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GRAVITATIONAL LENSING IN QSO 1208+10 FROM THE PROXIMITY EFFECT IN ITS Lyα FOREST

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ABSTRACT

The quasar Q1208+1011 ($z_{em} = 3.8$) is the second-highest redshift double quasar ever detected. Several indications point toward it being a gravitationally lensed system, although a definitive proof is still lacking. We present new evidence of its lensed nature, based on the weakness of the "proximity effect" measured in the high-resolution Lyman absorption spectrum of the QSO. A luminosity amplification as large as 22 has been derived from this analysis. Indications in the redshift of the lensing galaxy can be obtained from an analysis of the intervening heavy-element absorption systems discovered in the QSO high-resolution spectrum. On statistical and dynamical grounds, a Mg II system present at $z = 1.13$ appears to be the most likely candidate for the lensing galaxy. We compare the observed parameters with a simple isothermal model for the lens to derive the properties of the lensing galaxy. The resulting magnification factor is smaller, although marginally consistent with that derived by analysis of the proximity effect.

Subject headings: gravitational lensing — quasars: absorption lines — quasars: individual (Q1208+1011)

1. INTRODUCTION

High-resolution images both from ground-based telescopes (Magain et al. 1992) and the *Hubble Space Telescope* (*HST*) (Bahcall et al. 1992b) revealed that the image of the $z = 3.8$ QSO Q1208+1011 (Hazard, McMahon, & Sargent 1986) is split into two components, separated by 0".47 and with a brightness ratio of about 4, independent of wavelength.

Subsequent spectral observations from *HST* (Bahcall et al. 1992a) confirmed that both images are from a $z_{em} = 3.8$ QSO, although small differences in the emission-line profiles were noticed. Further ground-based imaging (Hjorth, Grundahl, & Festin 1995) has shown variability in the intensity ratio of the continuum that scaled to 3.3 in the *I* band in 1 yr, while a narrowband filter centered on the Lyα emission showed a more prominent Lyα in the brighter source.

The observed variability and the failure to detect the lensing galaxy cast some doubt on the possibility that the double image might correspond to a lensed source rather than a physical pair.

In this work we show that additional evidence for the lensing nature of this QSO can be obtained from an analysis of the proximity effect in its Lyα forest by means of new, high-resolution spectra of the QSO 1208+1011. The spectra of high-z quasars at wavelengths shorter than the Lyα emission are dominated by the crowded sequence of narrow absorption lines (the Lyα forest) that are produced by the population of intergalactic clouds (Lyα clouds) intervening along the line of sight to the quasar. In addition, absorption features from other elements are more easily detected at wavelengths longer than the Lyα emission peak of the spectrum. Systematic imaging and spectroscopic surveys have shown that these heavy-element (metal) systems are associated with intervening galaxies at the same redshifts (e.g., Bergeron & Boisse 1991; Steidel 1995).

The proximity effect consists of a reduction of the Lyα line density in the region near the QSO emission redshift caused by the increase of the ionizing flux by the QSO. It depends on the competing ionization level produced by the diffuse UV background and the flux by the nearby QSO. In this paper we show that the anomalously small proximity effect measured in Q1208+1011 implies an intrinsic QSO luminosity much smaller than observed, suggesting a large amplification of the QSO light by the gravitational lensing effect.

The detection and above all the measurement of the redshift of the lensing galaxy (presumably a faint object located in the middle of the two point sources) is probably beyond current observational possibilities. For this reason, hints as to its redshift have been sought in the absorption systems detected in the spectrum of Q1208+1011. Magain et al. (1992) presented a reanalysis of the medium-resolution spectrum of Q1208+1011 (Steidel 1990), identifying 19 possible metal systems, 14 of which are in the range $2.5 < z < 3.1$.

In this paper we also discuss a Mg II system at $z \simeq 1.13$ as the most likely galaxy candidate responsible for the gravitational lensing of the QSO. This identification has been proposed by Fontana et al. (1997) and more recently by Siemiginowska et al. (1998).

