LIMITS ON THE GUNN-PETERSON EFFECT AT z = 5

ANTOINETTE SONGAILA,1 ESTHER M. HU,1 AND LENNOX L. COWIE1
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822;
acowie@ifa.hawaii.edu, hu@ifa.hawaii.edu, cowie@ifa.hawaii.edu

AND

RICHARD G. McMATHON
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge,
CB3 0HA, England, UK; rgm@ast.cam.ac.uk
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ABSTRACT

We report new limits on the Gunn-Peterson effect at a redshift near 5 using spectroscopic observations of the z = 5 Sloan Digital Sky Survey quasar, J033829.31+002156.3, made with the Low Resolution Imaging Spectrometer (LRIS) and the High-Resolution Echelle Spectrometer (HIRES) on the Keck telescopes. Lower resolution spectrophotometrically calibrated observations made with LRIS over the wavelength region 4500–9600 Å were used to obtain a continuum shape and to flux-calibrate much higher resolution (R = 36,000) observations made with HIRES. The LRIS data show an Oke D4 index of 0.75. Portions of the HIRES spectrum return to near the extrapolated continuum level. Including both statistical and systematic errors, we place an upper limit of τ = 0.1 on the regions of minimum opacity. We argue that, even if this opacity arises in underdense regions of the intergalactic gas, we require a high value of the metagalactic ionizing flux at these redshifts (J ≫ 4 × 10^{-23} ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} at z ~ 4.72) to produce a solution which is consistent with even minimum nucleosynthesis estimates of the baryon density. We also report the presence of an Mg II absorption system of extremely high equivalent width [W_h, rest(2796) = 1.73 Å] at z = 2.304.

Subject headings: cosmology: observations — early universe — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

Soon after the discovery of cosmologically distant objects, it was realized (Field 1959) that the absence of strong Lyα scattering of light at the appropriate redshifted wavelengths placed strong constraints on the amount of neutral hydrogen in the intergalactic medium (Shklovskij 1964; Scheuer 1965; Gunn & Peterson 1965). The absence of significant neutral opacity in a uniformly distributed component of the intergalactic medium (IGM) is generally referred to as the Gunn-Peterson effect.

While it remains conceptually possible that there is a diffuse substrate of the IGM in a multiphase gas, modern interpretations of the Lyα forest of neutral hydrogen absorption lines suggest instead that the IGM is a highly structured warm ionized gas in which the amplitude of the perturbations grow gravitationally. In this interpretation, the Lyα forest is produced by scattering from the very small neutral hydrogen fraction of this undulating density intergalactic gas (e.g., Cen et al. 1994; Zhang, Anninos, & Norman 1995). Regions of minimum HI optical depth, in this scenario, occur in cosmic minivoids, which are underdense expanding regions in which growth is essentially frozen (Meiksin 1994; Reisenegger & Miralda-Escudé 1995). The cosmic minivoids are the closest analogs in this model to the Gunn-Peterson effect in a homogeneous diffuse gas, and the simple physics of these regions makes them powerful probes of the metagalactic ionizing flux relative to the baryon density of the universe.

Because of the rapid increase in the gas density with redshift, it is expected that the fraction of the quasar spectrum returning to the continuum level will diminish rapidly at the higher redshifts. As a specific example, Zhang et al. (1997) find at z = 5, for H_o = 50 km s^{-1} Mpc^{-1}, Ω_m = 0.06, and a Haardt-Madau (1996) spectrum and ionizing flux, that less than a fraction of a percent of the spectrum will have τ(H I) < 0.1. Moreover, they find that the spectrum of a z = 5 quasar will have an average flux in the region between 1050 and 1170 Å that is 10% of the continuum value which would be present in the absence of Lyα scattering.

