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A DIRECT MEASURE OF THE GUNN-PETERSON EFFECT AT $z = 3$: LIMITS ON THE BARYON DENSITY OF THE INTERGALACTIC MEDIUM AT HIGH REDSHIFTS[1]

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ABSTRACT

A measure of the average depression between Lyman absorption lines in the spectrum of the quasar Q2126−158 ($z_{\rm em} = 3.27$) is presented. Regions free of absorption lines, in the Lyα forest of the quasar, are selected on the basis of high-resolution data (FWHM $\gtrsim 0.2$ Å). We have extended the wavelength interval from 7000 to 8500 Å, by means of data taken at low resolution, to obtain a more reliable evaluation of the continuum shape redward of the Lyα emission, and we describe the procedure adopted to define the continuum level. We obtain a best estimate of $\tau = 0.013 \pm 0.026$ at $\langle z \rangle = 3$. Constraints on the baryon density of the intergalactic medium are discussed.

Subject headings: cosmology: observations — intergalactic medium — quasars: general

1. INTRODUCTION

An important source of information on the distribution and the physical state of the intergalactic medium (IGM) up to redshift $z \simeq 5$ is provided by the study of the absorption spectra of high-redshift quasars. The absence of the long-looked-for absorption trough shortward of the QSO Lyman-α emission, caused by Lyα absorption of *diffuse* intergalactic neutral hydrogen, with the average optical depth $\tau_{\rm GP} \lesssim 0.5$, implies that the IGM is highly ionized (GP test; see Gunn & Peterson 1965). Indeed, the estimate of the true continuum level shortward of the Lyα emission is made difficult by a crowd of narrow absorption lines interpreted as Lyα absorptions due to intervening clouds along the line of sight (Lynds 1971; Sargent et al. 1980).

Steidel & Sargent (1987, hereafter SS87) have shown that an upper limit to the diffuse absorption, relying on the knowledge of the average line absorption, can be obtained by subtracting the contribution of the Lyα lines to the total absorption observed between Lyα and Lyβ emissions in low-resolution QSO spectra. The GP test can then be used to constrain the physical state and evolution of the IGM (Steidel & Sargent 1987; Ikeuchi & Ostriker 1986; Barcons, Fabian, & Rees 1991).

On the other hand, direct measures of column densities and Doppler widths of the absorption lines provide typical values of $N_{\rm H\,I} = 10^{14}$ atoms cm^{-2} and $b = 20$–30 km s^{-1} corresponding to $T_c \sim 2$–5×10^4 K, assuming thermal broadening (see, however, Pettini et al. 1990).

The most recent and accurate estimate of the cloud sizes has been obtained by Smette et al. (1992) from the spectra of a gravitationally lensed high-redshift quasar, UM 673 ($z_{\rm em} = 2.7$). They derive lower and upper limits of 12 h_{50}^{-1} and 160 h_{50}^{-1} kpc, respectively, for the diameter of spherical clouds, or 24 and 320 kpc for oblate spheroids with an axis ratio less than 0.1.

Considering that the background ionizing UV flux produced by QSOs at $z = 2$–3, $J = 10^{-22} J_{-22}$ ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} (Madau 1992) keeps both the clouds and IGM ionized, the physical state and evolution of the IGM can be further constrained under the assumption that clouds are pressure confined (Sargent et al. 1980; Ostriker & Ikeuchi 1983; SS87). Taken together, the above conditions define a region in the density-temperature plane which provides an upper limit to the IGM baryon density $\Omega_{\rm IGM}$ which can give information about the efficiency of the galaxy formation processes.

Webb et al. (1992), from a high-resolution spectrum of the quasar Q0000−263 at $z \simeq 4$, estimate that $\tau_{\rm GP}$ could be about 0.04, if the column density distribution of the absorbing clouds can be extrapolated down to $N_{\rm H\,I} = 10^{13}$ cm^{-2} with the same power-law distribution of stronger lines.