2. THE LENSING MAGNIFICATION FROM THE PROXIMITY EFFECT

The high-resolution ($R = 35000$) spectrum of Q1208+1011 was included in the sample used by Giallongo et al. (1996) to estimate the UV background at high redshifts from the proximity-effect analysis. The data were obtained at the ESO NTT telescope with the EMMI echelle spectrograph in the framework of the ESO Key program 2-013-49 (principal investigator S. D'Odorico). During the observations, the slit was aligned along the parallactic angle. Since the slit width (1") and the typical seeing (0".8) were larger than the separation between the two images of the QSO (0".47), we assume that we have collected the spectra of both objects simultaneously. Four different exposures were taken, for a total exposure time of 30,000 s. The signal-to-noise (S/N) ratio of the final spectrum is greater

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than 20 per resolution element in the regions of interest here. We have analyzed all the absorption features in the spectrum of Q1208+1011, deriving the redshift, column density, and Doppler parameter of the absorbing cloud by fitting Voigt profiles to isolated lines and individual components of the blends. A detailed list of the absorption lines in this quasar will be given in a separate paper. Here we discuss the implications of what we can infer about the nature of the lensing system toward Q1208+1011.

The distribution of the Lyα absorption lines in QSO spectra provides a powerful method for estimating the UV background (UVB) at high redshift. Although their cosmological number density increases strongly with redshift in the interval $z = 1.5$–5, following a power-law distribution $\propto (1+z)^{\gamma}$, with $\gamma \sim 2.7$, their redshift distribution within a single QSO spectrum does not follow the general cosmological trend when approaching the QSO emission redshift. This effect has been interpreted as a "proximity effect." It consists of a reduction of the line density in the region near the QSO emission redshift as a result of the increase of the ionizing flux by the QSO. Near the QSO, the Lyα absorbers are more highly ionized, with a column density of $N_{\rm HI} = N_{\infty}/(1+\omega)$, where N_{∞} is the intrinsic column density that the same cloud would have at infinite distance from the QSO, and $\omega(z) = F/4\pi J$ is the ratio between the flux F that the cloud receives from the QSO and the flux $4\pi J$ that the cloud receives from the general UVB (see Bajtlik, Duncan, & Ostriker 1988 and Bechtold 1994 for details of the model).

Analysis of the proximity effect in the spectrum of the QSO 1208+10 shows that this QSO clearly stands out against the other quasars of similar redshift because of the large number of saturated absorption lines in the close vicinity of the quasar (see Fig. 1). This suggests that the ionization produced by the quasar is lower than for other QSOs of comparable apparent magnitude, as would be expected if Q1208+1011 is gravitationally amplified. To quantify this effect, we have inverted the procedure used in Giallongo et al. (1996), i.e., we have fixed the ionizing UV background, the functional shape, and the parameters that best describe the statistical distributions of the Lyα clouds and obtained (through the same maximum-likelihood analysis) the *intrinsic* luminosity of this QSO.

Following Giallongo et al. (1996), we have parameterized the cosmological distribution of the Lyα clouds at any distance from the QSOs as

$$\frac{\partial^2}{\partial z\,\partial N_{H\,I}} = A_0(1+z)^{\gamma}[1+\omega(z)]^{1-\beta_f} \times \begin{cases} N_{H\,I}^{-\beta_f} & for\ N_{H\,I} < N_{break} \\ N_{H\,I}^{-\beta_s} N_{break}^{\beta_s-\beta_f} & for\ N_{H\,I} \geq N_{break} \end{cases}, \qquad (1)$$

where the $(1+z)^{\gamma}$ term accounts for the redshift evolution of the absorbers, the double power-law in $N_{\rm H\,I}$ with slopes β_f and β_s accounts for the shape of their column density distribution, and the $(1+\omega)^{1-\beta_f}$ term describes the proximity effect.