The newly discovered z = 5 quasar J033829.31+002156.3 (Fan et al. 1999) presents an opportunity to look at this question at the highest redshift yet available, and we report here low- and high-resolution spectral observations of this object. As Schneider, Schmidt, & Gunn (1991b) found in the z = 4.897 quasar PC 1247+3406, 1 - D4 (the Oke index D4 is defined in § 3) is higher than the model values (0.25 in J033829.31+002156.3 and 0.36 in PC 1247+3406), and we also find that there are significant regions of low optical depth (τ < 0.1). Our results are similar to the minimum optical depth of τ = 0.02 ± 0.03 at z = 4.3 found in the z = 4.73 quasar BR 1202−0725 by Giallongo et al. (1994) and to the 2 σ lower limit of 0.1 found by Williger et al. (1994) in the z = 4.5 quasar BR 1033−0327. Both the Oke index and the low minimum opacity require a relatively high ionizing flux at these redshifts.

2. OBSERVATIONS

Long-slit spectroscopic observations of J033829.31+002156.3 were obtained with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on 1999 February 10 UT with a 1″ wide slit and 400 line mm^{-1} grating blazed at 8500 Å (spectral resolution 8.1 Å) and on 1999 February 17 UT with a 1.5″ wide slit, both with the 400 line mm^{-1} grating blazed at 8500 Å (spectral resolution 12.3 Å) and with the 300
line mm$^{-1}$ grating blazed at 5000 Å (spectral resolution 17.3 Å). Seeing was 0'7–0'9 FWHM on the first night and 0'7–1'0 on the second night; observations were made under dark, photometric conditions in each instance. A sequence of three exposures, shifted by 10' along the slit, was taken in each configuration with the position angle of the slit set to the parallactic angle for the middle exposure. This yielded net integrations of 3600 s (5542–9350 Å; 8.1 Å resolution; 1'9 slit), 3600 s (5799–9609 Å; 12.4 Å resolution; 1'5 slit), and 3000 s (3673–8708 Å; 17.3 Å resolution; 1'5 slit). A GG495 blocking filter was used to suppress second-order blue light. The observations are summarized in Table 1. Calibration stars (HZ4 and HZ44) were observed at the parallactic angle for each slit/grating configuration and used to flux-calibrate the data. The calibration stars used for the LRIS and HIRES data are category 1 Hubble Space Telescope (HST) standard stars (Bohlin & Lindler 1992), which are part of an ongoing effort to develop a consistent set of fundamental flux standards for observations with the HST over the wavelength region from 1050 to 10000 Å based on the Oke (1990) measurements taken on the Double Spectrograph of the Palomar 5 m telescope for optical measurements. Although both HZ4 and HZ44 have long-wavelength flux-calibration data measured by a variety of authors (e.g., Oke 1974; Stone 1977; Massey & Gronwall 1990), for self-consistency we use the Oke (1974, 1990) measurements. The estimated galactic extinction is $E_{B-V} = 0.10$ in this direction (Schlegel, Finkbeiner, & Davis 1998).

The High-Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994) observations were obtained using the red collimator and the D1 decker (1'7 × 14' slit; resolution $R = 36,000$) on the nights of 1999 February 14 and 15 under conditions of variable seeing. The four 2400 s exposures were taken at P.A. = 100' (nonparallactic angle) using the atmospheric dispersion corrector to maintain the guide object for this observation within the guide camera field. The white dwarf standard star G191-B2B (Oke 1990) was used to correct the continuum fit, which was then flux-calibrated by comparing an appropriately smoothed spectrum with the lower resolution LRIS data. The combined LRIS spectra, smoothed to the lowest resolution data taken with the 300 line mm$^{-1}$ grating (resolution 17.4 Å), is shown in Figure 1, and the HIRES spectrum is shown in Figure 2. Prior to any extinction corrections, both continua are well fit by a flat $f_{\nu}$ spectrum in the line-free portions of the red spectrum, and this is shown by the dashed line.