In this *Letter* we present a high-resolution spectrum ($R = 22{,}000$) of Q2126−158 at $z = 3.27$, extending from 4500 to 7000 Å, and give a direct measure of the IGM hydrogen opacity.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. *Data Acquisition and Reduction*

The quasar Q2126−158 has been observed at ESO (La Silla) in 1991 August, with the NTT telescope and the EMMI instrument in the echelle mode (see D'Odorico 1990). Two exposures of 7200 s each were obtained on August 6, and one of 9130 s on August 7. The slit was 1″.5 wide, and the seeing was always less or equal to 1″. Particular attention was paid in order to minimize the effects of the atmospheric dispersion. The absolute flux calibration was carried out by observing the standard star EG 274 (Stone & Baldwin 1983). The data reduction has been carried out using the standard echelle package described in the 91NOV edition of the MIDAS soft-

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[1] Based on material collected at the ESO–La Silla telescopes.

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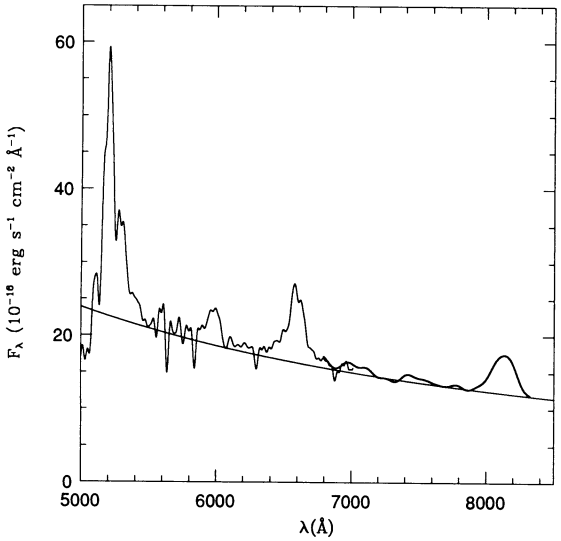

FIG. 1.—Spectra of Q2126−158 smoothed to FWHM > 10 Å. Darker curve derives from the low-resolution data. The fitted continuum is also shown.

ware (Banse et al. 1983). The weighted mean of the spectra has been obtained at the resolution $R = 22{,}000$ and is shown in Figure 1 smoothed to ~10 Å for illustrative purposes.

Q2126−158 had previously been observed by us at low resolution (~25 Å), using the Boller & Chivens spectrograph at the 2.2 m ESO/MPI telescope at La Silla on 1989 September 3. Two exposures of 30 m each were taken with a 5″ wide slit in the spectral range 3300–8650 Å. A standard reduction was carried out with the long-slit package of MIDAS. The absolute flux calibration was obtained observing the standard star LDS 749B (Oke 1974).

The two spectra have then been compared, finding that, apart from the difference of a factor 100 in resolution and a renormalization factor close to unity, there was a perfect correspondence within the noise. The red part ($\lambda > 7000$ Å) of the low-resolution spectrum has then been appended (after renormalization) to the echelle spectrum as shown in Figure 1.

2.2. *The Gunn-Peterson Test*

A direct estimate of the GP absorption requires two main steps in the analysis of the calibrated spectrum: (1) the definition of the continuum region longward of the Lyα emission; and (2) the selection of regions in the Lyα forest which are free of strong absorption lines, where the local continuum can be evaluated.

It is important to note that the continuum level longward of the Lyα emission, in QSOs with $z \gtrsim 3$, is better assessed in high-resolution spectra extended possibly up to 10,000 Å. In fact, the region between Lyα and C IV emissions is affected by the presence of weak emission lines whose broad wings tend to overlap ([O I] 1302, C II 1335, Si IV 1400). Thus, minima between weak emission features appear enhanced to higher intensities, when observed at low resolution. On the other hand, in the presence of noise, local minima represent underestimates of the true continuum level. We have applied a Fourier low-pass filter whose optimal cutoff frequency has been determined on the basis of the power spectrum of the data and on a signal-to-noise ratio $S/N \gtrsim 10$ obtained from the comparison of overlapping orders in the echelle spectrum. We have adopted as continuum estimates, in the selected regions defined below, the local minima which are not affected by absorption lines clearly recognized in the high-resolution spectrum.

From composite quasar spectra (Cristiani & Vio 1990; Francis et al. 1991) it is evident that there are few regions which can be considered representative of the true continuum level. A spectral range as wide as possible is then required to estimate the shape of the continuum.

