OBSERVATIONS OF THE GAS RESERVOIR AROUND A STAR-FORMING GALAXY IN THE EARLY UNIVERSE

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ABSTRACT

We present a high signal-to-noise spectrum of a bright galaxy at \( z = 4.9 \) in 14 hr of integration on VLT FORS2. This galaxy is extremely bright, \( i_{\text{SFO}} = 23.10 \pm 0.01 \), and is strongly lensed by the foreground massive galaxy cluster A1689 (\( z = 0.18 \)). Stellar continuum is seen longward of the Ly\( \alpha \) emission line at \( \approx 7100 \text{ Å} \), while intergalactic H\( \text{i} \) produces strong absorption shortward of Ly\( \alpha \). Two transmission spikes at \( \approx 6800 \) and \( \approx 7040 \text{ Å} \) are also visible, along with other structures at shorter wavelengths. Although this star-forming galaxy is fainter than a QSO, the absence of a strong central ultraviolet flux source in it enables a measurement of the H\( \text{i} \) flux transmission in the intergalactic medium (IGM) in the vicinity of a high-redshift object. We find that the effective H\( \text{i} \) optical depth of the IGM is remarkably high within a large 14 Mpc (physical) region surrounding the galaxy compared to that seen toward QSOs at similar redshifts. Evidently, this high-redshift galaxy is located in a region of space where the amount of H\( \text{i} \) is much larger than that seen at similar epochs in the diffuse IGM. We argue that observations of high-redshift galaxies like this one provide unique insights into the nascent stages of baryonic large-scale structures that evolve into the filamentary cosmic web of galaxies and clusters of galaxies observed in the current universe.

Subject headings: galaxies: clusters: general — galaxies: clusters: individual (A1689) — galaxies: high-redshift — gravitational lensing — methods: data analysis — techniques: spectroscopic

Online material: color figures

1. INTRODUCTION

Hydrodynamic simulations tell us that dark matter near the epoch of galaxy formation collapses into an ordered filamentary pattern, the so-called cosmic web. In turn, this cosmic web is thought to cradle high-redshift galaxies in dense nodes that are opaque to the extragalactic ultraviolet background radiation. Observations of H\( \text{i} \) surrounding these high-redshift objects provide information on the likely reservoirs from which galaxies assemble their gas. Hitherto, it has been possible to measure H\( \text{i} \) opacities toward only bright quasi-stellar objects (QSOs); unfortunately, the high ultraviolet flux from the QSOs ionizes the hydrogen clouds in their vicinity, thereby making the determination of H\( \text{i} \) cloud physical conditions unreliable close to the QSO.

New techniques and facilities in the past decade have enabled detailed observational studies of the IGM in the early universe (\( z > 5 \)). For example, the spectra of high-redshift QSOs show a plethora of H\( \text{i} \) Ly\( \alpha \) absorption lines, the “Ly\( \alpha \) forest,” as well as lines from a wide variety of heavier elements, all of which provide detailed information about the high-redshift IGM along the line of sight toward the QSO. Around the QSOs themselves, however, the ultraviolet flux is so high that it typically ionizes the surrounding gas. Thus, QSOs are not ideal for studying the pervasive IGM close to the QSO. Instead, we suggest that bright galaxies may provide better probes for the study of IGM conditions in the proximity of high-redshift objects, as these objects emit fewer ultraviolet photons than QSOs do.

The subject of this Letter is the Ly\( \alpha \) forest in the spectrum of an unusually bright high-redshift galaxy at \( z = 4.866 \) (Frye et al. 2002, 2007). The galaxy is situated behind the massive galaxy cluster A1689 (\( z = 0.183 \)), which magnifies the starlight of this background object by a factor of 10.3 by the effect of gravitational lensing (Broadhurst et al. 2005). Multicolor Hubble Space Telescope (HST) imaging of one of the faint lensed images, hereafter designated A1689.1, is shown in Figure 1. We assume a cosmology for this Letter of \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_{\Lambda,0} = 0.3 \), and \( \Omega_{M,0} = 0.7 \).

2. OBSERVATIONS AND SPECTRUM

Our spectrum of A1689.1 is made possible with current telescopes only by the combination of strong lensing and unusually long observations. We obtained the spectrum for A1689.1 in 14 hr at the Very Large Telescope (VLT) with the Focal Reducer and low-dispersion Spectrograph (FORS2) in 2001 June and July and report a spectral resolution of \( R = \lambda/\Delta \lambda \approx 530 \). We fluxed the data with the standard star LTT 9239 and performed the reductions with a code written by the first author in IDL designed to maximize the signal-to-noise ratio of background-limited objects. See Frye et al. (2007) for more details on this purpose-built spectroscopic reduction package.