The fluxed LRIS spectra are in excellent agreement with the photometric measurements of Fan et al. (1999) and with their estimated $A_{V,1450}$ continuum magnitude of 20.01 (35 μJy). A strong Mg ii doublet is visible superposed on the C iv emission (Fig. 1). We measure a doublet ratio $D_\lambda = 1.25$ and a redshift $z = 2.304$ for this system (Table 2). If the strong rest equivalent width $W_{\lambda,rest}(2796) = 1.73$ Å indicates a large galaxy along the line of sight (Bergeron & Boissé 1991; Steidel, Dickinson, & Persson 1994), the quasar may be ampliﬁed by lensing.

### Table 1: Spectroscopic Observations of J035829.31+002156.3

| UT Date (1999) | Air Mass | $t_{exp}$ (s) | $\lambda$ Range (Å) | Slit (arcsec) | P.A.$^b$ (deg) | Resolution$^c$ (Å) | Grating$^d$ | FWHM$^e$ (arcsec) |
|---------------|----------|--------------|----------------------|---------------|---------------|----------------|----------|----------------|
| Feb 10 ...... | 1.08     | 3600         | 5542–9350            | 1.0 × 274     | 28.0          | 8.1           | 400/8500 | 0.72 |
| Feb 17 ...... | 1.12     | 3600         | 5799–9609            | 1.5 × 274     | 50.0          | 12.4          | 400/8500 | 0.71 |
| Feb 15 ...... | 1.30     | 3000         | 3673–8708            | 1.5 × 274     | 62.0          | 17.3          | 300/5000 | 1.00 |

$^a$ The usable wavelength range for the multiorder HIRES data is ~6800–8000 Å.
$^b$ Set close to estimated parallactic angle at mid-exposure in the sequence of LRIS observations.
$^c$ $R = 36,000$ for HIRES.
$^d$ Identified by ruled line mm$^{-1}$ and blaze wavelength in Å for LRIS; for HIRES this is the RED configuration with D1 decker.
$^e$ Measured FWHM of quasar profile on slit.

The High-Resolution Echelle Spectrometer (HIRES; Vogt et al. 1991b) and Kennefick, Djorgovski, & de Carvalho (1991b) in quasars in the range and with the values $0.55±0.74$ measured by Schneider et al. for the quasar $z = 4.733$ quasar PC 1158+4635 and 0.64 for the $z = 4.897$ quasar PC 1247+3406. It is considerably smaller than the value of 0.9 predicted by Zhang et al. (1997) for models with the Haardt & Madau (1996) $J$, evolution, with $\Omega_0 = 0.06$ and $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, suggesting that these models are underestimating $f_\nu/\Omega_0^2$ at high redshift.

This can also be examined by looking at the regions of minimum opacity in the much higher resolution HIRES spectrum. As can be seen from Figure 2, portions of the HIRES spectrum return close to the extrapolated continuum. If we extrapolate the continuum with a $\nu^\tau$ power law, 14% of the spectrum has $\tau < 0.1$ in the observed wavelength range 6800–7000 Å. This fraction is not highly sensitive to the power-law choice and reduces only to 11% if we use a $\nu^\tau$ extrapolation. The regions of minimum opacity around 6790 and 6948 Å have extremely low optical depth. The mean optical depth be-

### Table 2: Mg ii Absorber

| Identification | $\lambda$ (Å) | $W_{\lambda,rest}$ (Å) |
|----------------|--------------|----------------|
| Mg ii λ2796 ...... | 9236.7 | 1.73 |
| Mg ii λ2803 ...... | 9260.4 | 1.38 |

3. DISCUSSION

The simplest measures of the opacity of the neutral hydrogen are the Oke & Korycanski (1982) indices. Following Schneider, Schmidt, & Gunn (1991a) and Schneider et al. (1991b), we measure the index

$$D_\lambda = \left(1 - \frac{f_{\nu}(\text{observed})}{f_{\nu}(\text{continuum})}\right)$$

