that Ly\( \alpha \) forest shows strong cosmological evolution (e.g. Sargent et al. 1980). Over a narrow range in redshift the evolution can be approximated by a power law

\[
\frac{dN}{dz} \propto (1 + z)\epsilon,
\]

where \( N \) is the number of lines above a threshold rest frame equivalent width (typically \( W > 0.32\AA \)). From high resolution Keck observations, Kim et al. (1997) find \( \epsilon = 2.78 \pm 0.71 \) in the redshift range \( 2 < z < 3.5 \). Williger et al. (1994) find 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; Bahcall et al. 1991, 1993; Impey et al. 1996).

The evolution of the Ly\( \alpha \) forest, including the low rates of evolution at redshifts \( z \gtrsim 2 \) can be reproduced quite simply in CDM models (Theuns, Leonard and Efstathiou 1998b; Davé et al. 1999). This is illustrated in Figure 4 which shows the evolution of the number of Ly\( \alpha \) 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 Section (3a) we adopt the HM model of the photoionizing background with an amplitude

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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 reference model S (described in the text) run at different numerical resolutions. The large open pentagon shows a reanalysis 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 (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).

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 range $10^{12.5} \text{ cm}^{-2} \lesssim N_{\text{HI}} \lesssim 10^{15} \text{ cm}^{-2}$ (see Figure 2 of Theuns et al. 1998b) 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 the Ly$\alpha$ lines found from HST observations arises from the steep decline in the photoionizing background at $z \lesssim 2$ caused by the rapid drop in quasar numbers at low redshift.

(c) Reconstruction of the matter power spectrum

Equations (2.1) and (3.1) can be combined to write the observed transmitted flux in terms of fluctuations in the baryon density,

$$F = \exp \left[ -A(p_b/\bar{p}_b)^\beta \right], \quad \beta \approx (2.76 - 0.76\gamma). \quad (3.4)$$
Croft et al. (1998) have used this relation to infer the 1-dimensional power spectrum $P_{1D}(k)$ of the baryon fluctuations, from which the three-dimensional power spectrum can be recovered by differentiation,

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

(3.5)

Croft et al. (1998) calibrate the amplitude of the matter power spectrum by comparing against 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 authors find that the amplitude and 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, that incorporates a correction for the distortion of the clustering pattern by peculiar velocities, is described by Nusser and Haehnelt (1999).

Croft et al. (1999) 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 $2\pi/k \sim 2–12 \, h^{-1}\text{Mpc}$ 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 attempted determination of the matter power spectrum at high redshift. The amplitude of the inferred power spectrum is high compared to that expected for spatially flat CDM models with $\Omega_m = 1$ normalized to reproduce the abundance of rich clusters at the present day. The best fitting CDM models have $\Omega_m + 0.2\Omega_\Lambda \approx 0.46$ (Weinberg et al. 1999; Phillips et al. 2000), in agreement with the parameters $\Omega_m \approx 0.3$, $\Omega_\Lambda \approx 0.7$ derived from combining observations of anisotropies in the cosmic microwave background radiation and distant Type Ia supernovae (e.g., Efstathiou et al. 1999 and references therein). Constraints on neutrino masses from estimates of $P(k)$ at high redshift are discussed by Croft, Hu and Davé (1999).

(d) Widths of the Lyα lines

The widths of the Lyα lines are usually characterised by the broadening parameter $b$ determined by fitting Voigt profiles. If the line width is caused by thermal broadening, the parameter $b$ is related to the temperature of the gas by

$$b = \left(\frac{2 k T}{m_p}\right)^{1/2} = 12.8 \, T_4^{1/2} \, \text{km s}^{-1}.$$  

(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 and the smoothing of small scale fluctuations by gas pressure (Bryan et al. 1999; Theuns, Schaye and Haehnelt 2000).

The first sets of simulations of the Lyα forest in CDM models appeared to show 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. 1998a; Bryan et al. 1999). This is illustrated in Figure 5 which shows observations of the $b$ distribution at $z \approx 3$ compared to the results from numerical simulations. The figure to the left shows the distribution
Figure 5. The figure to the left shows the distribution of line widths at $z = 3$ derived from simulations of the reference model S and for a spatially flat $\Lambda$ dominated universe (model L) with $\Omega_{\Lambda} = 0.7$ and identical photoionizing background. Both of these models have a baryon density of $\omega_b = 0.0125$. The figure to the right shows models with $\omega_b = 0.025$ and with double the amplitude of the photoionizing background so that the optical depth of HI absorption is almost unchanged. The error bars show observational results from Hu et al. 1995.