The spectrum of A1689.1 (Fig. 2) shows an H\( \text{i} \) Ly\( \alpha \) emission line and several strong low- and high-ionization metal...
absorption lines detected against the stellar continuum. On the basis of a mean velocity difference of \( v = 470 \text{ km s}^{-1} \) between the positional centroids of the metal absorption features and the Ly\( \alpha \) emission line, we apply an offset correction (Adelberger et al. 2003) and measure a systemic redshift of \( z = 4.866 \) for the galaxy. Interestingly, Ly\( \alpha \) absorption immediately shortward of the emission line is not obviously damped at our spectral resolution, with a column density of \( \log [N_{\text{H}}/\text{cm}^{-2}] \) < 20.0 \( \pm \) 0.3 dex (see Fig. 2, inset). At our spectral resolution, the detected absorption lines are strongly saturated and thus are not suitable for deriving metallicities. The most unusual feature of the spectrum is the broad absorption trough in the Ly\( \alpha \) forest first appearing at the Ly\( \alpha \) emission feature and extending toward shorter wavelengths. Although two transmission spikes are visible at \( \sim 6800 \) and \( \sim 7040 \) \AA, nearly 100\% of the continuum is absorbed between wavelengths of 6850 and 7100 \AA.

What might this absorption represent? It is likely that we are detecting the presence of many more overlapping Ly\( \alpha \) forest clouds closer to the galaxy than can survive the UV radiation field of QSOs at comparable distances. At the resolution of our data, individual Ly\( \alpha \) forest lines cannot be resolved, and we would see only the effects of a large number of blended lines. It is also possible that the enhanced absorption could be from only a few overlapping, but very high \( N_{\text{H}} \), clouds, but we might then expect to see more metal absorption lines from these clouds redward of the Ly\( \alpha \) emission line, which are absent in our data. Even less likely is that this H\( \alpha \) overdensity signals the late completion of cosmic reionization, as recent observational studies have set convincing constraints for this epoch at \( z \gtrsim 6.3 \) (Fan et al. 2006; Songaila 2004).

We explore the nature of this remarkably large absorption trough with a comparison to the Ly\( \alpha \) absorption seen toward their brighter counterpart objects, the QSOs. QSOs produce radiation fields that ionize hydrogen over large, \( \sim 16 \) \text{ physical Mpc}, regions at \( z = 5 \) (Fan et al. 2006) (red solid line in Fig. 2, inset). Although evidence has emerged of a softening of this proximity effect in the transverse direction on small scales of \( \sim 1.5 \) \text{ Mpc} from studies of QSO pairs (Bowen et al. 2006; Tytler et al. 2007), detailed studies of the Lyman series forest are made routinely only outside the ionizing influence of the QSOs. In contrast, ordinary star-forming galaxies have modest proximity zones of size \( \lesssim 0.1 \text{ h}^{-1} \text{ physical Mpc} \) (Adelberger et al. 2003), thereby enabling the study of H\( \alpha \) and its structure in the vicinity of deep potential wells where the gas is not ionized. Despite the advantage of a small proximity zone, galaxies suffer from being much fainter in the ultraviolet. Unlike the vast majority of star-forming galaxies, our target is bright because it is strongly lensed, thereby yielding a spectrum suitable for measuring the transmitted flux \( T \) in the Ly\( \alpha \) forest in the proximity of a galaxy.

3. H\( \alpha \) FLUX TRANSMISSION

We calculate the Gunn-Peterson (GP) optical depth (Gunn & Peterson 1965), \( \tau_{\text{GP}} = -\ln (T) \), where \( T \) is the ratio of the average observed flux to the average unabsorbed continuum flux, \( T = \langle f / f_{\text{cont}} \rangle \), and \( f_{\text{cont}} \) is determined by stellar synthesis.
models fitted to the photometric data. We compute $t_{\text{eff}}^{\text{GP}}$ in several redshift bins extending from a wavelength clear of the red wing of Ly$\beta$ up to the blue edge of our model fitted to the H i in the source (blue dashed line in Figure 2, inset, delimits the extent of the highest redshift bin). Uncertainties in $t_{\text{eff}}^{\text{GP}}$ are dominated by the intrinsic scatter of the continuum flux levels due to the stochastic nature of the absorption in the IGM, or sample variance, and also include continuum placement uncertainties and shot noise.

We emphasize that the values for $t_{\text{eff}}^{\text{GP}}$ are measured in the same way toward both the QSOs and the galaxy, and after first excluding the proximity zone, thereby yielding information with provides a poor fit to the slope of data, as the continuum becomes significantly flatter in the blue with the addition of even moderate amounts of dust. Thus, we restrict our parameter space to $E(B-V) \leq 0.1$.