in the rest-frame wavelength range 1050–1170 Å, obtaining $D_\lambda = 0.75$ in both of the lower resolution spectra. This can be compared with the values of 0.55–0.74 measured by Schneider et al. (1991b) and Kennefick, Djorgovski, & de Carvalho (1995) in quasars in the range $z = 4.35$–4.5 and with the values of 0.74 obtained by Schneider et al. for the $z = 4.733$ quasar PC 1158+4635 and 0.64 for the $z = 4.897$ quasar PC 1247+3406. It is considerably smaller than the value of 0.9 predicted by Zhang et al. (1997) for models with the Haardt & Madau (1996) $J$, evolution, with $\Omega_0 = 0.06$ and $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, suggesting that these models are underestimating $f_\nu/\Omega_0^2$ at high redshift.
Fig. 1.—Both the 300 and 400 line mm$^{-1}$ fluxed LRIS spectra are shown in microjanskys vs. wavelength. The 300 line mm$^{-1}$ spectrum is shown over the wavelength range 4000–8200 Å, and the combined 400 line mm$^{-1}$ data from 5700 to 9700 Å. The spectra agree extremely well in the overlap region. The dashed and dotted lines show $n^0$ and $n^1$ continuum fits, normalized to the region 7700–8000 Å, which lies redward of the atmospheric A band but blueward of the Si iv emission line.

Fig. 2.—Flux-calibrated HIRES spectrum over the range 6800–7700 Å. The spectrum has been smoothed to a resolution of 2 Å. The dotted and dashed lines show the same continuum fits as in Fig. 1.
between 6946 and 6949 Å is $-0.05 \pm 0.05$ for a $v^2$ extrapolation and $0.05 \pm 0.05$ for a $v^4$ extrapolation, where the errors are based only on the statistical noise in the region. In the subsequent discussion, we will adopt what we believe is a conservative limit of $\tau < 0.1$ at this redshift of 4.72.

For a uniformly distributed IGM and $q_0 = 0.5$,

$$\tau = 1400 h_5^3 \Omega_h^2 J_{-22}^{-1} T_4^{-0.75} \left( \frac{1 + z}{5.72} \right)^{1.5},$$

where $h_5$ is the Hubble constant in units of 50 km s$^{-1}$ Mpc$^{-1}$, $J_{-22}$ is the metagalactic flux at the Lyman edge [$J_{-22}(v/v_{H I})^{-1}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ with $\alpha = 0.7$], and $T_4$ is the temperature of the gas in units of 10$^4$ K (Giallongo et al. 1994). For $\tau < 0.1$ we obtain

$$\Omega_h h_5^2 < 8.4 \times 10^{-3} h_5^{0.5} J_{-22}^{-0.5} T_4^{-0.375}.$$

Using Haardt & Madau’s value of $J_{-22} = 0.4$ at $z = 4.72$ would give $\Omega_h h_5^2 < 0.005 h_5^{0.5} T_4^{-0.375}$.

If, however, the minimum opacity arises in cosmic voids, this number must be corrected upward to allow for the underdensity in these regions. Simulations with current cosmological parameters suggest that the profile of the density distribution at $z = 5$ will be centered on a mode of an underdensity of about 0.5 and will have very little volume indeed at underdensities of 0.2 or less (e.g., Zhang et al. 1998). The underdense regions are relatively cold, with temperatures of around 5000 K. If we conservatively assume that the minimum opacity portions of the current spectrum arise in regions which are underdense by a factor of 5 and set $T_4 = 0.5$, we would obtain $\Omega_h h_5^2$ of 0.019 for $J_{-22} = 0.4$. We can compare this estimate of the baryon density to that derived from measurements of primordial $D/H$. The lowest value of $\Omega_h h_5^2 (0.02)$ that might currently be possible would correspond to $D/H = 2 \times 10^{-4}$ (Songaila, Wampler, & Cowie 1997; Webb et al. 1997), whereas $D/H = 3.3 \times 10^{-4}$, or $\Omega_h h_5^2 = 0.077 \pm 0.006$, is obtained by Tytler’s group (Burles & Tytler 1998). Even with the minimum $\Omega_h h_5^2 = 0.02$, we require $J_{-22} > 0.4$ at $z = 4.72$, whereas the low $D/H$ value would require $J_{-22} > 7$, more than an order of magnitude higher than the Haardt-Madau estimate.

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