We have chosen as indicative of the true continuum level the minimum in the region on the red part of the spectrum between the C IV and C III] emissions ($\lambda \simeq 7210$ Å) and the one in the region between Si IV and C IV emissions ($\lambda \simeq 6235$ Å). The region near 7200 Å is just longward of the weak emission lines He II 1640 and C III] 1663 but can be affected by the blue end of the blended Fe II 2000 complex. From a visual comparison of Figure 7 in Francis et al. (1991) with our $F_\lambda \lambda$ plot, we have established that Fe II emission is likely to be too small to affect appreciably our continuum estimate.

An upper limit to the true continuum level can also be obtained in the region between the Lyα and O I emissions. We have used the local minimum in the interval $\Delta\lambda = 5450$–5550 Å, which can still be affected by the wings of the Lyα + N V and O I emissions. Any overestimate of the true continuum level in this region would cause an overestimate of $\tau_{\rm GP}$, and therefore the computed value has to be considered an upper limit. We show in Figure 2 the two selected regions in the high-resolution part of the spectrum ($\lambda < 7000$ Å) and their local minima.

As a second step we have defined regions in the Lyα forest which are free of strong absorption lines. The choice is obvi-

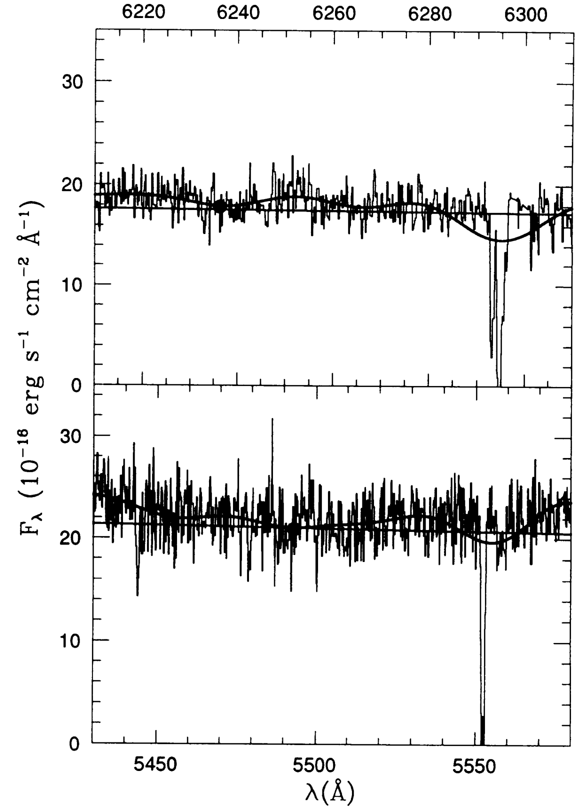

FIG. 2.—Selected regions in the high-resolution part of the spectrum. Darker curve represents the Fourier filtered spectrum; the local minima and the fitted continuum are also shown.

ously somewhat arbitrary. We have adopted a well-defined procedure based on the following criteria. First of all, we have excluded the region presumably subject to QSO ionization ($\lambda > 5000$ Å), that is, the region affected by the proximity effect, corresponding to $\sim 27\ h_{50}^{-1}$ Mpc from the QSO (see Bajtlik, Duncan, & Ostriker 1988). Then we have selected regions between strong absorption lines where the rms fluctuation σ about the mean $\langle F \rangle$ becomes consistent with noise statistics. Specifically we have assumed as a threshold the signal-to-noise ratio shortward of 5000 Å which was estimated to be about 8. Four regions have been selected in the interval $4700 < \lambda < 5000$ Å, and the average continuum levels are shown in Figure 3 for two of these.

At this point, a given spectral shape for the continuum has been fitted using the regions selected longward of the Lyα emission. The continuum I_c has been extrapolated in the Lyα forest, and the ratio I/I_c has been computed for every wavelength element of the selected regions shortward of the Lyα emission. The average GP absorption is then given simply by $\tau_{\rm GP} = -\ln \langle I/I_c \rangle$.

