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IUE OBSERVATIONS OF PG 1115+080: THE He I GUNN-PETERSON TEST AND A SEARCH FOR THE LENSING GALAXY

TODD M. TRIPP
Lunar and Planetary Laboratory, University of Arizona

RICHARD F. GREEN[1]
Kitt Peak National Observatory, National Optical Astronomy Observatories[2]

AND

JILL BECHTOLD[1]
Steward Observatory, University of Arizona

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ABSTRACT

We have obtained new *IUE* observations of PG 1115+080 ($z_{\rm em} = 1.722$), the "triple quasar," in order to carry out the He I Gunn-Peterson test with greater sensitivity and to search for a Lyman-limit discontinuity which could reveal the redshift of the gravitational lens. We find that $n_{\rm He\,I}(z = 1.722) \leq 7 \times 10^{-11} h_{100}$ cm^{-3} at the 3 σ level. We have used this density to set a curve of constraint in the log $T_{\rm IGM}$–log $n_{\rm He}$ plane according to the shock-heated and photoionized IGM models. The predominantly shock-heated IGM model requires that $T_{\rm IGM} \geq 10^{5.3}$ K. If the IGM is both photoionized by the standard QSO diffuse radiation field and shock-heated, then the limits on hydrogen Lyman-alpha provide more stringent limits on the density and temperature of the IGM. We have found no evidence of the gravitational lens, placing an upper limit on $N_{\rm H}$ of 3×10^{16} cm^{-2} for $z_{\rm lens} \gtrsim 0.39$.

Subject headings: galaxies: intergalactic medium — gravitational lenses — quasars — ultraviolet: spectra

I. INTRODUCTION

PG 1115+080 ($z_{\rm em} = 1.722$), the "triple quasar," is one of two QSOs observed to date with the *International Ultraviolet Explorer Satellite* (*IUE*) to have an EUV continuum that is not severely depressed by intervening absorbers at the short-wavelength end (Green *et al.* 1980; Reimers *et al.* 1989). Its continuum emission can be detected at the 4 σ level by the *IUE* satellite down to <480 Å in the rest frame; consequently, it provides a unique opportunity to place a tighter upper limit on the density of intergalactic neutral helium via the Gunn-Peterson test. This density limit, in turn, sets a model-dependent (e.g., shock-heated or photoionized) lower limit on the temperature of the diffuse intergalactic medium (IGM).

While it is widely believed that the multiple images of PG 1115+080 are produced by the gravitational lens effect, the redshift of the lens has not been conclusively determined despite extensive studies (cf. Turner 1989; Christian, Crabtree, and Waddell 1987). Christian, Crabtree, and Waddell (1987) have suggested, based upon their analysis of high-quality *B*, *V*, and *R* images of the quasar, that the lens may be a spiral galaxy with $0.3 < z < 0.45$. If such a galaxy has a sufficient neutral hydrogen column density, intercepts the line of sight, and has the rest frame Lyman edge redshifted above geocoronal Lyman-α emission ($z_{\rm lens} \gtrsim 0.39$), then it should produce a detectable Lyman-limit discontinuity in low-resolution *IUE* spectra (cf. Bechtold *et al.* 1984; Weymann, Carswell, and Smith 1981).

We have combined five observations of PG 1115+080 taken with the *IUE* SWP camera in order to carry out the He I Gunn-Peterson test and to search for a Lyman limit which could pin down the redshift of the lens candidate reported by Christian, Crabtree, and Waddell (1987). In this *Letter* we present our findings.

II. OBSERVATIONS AND DATA REDUCTION

A log of the *IUE* observations is given in Table 1. The new SWP spectra were obtained by blind offset into the large aperture; exposures were terminated when Earth occultation was imminent. The spectra reported by Green *et al.* (1980) were reduced with the new data for uniformity. In order to improve the signal-to-noise ratio, the data were extracted with the Gaussian Extraction (GEX) technique (Urry and Reichert 1988). Hackney, Hackney, and Kondo (1984) have warned that SWP observations of faint sources suffer an exposure-dependent continuum distortion that produces a 10%–50% flux deficit centered at $\sim$1650 Å, and Finley, Basri, and Bowyer (1990) have used observations of hot DA white dwarfs to obtain a flux calibration correction for this problem. This correction was applied to the observations in Table 1, and the spectra were combined, weighted by the exposure time, using the IRAF "avsigclip" algorithm after a few cosmic-ray hits were cleaned out. The resultant spectrum is shown in Figure 1. It confirms the result of Green *et al.* (1980) that continuum flux is detected to the short-wavelength limit of the SWP camera and shows an observed spectral energy distribution similar to that of the higher redshift object HS 1700+6416 (Reimers *et al.* 1989), in this case with a relatively flat energy distribution shortward of the rest frame Lyman limit.

