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THE GUNN-PETERSON EFFECT IN THE SPECTRUM OF THE $z = 4.7$ QSO 1202−0725: THE INTERGALACTIC MEDIUM AT VERY HIGH REDSHIFTS[1]

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ABSTRACT

A measure of the average depression between Lyman absorption lines in the spectrum of the faint quasar BR 1202−0725 ($z_{\rm em} = 4.695$) is presented. The relatively high resolution of the spectrum ($\sim$40 km s^{-1}) allows the selection of regions free of strong absorption lines in the Lyα forest. A reliable evaluation of the continuum shape is based on the careful flux calibration and on the large wavelength interval covered (5000–9300 Å). A best estimate of $\tau_{\rm GP} \leq 0.02 \pm 0.03$ has been found for the Gunn-Peterson optical depth at the highest absorption redshift observed at this resolution, $z \simeq 4.3$. The derived baryon density of the intergalactic medium is $\Omega_{\rm IGM} \lesssim 0.01$ if the observed quasars are the major contributor to the ionizing UV background flux. This limit, when compared with the total baryon density deduced from the nucleosynthesis, could imply that most of the baryons are already in bound systems at $z \sim 5$.

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

1. INTRODUCTION

The absence of the H Lyα absorption trough in the observed spectra of high-redshift quasars (Gunn-Peterson effect) implies that any smoothly distributed intergalactic medium (IGM) present along the line of sight to the quasars must be highly ionized at early epoch (Gunn & Peterson 1965).

In fact, any estimate of the average depression of the quasar continuum level shortward of the Lyα emission is made difficult by a crowd of strong, narrow absorption lines interpreted as Lyα absorptions due to intervening clouds along the line of sight (Lynds 1971; Sargent et al. 1980).

Previous estimates of the Gunn-Peterson effect were obtained by subtracting the line contribution to the measured average depression, D_A, present in low-resolution spectra just shortward of the Lyα emission line (Steidel & Sargent 1987; Schneider, Schmidt, & Gunn 1989, 1991; Giallongo & Cristiani 1990; Jenkins & Ostriker 1991). However, different kinds of biases can affect such indirect estimates, as pointed out by Giallongo & Cristiani (1990). The measured average depression depends on the resolution and spectral range used to estimate the slope and the level of the continuum longward of the Lyα emission. The estimate of the line contribution to the absorption suffers from the poor knowledge of the line statistics, especially at high redshift.

Recently, it has become feasible to obtain at 4 m class telescopes high-resolution ($R > 20{,}000$) data of relatively faint quasars which are well calibrated in flux and extended over a wide wavelength interval. This leads to relatively accurate estimates for the continuum and for the contribution of discrete absorption clouds. Moreover, the strength of the Gunn-Peterson effect increases rapidly with redshift even assuming a constant ionizing background flux (Miralda-Escudé & Ostriker 1990). Thus, tighter upper limits on the optical depth of the neutral IGM or on the number of ionizing sources can be placed by observations of faint QSOs at the highest redshifts.

Webb et al. (1992) give an estimate of $\tau \simeq 0.04$ at an average absorption redshift $z \simeq 3.8$ depending on the assumptions about the shape and the low cutoff of the line column density distribution. A more stringent and direct upper limit to the Gunn-Peterson (GP) effect has been given by Giallongo, Cristiani, & Trevese (1992), who found $\tau \simeq 0.01$ at $\langle z \rangle = 3$ just measuring in the Lyα forest of PKS 2126−158 the average depression of the quasar continuum level in regions free of strong absorption lines.

We present here a direct measure of the GP effect from observations of a high-redshift ($z = 4.7$) quasar and discuss the relevant consequences for the physical state of the IGM at this high redshift.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. *Data Acquisition and Reduction*

The quasar BR 1202−0725 ($z_{\rm em} = 4.695$) was discovered by Hazard, Irwin, and McMahon in the framework of the APM wide-field multicolor (*BRI*) photographic survey for bright high-redshift ($z > 4$) quasars (see, e.g., McMahon, Irwin, & Hazard 1993). The coordinates of this QSO are given in McMahon et al. (1994).

This quasar has been observed at ESO (La Silla) in 1993 March, with the NTT telescope and the EMMI instrument in the echelle mode (see D'Odorico 1990), in the framework of an ESO key program devoted to the study of the absorption spectra of high-z quasars (D'Odorico et al. 1993). The detector used was a LORAL CCD (2048 × 2048 pixels^2).