...
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 $z = 3$. The figure to the left shows results for a model with a hot IGM (see text). Only lines with VPFIT errors $\Delta b/b < 0.5$ and $\Delta N_{HI}/N_{HI} < 0.5$ are plotted. The dashed line shows the best fit to the lower envelope of the $b(N)$ distribution over the column density range $10^{12.5}\text{cm}^{-2} \leq N_{HI} \leq 10^{14.5}\text{cm}^{-2}$ determined using the algorithm of Schaye et al. (1999). This dashed line is reproduced in the figure to the right together with the $b(N)$ distribution for the colder reference model S.

Constraining the equation of state of the IGM

As we have mentioned, a number of physical mechanisms contribute to the breadth of the $b$-distribution. However, the minimum line-width 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 ‘$b(N)$’ distribution) one can therefore reconstruct the effective equation of state of the IGM (Schaye, et al. 1999; Ricotti, Gnedin and Shull 2000; Bryan and Machacek 2000).

The method is illustrated by 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 Figure (6b). Figure (6a) 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 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 envelope of the $b(N)$ distribution of Figure (6a) determined by applying the iterative fitting algorithm of Schaye et al. (1999). The same line is plotted in Figure (6b) and 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 characteristic temperature of the Ly\(\alpha\) clouds 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, $b = b_0(N/N_0)^{\Gamma - 1}$, into the parameters $T_0$ and $\gamma$ of the effective equation of state of the IGM (equation 2.1). This is done by calibrating $b_0$ and $\Gamma$ against $T_0$.
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 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 Lyα forest spectra were divided in two to reduce the effects of redshift evolution and signal-to-noise variations across a single spectrum. From z ∼ 3.5 to z ∼ 3, the inferred temperature at the mean density of the IGM, T₀, increases and the gas is close to isothermal (γ ∼ 1). This behaviour 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, both hydrogen and helium are fully ionized by z ≈ 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 ∼ 3 inferred from the observations. Instead, we associate the peak in T₀, and the low value of γ, with reheating caused by the second reionization of helium (HeII → HeIII). This interpretation is supported by the abrupt change in HeII opacity at z ∼ 3 from the measurements of Heap et al. (2000) discussed in Section 3(a). It is also consistent with evidence from the ratio SiIV/CIV that the spectrum of the photoionizing background hardens abruptly at z ∼ 3 (Songaila and Cowie 1996; Songaila 1998).

4. Summary and Outlook

The work reviewed in this article provides a powerful case that the Lyα forest arises from a space-filling, highly photoionized diffuse IGM that contains most of the 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 Lyα forest in quantitative detail. The general features of the model thus seem to us to be reasonably secure.

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, Norman and Madau 1999; Gnedin 2000; Madau these proceedings) but the computational problems are formidable. Some outstanding problems that deserve further attention include:

† Note, however, that Boksenberg, Sargent and Rauch (1998) find a more gradual change of the SiIV/CIV ratio with redshift.

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Figure 7. The figure to the left shows the temperature at the mean density as a function of (decreasing) redshift inferred from the lower envelope in the $b(N)$ distribution determined from 9 high resolution spectra (Schaye et al. 2000). The figure to the right shows 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 show estimates of $1\sigma$ 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.

- detailed simulations of the inhomogeneous reionization of hydrogen and helium;
- extending the analysis of Ly$\alpha$ line widths to redshifts $z \gtrsim 4$, perhaps leading to constraints on the epoch of reionization of hydrogen;
- analysis of inhomogeneities in the temperature of the IGM. Are there, for example, regions in the spectra of quasars in which Ly$\alpha$ line-widths are systematically broader or narrower than in other regions?
- further observations of absorption gaps in HeII Ly$\alpha$ absorption (reported by Heap et al. (2000) and others) and the development of a model to understand their sizes;
- searching for signatures of outflows around protogalaxies in the Ly$\alpha$ forest;
- determining the mean metallicity of the IGM and understanding how the metals were transported from protogalaxies.

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