III. THE He I GUNN-PETERSON TEST

Following the method outlined by Gunn and Peterson (1965), one can show that the total optical depth (at a given

[1] Guest Observers with the *International Ultraviolet Explorer Satellite*.

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TABLE 1

IUE OBSERVATIONS OF PG 1115+080

IUE Image Number	Date (UT start)	Duration (s)
SWP 3579	346.1978 18:58	24,300
SWP 33231	099.1988 09:44	16,200
SWP 33242	101.1988 09:51	15,300
SWP 33254	102.1988 10:04	14,700
SWP 33263	103.1988 10:13	13,800
LWR 3142	344.1978 20:24	29,280

redshift) in He I λ584 is given by

$$\tau_{\rm HeI}(z) = \frac{n_{\rm HeI}(z)}{H_0(1+z)(1+2q_0 z)^{1/2}}\left(\frac{\pi e^2 f_{\lambda 584}}{m\nu_{\lambda 584}}\right) = \frac{1.32 \times 10^{10} n_{\rm HeI}(z)}{h_{100}(1+z)(1+2q_0 z)^{1/2}}, \quad (1)$$

where $f_{\lambda 584}$ is the oscillator strength and $\nu_{\lambda 584}$ is the frequency of the He I resonance line. The other symbols have their usual meanings. Thus, if the continuum shortward of $\lambda 584(1+z)$ is depressed by $e^{-\tau_{\rm HeI}}$, then the neutral helium number density at a given redshift can be obtained from equation (1).

As shown in Figure 1, no Gunn-Peterson trough is readily apparent in the *IUE* data, and we can only set an upper limit on $\tau_{\rm He\,I}$. Since the correction for calibration artifacts at very low net signal may not have been adequate, a normalized continuum was produced by division by the best-fit four-piece cubic spline (see Fig. 2). Division by a smooth spline should not remove the discontinuity at the edge of a Gunn-Peterson trough or a Lyman limit, although it may slightly affect a limit on the optical depth of the He I trough. By comparing the rms levels of the continuum longward and shortward of $\lambda 584(1+z)$ and by combining the uncertainties in the flux measurements on each side via quadrature, we estimate that $\tau_{\rm He\,I} < 0.21$ at the 3 σ level. This limit requires that at $z = 1.722$,

$$n_{\rm He\,I} \leq 7.1 \times 10^{-11} h_{100}({\rm cm}^{-3}) \quad (q_0 = \tfrac{1}{2})$$
$$\leq 4.3 \times 10^{-11} h_{100}({\rm cm}^{-3}) \quad (q_0 = 0)\,, \quad (2)$$

where h_{100} = the Hubble constant in units of 100 km s^{-1} Mpc^{-1}.

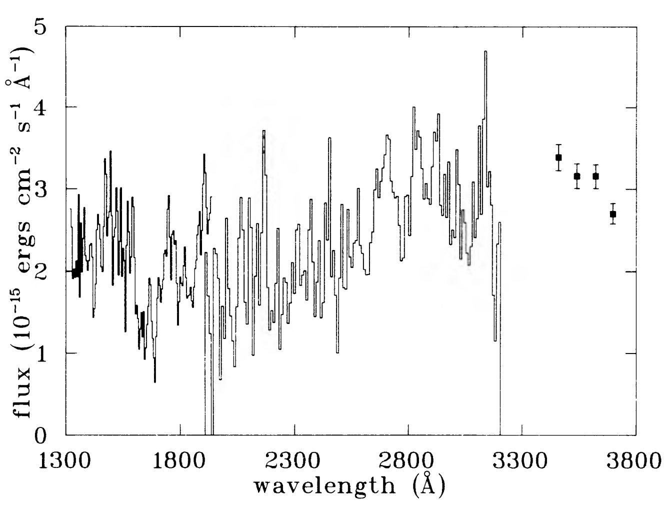

FIG. 1.—*IUE* spectra of PG 1115+080. The SWP images have been combined as described in the text, and the squares are flux measurements obtained by Neugebauer *et al.* (1987).