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Two spectra of 8000 and 6850 s exposures were obtained on March 13 and 14, respectively, covering the wavelength range 4700–8400 Å. Two other spectra, of 7200 and 8000 s, were obtained on March 15, covering the wavelength range 6000–9500 Å.

The slit was 1.″2 wide and 15″ long. The seeing was in the range 0.″8–1.″2. All spectra were taken at air masses lower than 1.2 and with the slit oriented along the average direction of the atmospheric dispersion to minimize the wavelength dependence of any slit losses. The absolute flux calibration was carried out by observing two standard stars, HR 5501 and CD 32EG (Hamuy et al. 1993). Two exposures with slits of 1.″2 and 5″ were obtained for each star in the two wavelength intervals in order to check the flux calibration procedure.

The data reduction has been carried out using the standard echelle package described in the 1992 November edition of the MIDAS software (Banse et al. 1988). Sky subtraction was carried out by sampling the sky above and below the QSO spectrum. The fluxes have been dereddened for Galactic extinction according to the Savage & Mathis (1979) curves and adopting a value $E_{B-V} = 0.025$ on the basis of the Burstein & Heiles (1982) maps. The weighted mean of the spectra has been obtained at the resolution $R = 7500$ after rebinning at uniform $\Delta\lambda$ bins close to the original sampling. On average the resolution element was 3 pixels wide. The signal-to-noise ratio ranges from 6 to 12 per pixel in the interval 6000–9300 Å.

We have checked the accuracy of the flux calibration, comparing individual calibrated spectra taken on different nights using the two different stars. We found differences up to 5% in the average flux levels among the different spectra, but any λ-dependent trend in the flux difference was confined to within 1% of the average flux.

Using the magnitude at $\lambda = 1450$ Å rest frame, defined by $m_\nu(1450) = -2.5 \log f_\nu - 48.60$, with $f_\nu = f_\nu[1450(1 + z)]$ (Oke & Gunn 1983), and applying a correction for the slit loss of 20% as estimated from the observations of the standard stars through narrow and wide slits, we obtain $m_\nu(1450) = 17.9$.

2.2. *The Gunn-Peterson Test*

We adopted the following general procedure: first of all, regions longward of the quasar Lyα emission were selected for the definition of the continuum level. A power-law continuum was fitted within these regions and extrapolated in the Lyα forest. Then regions in the Lyα forest which are free of strong absorption lines were selected for the estimate of the local continuum level. The average Gunn-Peterson optical depth was simply derived from the ratio of the local continuum level to the extrapolated one.

Since there are few regions which can be used to estimate the continuum level, it is important to get a spectral range as wide as possible to constrain the continuum shape. In particular, the spectrum should extend beyond the C IV emission, since the local minima selected in the region between Lyα and C IV emissions can be spuriously enhanced by the overlapping wings of the other strong emissions, such as O I λ1302, C II λ1335, and Si IV λ1400. In our case a good flux calibration was obtained from $\lambda \sim 5200$ up to $\lambda \sim 9300$ Å (Fig. 1).

We chose a region longward of the C IV emission line in the interval $\Delta\lambda = 9150$–9250 Å, i.e., at the minimum between C IV and the weak He II λ1640 emissions. A second interval to estimate the continuum level was taken at the minimum between the Lyα and the O I emissions ($\Delta\lambda = 7226$–7261 Å) which could be still contaminated by an extended wing of the Lyα + N V line. In this case the overestimate of the continuum level results in an overestimate of the Gunn-Peterson optical depth.