The quasar UV continuum is customarily fitted by a simple power law, although other spectral shapes are not excluded. First, we have tried to fit a straight line through the F_λ spectrum longward of the Lyα emission. We have obtained a good fit at 95% confidence level, but the continuum extrapolated in the Lyα region falls below the local average continuum with an average value of $I/I_c = 1.06 \pm 0.01$, showing that the straight line is not a good representation of the continuum in the observed spectral range. Then we have fitted a power-law continuum obtaining a good fit at 95% confidence level of the type $F_\lambda = b(\lambda/6165)^a$ with $b = (17.9 \pm 0.1) \times 10^{-16}$ ergs s^{-1} cm^{-2} Å^{-1} and $a = -1.38 \pm 0.06$ (corresponding to a spectral index $\alpha_\nu = -0.62$). The extrapolated continuum gives in this case $\tau_{\rm GP} = 0.013 \pm 0.015$ at the average absorption redshift $\langle z_{\rm abs} \rangle = 3$. One should note that uncertainties in the power-law fit give a further 0.021 uncertainty on the average $\tau_{\rm GP}$, which should be added in quadrature to the above value to give $\tau_{\rm GP} = 0.013 \pm 0.026$ consistent with zero at 0.5 σ.

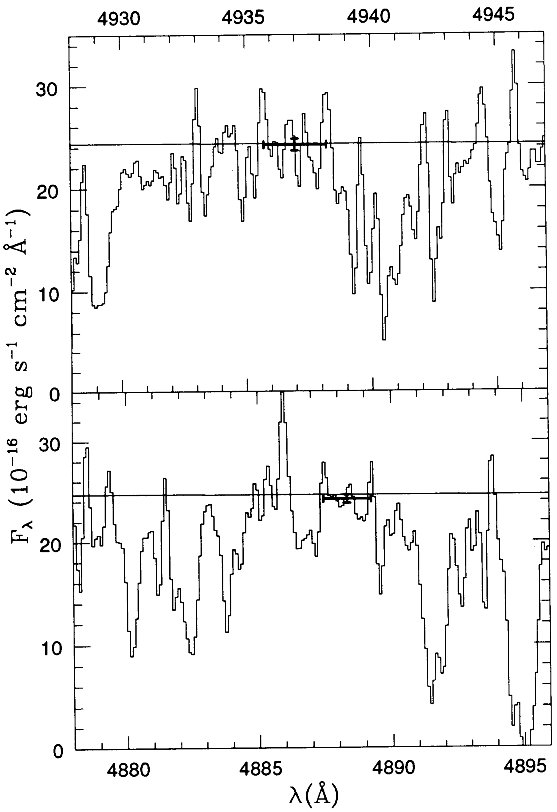

FIG. 3.—Selected regions in the Lyα forest. The average flux levels with their uncertainties are shown together with the fitted continuum.

3. DISCUSSION

The value of $\tau_{\rm GP}$ obtained from our spectrum at $z = 3$ can be compared with the ones estimated from the average absorptions measured at the lower $z = 2.6$. SS87 find a best estimate of $\tau_{\rm GP} = 0.02 \pm 0.03$, while Jenkins & Ostriker (1991), on the basis of a reanalysis of the same SS87 data, put a limit of $\tau_{\rm GP} = 0.06 \pm 0.06$. The Jenkins & Ostriker analysis has recently been questioned by Zuo (1992). In any case, variations in the average absorptions between different authors are larger than internal dispersions (cf. Giallongo & Cristiani 1990), and the larger sample collected by Schneider, Schmidt, & Gunn (1991) gives an average fractional absorption $D_A = 0.29$ in the same redshift interval, to be compared with the value of $D_A = 0.24$ of SS87 data. Accordingly, the GP opacity should raise from 0.02 to 0.07 if the line contribution $D_A = 0.22$, estimated by SS87, is assumed.

Our different method, giving a direct measure of the average opacity through high-resolution spectroscopy, is particularly suitable to resolve the controversy, especially when more quasars will be measured. On the basis of the intrinsic quasar spectrum, it is possible to reduce statistical uncertainties in the measure of the GP absorption, using high-resolution spectra and a well-defined procedure to estimate the continuum shape.