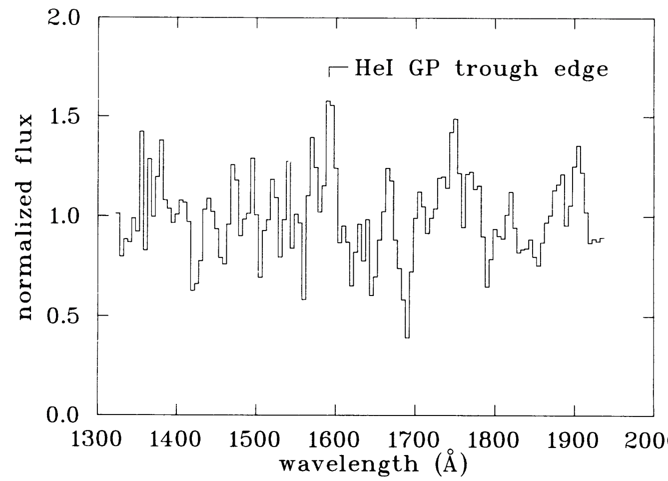

FIG. 2.—The short-wavelength *IUE* spectrum of PG 1115+080 divided by a four-piece cubic spline in order to remove calibration artifacts. The expected position of the He I Gunn-Peterson trough is indicated.

That no Gunn-Peterson trough is observed is not surprising. The H I Gunn-Peterson trough has been searched for since Schmidt (1965) first observed a quasar, 3C 9, on which the test could be carried out, and to date no trough has been detected. The tightest limit on the neutral hydrogen component has been set by Steidel and Sargent (1987) who find that at the 3 σ level $n_{\rm H\,I} < 9.7 \times 10^{-12} h_{100}({\rm cm}^{-3})$ at $z = 2.64$ with $q_0 = 0$. Indeed, most IGM models ignore the He I Gunn-Peterson test in favor of the He II Gunn-Peterson test because they predict that photoionization by the QSO UV background will make helium too highly ionized to allow useful information to be obtained from a limit on $n_{\rm He\,I}$ (Miralda-Escudé and Ostriker 1990; Shapiro 1989; Shapiro, Giroux, and Kang 1987; Ikeuchi and Ostriker 1986; Ostriker and Ikeuchi 1983; Sargent *et al.* 1980). Nevertheless, the ionization potential of He I is 1.8 times that of H I; consequently, in the collisionally ionized model $n_{\rm He\,I}$ can be used to place a tighter limit on the temperature of the IGM.

We have obtained limits on the IGM temperature using (1) a predominantly shock-heated IGM model, and (2) a photoionized and shock-heated model. In order to place limits on the temperature of the IGM in the predominantly shock-heated case, we have used our neutral helium density limit and the steady-state relative ionization abundances calculated by Shapiro and Moore (1976) for an initially shock-heated cosmic gas. These limits are the solid lines shown in Figure 3. Using the ionization rates given by Black (1981), we find that collisional ionization begins to dominate over photoionization when $n_e \simeq 10^{-4.2}$ cm^{-3} and $T_{\rm IGM} \simeq 10^{5.4}$ K, so we have chosen this point for the lower boundary of our calculation. For purposes of comparison, we have also used the same procedure to obtain the temperatures required to satisfy the limit on $n_{\rm H\,I}$ given by Steidel and Sargent (1987), and the resultant curve of constraint is the dashed line in Figure 3.

There are a couple of potential problems with these temperature limits:

1. We had to extrapolate Figure 1 from Shapiro and Moore (1976) in order to determine the temperatures at which the $n_{\rm He\,I}/n_{\rm He}$ ratios in the IGM occur. When $n_{\rm He\,I} \ll n_{\rm He}$, this extrapolation may not be completely correct and the temperature may be *higher* than that shown in Figure 2.