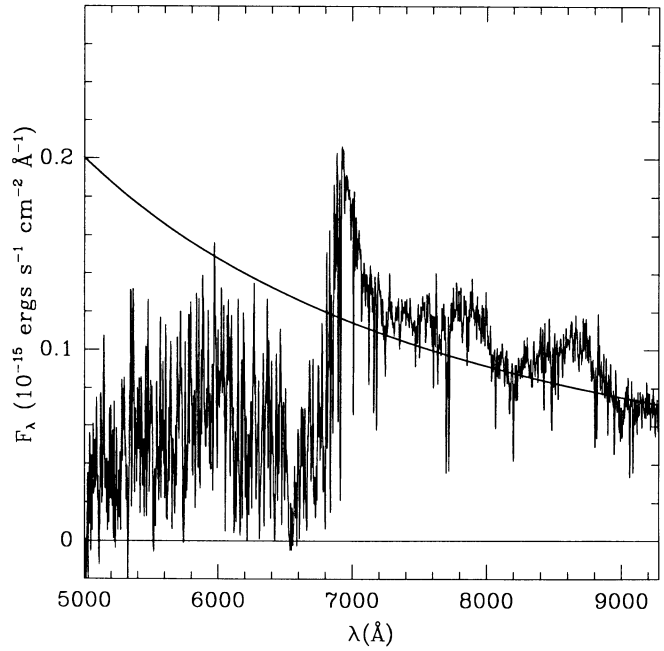

FIG. 1.—Absolute flux distribution of BR 1202−0725 smoothed to FWHM ~6 Å. The data have not been corrected for slit losses. They are estimated at 20% from the observations of the standard stars. The fitted power-law continuum is also shown. The region between 7600 and 7680 Å has been corrected for atmospheric absorption.

The UV continuum of the quasar was then fitted by a simple power law of the type $F_\lambda = b(\lambda/7244)^a$ with $b = (0.108 \pm 0.003) \times 10^{-15}$ ergs s^{-1} cm^{-2} Å^{-1} and $a = -1.67 \pm 0.08$ (i.e., $\alpha_\nu = -0.33$). The two intervals used for the fitting procedure and the power-law fit are shown in Figure 2.

Finally, four regions free of strong absorption lines in the Lyα forest were selected in the interval $\Delta\lambda \sim 6100$–6400 Å (Fig. 3). This way any contamination by the strong Lyα emission and the highest $z \simeq 4.4$ damped system present longward of $\lambda \sim 6400$ Å was avoided. Similarly, any contamination by the Lyβ + O VI emission blend present shortward of $\lambda \sim 6100$ Å was also excluded.

The ratio I/I_c between the observed continuum level in the selected regions and the extrapolated one in the Lyα forest was computed, giving an average optical depth $\tau_{\rm GP} = 0.02 \pm 0.03$, where the error is due to the noise in the spectrum and to the slope uncertainty in the extrapolated continuum. We note, however, that the quoted uncertainty can be an underestimate if systematic errors are present. These could be due to unidentified emission-line profiles in the regions selected for the estimates of the continuum level and/or to the non–power-law shape of the continuum.

3. DISCUSSION AND CONCLUSIONS

The value of $\tau_{\rm GP} \simeq 0.02 \pm 0.03$ obtained from our spectrum in the interval $\Delta z = 4.1$–4.3 can be compared with the one obtained by Giallongo et al. (1992) from the spectrum of PKS 2126−158 observed at a resolution of ≃23,000. Using the same procedure, they derived an upper limit $\tau_{\rm GP} \simeq 0.01 \pm 0.03$ at an average redshift $z = 3$.

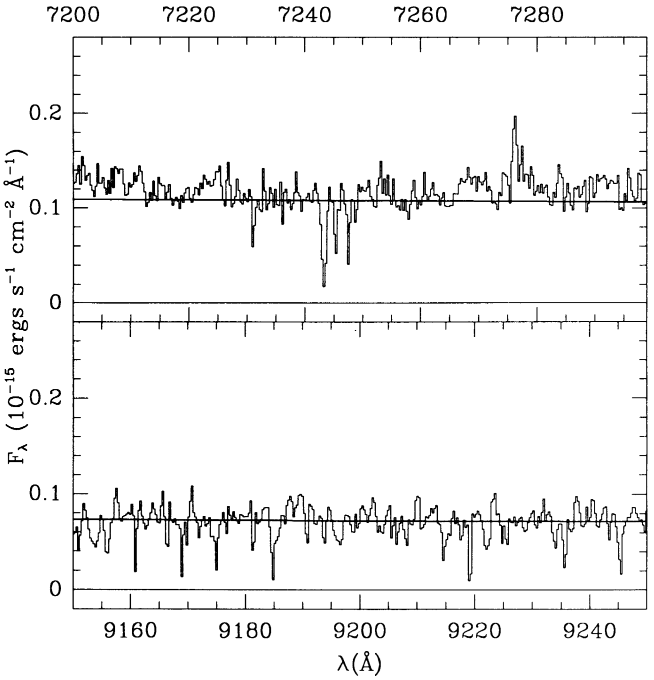

FIG. 2.—Selected regions of the spectrum longward of the Lyα emission used for the continuum fitting. The fitted continuum is also shown.

These two upper limits, covering the redshift interval $z = 3$–4.3, can be used to constrain the density of the IGM within a consistent scenario for the thermal history of the IGM and for the cosmological evolution of the ionizing UV background (UVB) flux.