Model spectral energy distributions are generated using the stellar synthesis code of Bruzual & Charlot (2003). We select a Chabrier initial mass function, Padova 1994 stellar evolution tracks, and solar metallicity. We choose a single starburst model with a range of decay rates $\tau$ and a star formation rate (SFR) that depends exponentially on $\tau$ as follows: \( \text{SFR}(t) \propto \exp(t/\tau) \) with $\tau = 0.1, 0.2, 0.3, 0.5, 1, \text{ and } 1.2 \text{ Gyr. Continuous star formation models are also considered, as approximated by selecting } \tau = \text{ the age of the universe at } z = 5, \text{ and we do not consider more complicated star formation histories. For each } \tau, \text{ three parameters remain to be fitted to the data: age } t, E(B-V), \text{ and stellar mass } M_\star. \text{ A suite of models are constructed over the allowable parameter space for these three variables, and each model is corrected for the effects of dust extinction (Calzetti et al. 2000) and attenuation by the intervening Lyman series forest (Madau 1995).}
We compute synthetic photometry on our models by a convolution of the model spectra with the observed filter bandpass transmission functions. We compare the synthetic photometry with the observed photometric values until the lowest value of reduced $\chi^2$ is obtained. Figure 4 shows our best-fit model to the joint variation of the parameters of dust extinction, age, and mass, with values $E(B-V) = 0.03^{+0.03}_{-0.02}$, $t = 100 \pm 14$ Myr, and $M^* = (7.3 \pm 0.70) \times 10^8 M_\odot$. Note that as the exponentially decaying models are normalized to have a total mass of $1 M_\odot$ as $t \rightarrow \infty$, we obtain the mass for A16897.1 by the flux normalization that yields the lowest value for the reduced $\chi^2$ fit. Our best fit is for a no-dust model. We compute formal $\chi^2$ uncertainties that represent 68% uncertainties for our input model. We follow the prescription in Cash (1976) originally developed for use with X-ray spectral data that allows for the joint estimation of confidence intervals.

The best-fit synthetic spectrum is also shown in Figure 2 in the main text, but without corrections for dust extinction and absorption by the intervening Ly$\alpha$ forest. This intrinsic form is used to define the unabsorbed continuum level $f_{\text{cont}}$ for A16897.1 against which the flux transmission of the Ly$\alpha$ forest is measured.

5. DISCUSSION

Despite the strong magnification, the intrinsic luminosity of the galaxy is not high; we measure an unabsorbed luminosity of $L_{1400} = 7.7 \times 10^{28}$ erg s$^{-1}$ Hz$^{-1}$ and an unlensed $K = 24.5, 2$ mag fainter than $K^*$ at $z = 3$ (Shapley et al. 2001). Galaxies at $z \geq 5$ are faint and hence only a few high-quality spectra exist (Price et al. 2007; Kawai et al. 2006; Dow-Hygelund et al. 2007; Franx et al. 1997).

We are aware of a few other high-quality spectra of high-redshift galaxies (Price et al. 2007; Dow-Hygelund et al. 2007; Kawai et al. 2006; Franx et al. 1997). Some of these are at $z > 6$ where $\tau_{\text{eff}}$ is expected to be high (from the QSO measurements), but the spectrum of the gamma-ray burst GRB 060510B at $z = 4.94$ (Price et al. 2007) shows some similar characteristics to the spectrum of A16897.1. The IGM transmission measured over a broad redshift bin of the former is $T = 0.18$, similar to the values observed toward QSOs. However, this broad average smears out the structure in $\tau_{\text{eff}}$ as a function of redshift. The GRB 060510B spectrum shows evidence of higher than expected GP optical depth extending beyond the region affected by the damped Ly$\alpha$ absorption at the redshift of the GRB host. It would be interesting to reanalyze this GRB spectrum using smaller redshift bins. If the opacities were also measured inside the proximity zones of QSOs; although significantly ionized, the proximity zones are found to have neutral hydrogen fractions that exceed theoretical expectations. This indicates that at least some QSOs are also found in regions of gaseous overdensity with large sizes of 15 h$^{-1}$ Mpc (Guimarães et al. 2007).

Might A16897.1 still be in the process of accreting much of its mass from its overdense surrounding cosmic structure? Theoretical models predict that H i gas is funneled into young galaxies via large-scale filamentary structures (Kereš et al. 2005; Birnboim & Dekel 2003). We have presented here observational evidence that H i column densities are higher than expected near one high-redshift galaxy. Based on the large physical size implied by the H i excess, it is unlikely that this gas will accrete onto a single galaxy. Alternatively, poststarburst galaxies are known to drive high-velocity outflows with velocities of $\approx 2000$ km s$^{-1}$ in low-ionization stages such as Mg II (Trentori et al. 2007). Given sufficient time, the observed excess of H i optical depth could be explained by such an outflow; however, A16897.1 is too young by a significant factor given the best-fit stellar age of 100 $\pm$ 14 Myr. On the other hand, QSOs are known to drive outflows with terminal velocities in excess of 10$^4$ km s$^{-1}$. A16897.1 does not show obvious signatures of being an AGN, but even if there was a low-metallicity outflow undetected in our spectrum, the velocities would still fall short by more than a factor of 10 of that required to explain the H i excess. As more data become available to study the neutral H i absorption toward the several recently discovered strongly lensed Lyman break galaxies, it may be found to be typical for high-redshift objects, both galaxies and QSOs, to be located in regions of space with neutral hydrogen gas fractions significantly larger than that of the pervasive IGM. This reevaluation of the H i structure in the densest regions of the universe at these epochs will provide the necessary calibration for modeling the formation and evolution of galaxies in the early universe.

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