2. In the calculation of Shapiro and Moore (1976), the ionization-balance equations are coupled to an energy conser-

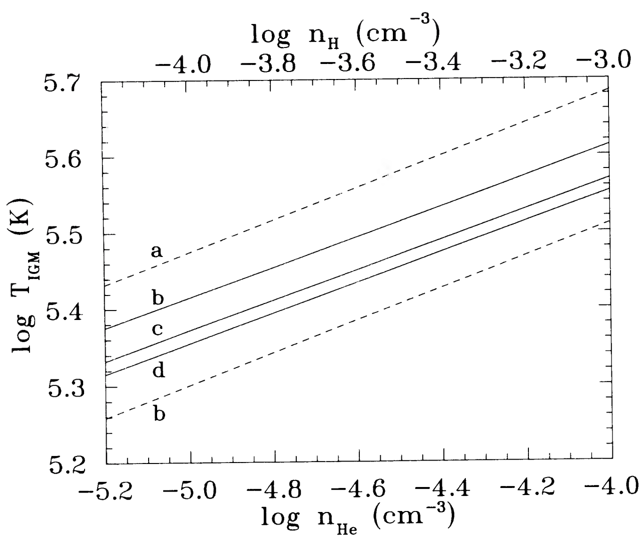

FIG. 3.—Curves of constraint for the predominantly shock-heated IGM in the rest frame of PG 1115+080 ($z = 1.722$) over a plausible range of helium densities (assuming $n_{He} = 0.1 n_H$) for the following cosmological parameters: (*a*) $h_{100} = \frac{1}{2}$, $q_0 = 0$, $z = 2.64$; (*b*) $h_{100} = \frac{1}{2}$, $q_0 = 0$, $z = 1.72$; (*c*) $h_{100} = \frac{1}{2}$, $q_0 = \frac{1}{2}$, $z = 1.72$; and (*d*) $h_{100} = 1$, $q_0 = 0$, $z = 1.72$. The allowed regions are above and to the left of the curves. The solid lines are obtained from the 3 σ limit on the neutral helium density reported in this *Letter*, and the dashed lines are obtained from the 3 σ limit on the neutral hydrogen density reported by Steidel and Sargent (1987). In order to put the hydrogen curve of constraint into the rest frame of PG 1115+080, adiabatic expansion was assumed.

vation equation which includes an energy-loss term and a steady heating term. In that work, the energy-loss term included radiative cooling and ionization of heavy elements as well as hydrogen and helium. In this work, the heavy elements perhaps should not be included. Furthermore, Shapiro and Moore (1976) set the steady heating term equal to zero while the hot IGM model of Ikeuchi and Ostriker (1986) assumes continuous shock heating.

A detailed discussion of the implications of such hot temperatures for the IGM is beyond the scope of this *Letter*. However, we note that if $T_{IGM} = 10^5$ K and $n_{IGM} \simeq 10^{-3.6}$ cm^{-3} at $z = 1.72$, then for the highest redshift quasars known ($z = 4.7$; Schneider, Schmidt, and Gunn 1989), $T_{IGM} \simeq 4.4 \times 10^5$ and $n_{IGM} \simeq 2.3 \times 10^{-3}$ cm^{-3} assuming adiabatic expansion. At this temperature and density the evaporation time scale for a Lyman-alpha forest cloud is very much shorter than the Hubble time (cf. Ikeuchi and Ostriker 1986, eqs. [68] and [71]). Thus, in this model, evaporation may be an important process affecting the evolution of the Lyman-α forest clouds at very high redshift.

We have also examined the photoionized and collisionally ionized IGM model using the code CLOUDY (version 70.06; Ferland and Rees 1988) kindly loaned to us by Gary Ferland. We have calculated the log T_{IGM}–log n_H curve of constraint which satisfies our 3 σ limit on n_{HeI} for an IGM photoionized by the UV radiation field from QSOs and assumed to be in photoionization equilibrium but not thermal equilibrium. Thermal equilibrium was not required because IGM thermal history models (Ikeuchi and Ostriker 1986; Ostriker and Ikeuchi 1983) indicate that pure photoionizing models cannot sufficiently ionize the IGM. CLOUDY was run in the constant temperature mode and n_H was varied until the calculated neutral component satisfied the Gunn-Peterson test. We used $n_{He} = 0.1 n_H$ and omitted all of the heavier elements for this optically thin calculation; the diffuse UV background was assumed to be an $\alpha = -1$ power law from the optical through the soft X-ray (however, the calculation is insensitive to the assumed X-ray spectrum) with the flux density at 912 Å given by Ostriker and Ikeuchi (1983) and Ikeuchi and Ostriker (1986):

$$J(\nu_{LL}) = \left[\frac{1+z}{3.5}\right]^4 (10^{-21} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1}) . \quad (3)$$