For a highly ionized IGM, the Gunn-Peterson optical depth can be expressed as a function of the IGM density, assuming ionization equilibrium, where the heating is dominated by photoionization of the UVB; this yields

$$\tau_{\rm GP}(z) = 150T^{-0.75}(z)h_{50}^3\,\Omega_{\rm IGM}^2(3+\alpha)(1+z)^{4.5}J_{-22}^{-1}(z)\,, \quad (1)$$

where $H_0 = 50\ h_{50}$ km s^{-1} Mpc^{-1} is the local Hubble constant, $J = J_{-22} \times 10^{-22}$ ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} is the ionizing UVB flux [$J \propto (\nu/\nu_{912})^{-\alpha}$] and T and $\Omega_{\rm IGM}$ are respectively the temperature and the baryon density of the IGM in units of the cosmological critical density. A value of $\Omega = 1$ has been assumed for the cosmological parameter throughout the paper.

The thermal history of a photoionized IGM at high z depends on the number and distribution of ionizing sources and on the effects of the helium reionization (Miralda-Escudé & Rees 1994; Sciama 1994). In particular, Miralda-Escudé & Rees (1994) have shown that the temperature at a given z depends on the temperature and redshift immediately after the IGM is wholly ionized, since its successive thermal evolution is mainly due to adiabatic cooling. They showed that the temperature at the end of the reionization process can assume values in the interval 20,000–50,000 K.

If the ionization redshift is as high as $z = 9$, the final temperature at $z \sim 4.5$ is almost independent of its initial value, being $T \sim 10^4$ K. If the ionization of the IGM is just completed at $z = 5$, then its density depends on the initial values assumed for the temperature. Miralda-Escudé & Rees (1994) compute two thermal evolutions for the ionized IGM, starting at $z = 5.7$ with $T = 16{,}000$ and 48,000 K. We have used both curves in equation (1) to estimate the baryon density of the IGM.

The evolution of the ionizing UV flux is the other function appearing in equation (1) and depends on the kind of sources and on their space density. The observations suggest that quasars could be the main contributors to the UVB. However, the UVB flux level at $z > 4$ depends on poorly known details