For comparison with previous work, we can use the new value of $\tau_{\rm GP}$ to constrain the density and temperatures of the IGM supposed to be ionized by the UV flux of quasars at $z = 3$. Madau (1992) estimates the quasar contribution to the UV background (*UVB*) at $z = 3$ to be $J_{-22} \simeq 1$. Assuming ionization equilibrium, the best estimate $\tau_{\rm GP} \simeq 0.01$ results in a limit on the baryon density of the IGM for each assumed temperature. This is shown in Figure 4 (where $\Omega = 1$ and

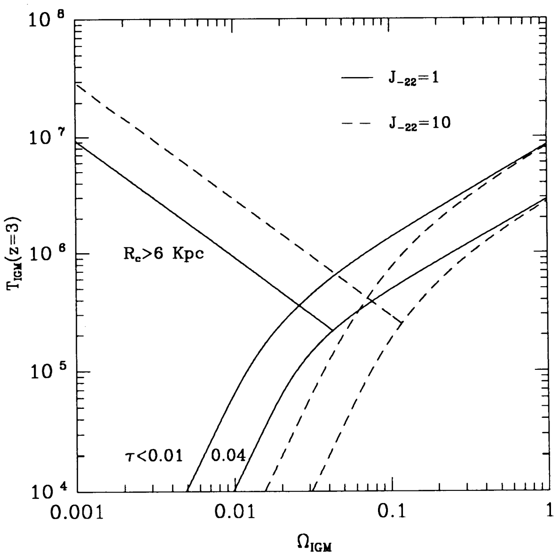

FIG. 4.—Constraints on the temperature and density parameter for the IGM at $z = 3$. Limits provided by the GP test and the cloud sizes are shown for different values of the ionizing *UVB*.

$H_0 = 50\ h_{50}$ km s^{-1} Mpc^{-1} have been assumed) together with the 1 σ upper limit $\tau \simeq 0.04$.

The value of the *UVB* adopted is one order of magnitude lower than the one derived from the statistical analysis of the proximity effect (Bajtlik et al. 1988). However, estimates of the proximity effects in quasar spectra are based on high-ionization-line redshifts (e.g., C IV). Low-ionization-line redshifts (Hα, etc.), which are higher, seem to provide a more reliable estimate for the systemic redshift of the quasars (Carswell et al. 1991; Tytler & Fan 1992). Higher redshifts imply that the distances from the quasars, where the UV flux of the quasars equals the *UVB*, are larger. This would lower the estimate of the *UVB* derived from the analysis of the proximity effect and would reduce the discrepancy with the total UV flux produced by the quasar population. In turn, a lower *UVB* results in a lower value of the IGM baryon density for each temperature. We show in Figure 4, for comparison, the density limit obtained assuming the value $J_{-22} = 10$ derived by Bajtlik et al. (1988).

Different limits to the baryon density of the IGM can be obtained depending on the thermal history of the IGM. Heating by photoionization provides a mean temperature $T_{\rm IGM} \lesssim 2 \times 10^4$ K at $z = 3$, while shock heating models can rise the mean temperature to $T_{\rm IGM} \sim 10^{5-6}$ K allowing the IGM to pressure-confine the cooler ($T_c = 2 \times 10^4$ K) and denser Lyα clouds (Ikeuchi & Ostriker 1986). In the former case we find $\Omega_{\rm IGM} = 0.006$–0.013 for our best-fit and 1 σ GP estimate, respectively.

In the latter case, the lower limit on the clouds dimensions by Smette et al. (1992) ($R_c \sim 6$ Kpc) provides a constraint on the pressure of the IGM that, taken together with our GP estimate, implies an upper limit on the density $\Omega_{\rm IGM} = 0.026$–0.043, respectively. Nucleosynthesis constrains the cosmological baryon density to be $\Omega_b h_{50}^2 \geq 0.04$ (Walker et al. 1991) and would be consistent with the above limits, in the case of pure photoionization heating, only if less than ~15%–33% of baryons, respectively, were in a uniformly distributed medium, the rest having collapsed into bound systems. We finally note that for $h_{50} = 2$, the limits on the IGM baryon density were a factor 0.35 lower.

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