This curve of constraint is shown in Figure 4 along with the curve of constraint (also calculated with CLOUDY) which satisfies the 3 σ limit on $n_{H\,I}$ obtained by Steidel and Sargent (1987). While the He I Gunn-Peterson test may provide a tighter limit on T_{IGM} in the mostly shock-heated model, it is interesting to note that the H I Gunn-Peterson test provides much more leverage than the He I test in the photoionized case. Thus we must carry out the difficult He II Gunn-Peterson test in order to obain truly stringent limits on photoionized IGM models. We note that for the hydrogen curve of constraint, CLOUDY requires, for the most part, additional heating beyond that provided by the UV background. Again, this is consistent with the conclusions of Ostriker and Ikeuchi (1983) and Ikeuchi and Ostriker (1986): the purely photoionized IGM model cannot satisfy the hydrogen Gunn-Peterson test. Additional shock heating is required. On the other hand, the CLOUDY calculation mostly required additional cooling to produce the helium curve of constraint. This only reaffirms that our limit on $n_{He\,I}$ does not limit T_{IGM} very stringently when photoionizaton is significant. We have indicted in Figure 4 the point at which the additional cooling required becomes implausible.

The Gunn-Peterson test (eq. [1]) can be rewritten in terms of the cosmological density parameter (Ω) and the hydrogen or helium neutral fraction (y). For helium,

$$\tau_{He\,I}(z) = \frac{1.07 \times 10^4 h_{100}\, y_{He\,I}\, \Omega_{IGM}(1+z)^2}{(1+2q_0 z)^{1/2}} . \quad (4)$$

Using the neutral fractions calculated by CLOUDY (Fig. 4),

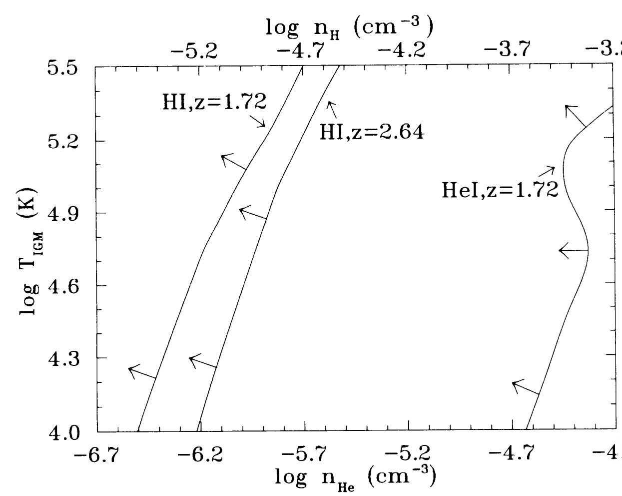

FIG. 4.—Curves of constraint for the photoionized IGM that satisfy the limit on $n_{He\,I}$ reported in this *Letter* and the limit on $n_{H\,I}$ obtained by Steidel and Sargent (1987). The allowed regions are indicated by the large arrows. The calculations were carried out with CLOUDY. When $n_{He} \geq 10^{-4.3}$, the additional cooling required by CLOUDY to produce the He I curve of constraint is implausible. In order to put the hydrogen curve of constraint into the rest frame of PG 1115+080, adiabatic expansion was assumed. For these calculations we have used $h_{100} = \frac{1}{2}$ and $q_0 = 0$.

we find that for $T_{IGM} = 10^5$ and $q_0 = 0$, the limit from the helium test implies that $\Omega_{IGM} \leq 4.5/h_{100}$, while the hydrogen test implies that $\Omega_{IGM} \leq 0.08/h_{100}$ at the 3 σ level.

IV. THE GRAVITATIONAL LENS

We have carefully examined the short-wavelength *IUE* observations of PG 1115+080, and we have not found any Lyman-limit discontinuities. This implies that the lensing galaxy does not intercept the line of sight or does not contain enough neutral hydrogen to be detected as a Lyman-limit edge. Our spectra are admittedly quite noisy, and it may be difficult to quantify a step, so we also searched for steps with a "shift, multiply, and sum" cross-correlation function. This consisted of shifting the normalized spectrum to zero, multiplying each pixel by a step function ranging from -1 to $+1$, summing the products, and then shifting the step function 1 pixel longward and repeating the procedure. This algorithm did not reveal the presence of any discontinuities. We estimate that the lens column density for neutral hydrogen is therefore $\leq 3 \times 10^{16}$ cm^{-2} if it intercepts the line of sight.

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JILL BECHTOLD: Steward Observatory, University of Arizona, Tucson, AZ 85721

RICHARD F. GREEN: Kitt Peak National Observatory, P.O. Box 26732, Tucson, AZ 85726

TODD M. TRIPP: Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721