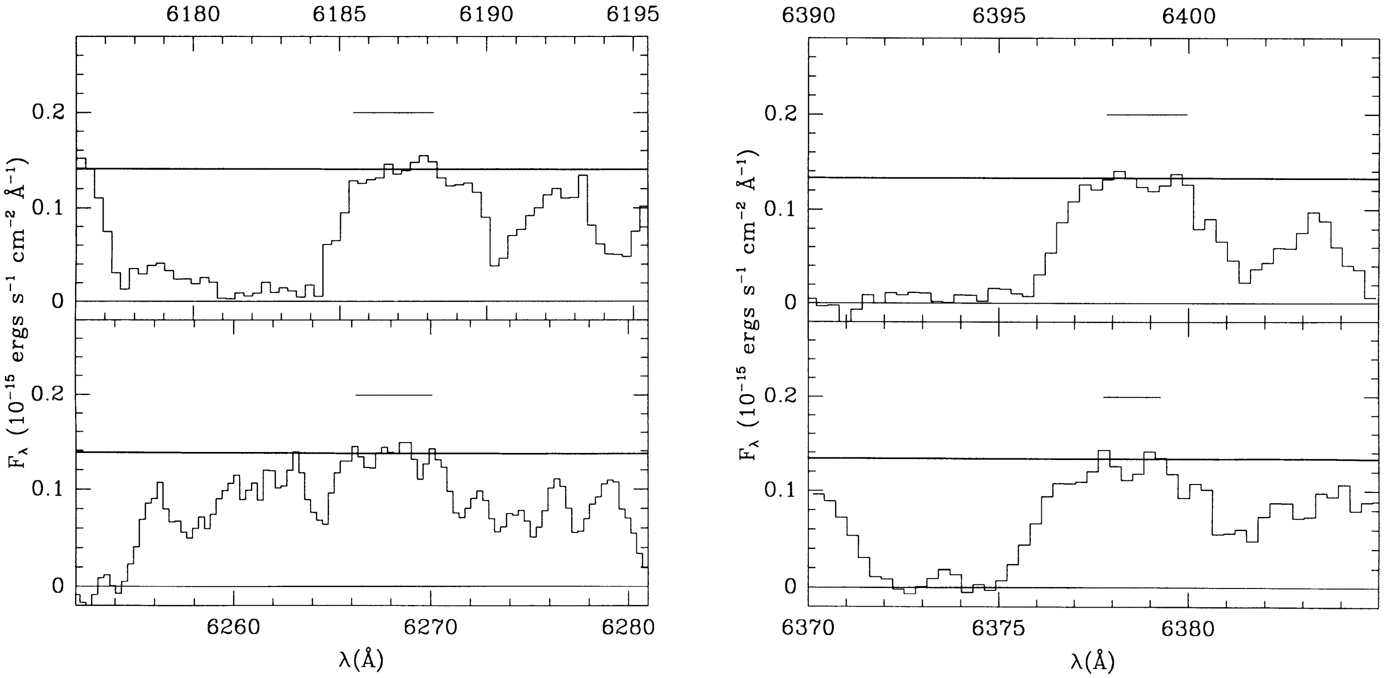

FIG. 3.—Four regions in the Lyα forest where the Gunn-Peterson optical depth has been measured by comparing the local continuum level with the extrapolated one (*continuous line*). The horizontal bars mark the intervals over which the ratio has been measured.

about the shape and evolution of the quasar luminosity function (Warren, Hewett, & Osmer 1994). Madau (1992) and Meiksin & Madau (1993) have computed different evolutionary paths for the UVB flux assuming various cosmological evolutions of the number of quasars and different amounts of UV absorption due to intervening systems such as strong Lyα lines and Lyman limit and damped systems.

Given our low value for the Gunn-Peterson optical depth, we choose to maximize the ionizing flux provided by known quasar statistics in order to obtain the maximum value of the density of diffuse hydrogen compatible with the observation (see eq. [1]).

Thus we adopt the model where the comoving space density of quasars remains constant for $z > 3$ together with the low continuum opacity model for the UVB absorption by intervening Lyman absorption systems. This last model is supported by recent high-resolution Lyα samples where a cutoff or a strong steepening of the column density distribution of the Lyα lines at $N_{\rm H\,I} \sim 10^{14.5}$ cm^{-2} has been suggested (Giallongo et al. 1993). The ionizing UV flux is assumed constant for $z > 3$, taking the value $J_{-22} \sim 3$ with $\alpha = 0.7$.

From equation (1) the IGM baryon density is $\Omega_{\rm IGM} \lesssim 0.008$, 0.011 for the 16,000 and 48,000 K thermal evolution scenarios, respectively. Thus, the best estimates on the optical depth derived from the data constrain the IGM baryon density to be $\Omega_{\rm IGM} \lesssim 0.01$, almost independently of the initial condition for the temperature.

Fall & Pei (1993) have estimated that the contribution of quasars to the UVB at $z \sim 3$ can raise up to $J_{-22} \simeq 7$ if dust obscuration affects the quasar statistics. This value has been found by Giallongo et al. (1993) at about the same redshift from the analysis of the proximity effect in a high-resolution Lyα sample. However, it is not clear whether this value can be extrapolated to $z > 4$. If this is the case, the baryon density can rise to $\Omega_{\rm IGM} \lesssim 0.012, 0.017$.

If the UV background is not far from the value predicted on the basis of the observed quasar counts, then much of the baryon density $\Omega_b = 0.05\, h_{50}^{-2}$ derived from the nucleosynthesis (Walker et al. 1991) remains to be explained. Indeed, optically thick absorbers observed along the line of sight to quasars as Lyman limit systems and damped systems, which are thought to be connected with protogalaxy halos and disks, can contribute to the baryon density a total amount $\Omega_{\rm LL+D} = 0.011$ (Steidel 1990; Lanzetta et al. 1991). Since the contribution of luminous matter is of the order of $\Omega_{Lb} \sim 0.003$ (Persic & Salucci 1992), then, even assuming the highest estimate for the density of the IGM, we obtain a total baryon density $\Omega_b = \Omega_{\rm IGM} + \Omega_{\rm LL} + \Omega_{\rm D} + \Omega_{Lb} = 0.028$, i.e., about half of the nucleosynthesis value. It is to be noted that compensating this deficit by increasing $\Omega_{\rm IGM}$ to 0.036 requires a value for the ionizing UVB as high as $J_{-22} \gtrsim 30$.

This conclusion leaves room for a scenario where most of the mass in the high-redshift universe can be in the Lyα clouds. In fact, the total mass of these clouds depends on the ionization ratio and on their sizes. An appreciable contribution of the order of 0.01 can be obtained assuming ionization equilibrium with the quasar UVB and spherical diameters as large as 200 kpc for clouds with column density $N_{\rm H\,I} \sim 10^{15}$ cm^{-2}.

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