To derive the intrinsic luminosity of Q1208+1011, we have computed a maximum-likelihood analysis on the same line sample, fixing the parameters describing the Lyα statistics and the value of J to the result of Giallongo et al. (1996), i.e., $\gamma = 2.65$, $\beta_f = 1.35$, log $N_{\rm break} = 13.98$, $\beta_s = 1.8$, $J = 5J_{-22}$ ($J_{-22} = 10^{-22}$ ergs s^{-1} cm^{-2} Hz^{-1} sr^{-1}), and

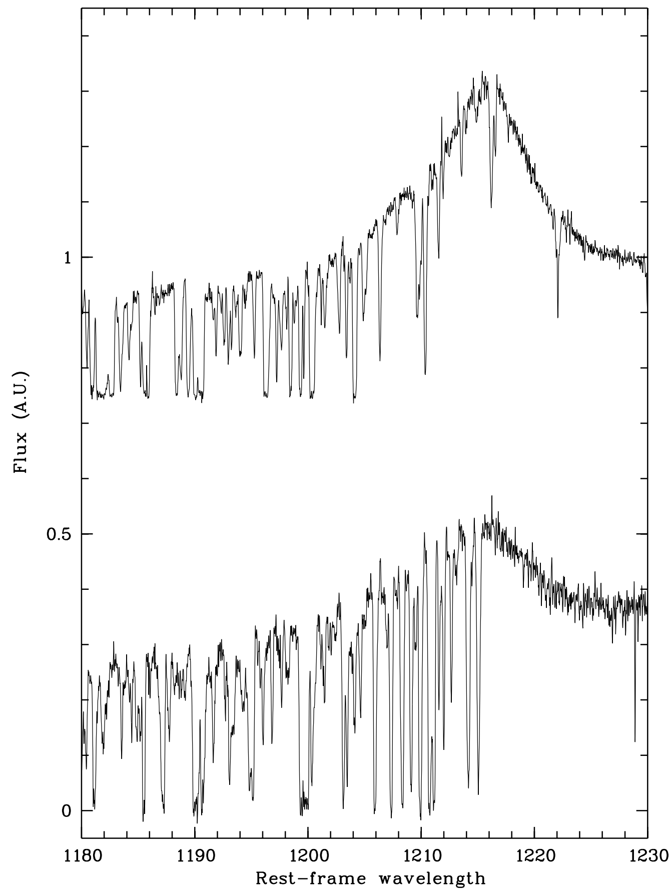

FIG. 1.—Lyα forest, affected by the proximity effect in two QSOs of comparable apparent magnitude $V \sim 17.5$ and at the same $z \sim 3.8$. Upper graph shows Q2000−33, lower graph Q1208+1011.

leaving the intrinsic Lyman limit flux of Q1208+1011 as a free parameter (see Table 3 in Giallongo et al. 1996, where the lines in the region affected by the proximity effect in Q1208+1011 were not used to minimize the lensing bias). The resulting flux predicted from this proximity-effect estimate is $F_{\rm PE} = 1.5 \times 10^{-28 \pm 0.35}$ ergs s^{-1} cm^{-2} Hz^{-1}, to be compared with the observed value $F_{\rm obs} = 3.33 \times 10^{-27}$ ergs s^{-1} cm^{-2} Hz^{-1} estimated by Bechtold (1994). As a further test, we have released the previously mentioned parameters and performed a global fit, obtaining the same QSO intrinsic flux as above and the best-fit values as in Giallongo et al. (1996). The total amplification factor derived from this analysis is $A = F_{\rm obs}/F_{\rm PE} \simeq 22$.

As discussed in the following section, current estimates of J range from 5 to 10 J_{-22}, depending on the sample and the statistical representation adopted. Since the estimated intrinsic QSO flux scales with the adopted value of the UVB, for $J = 10J_{-22}$ the derived intrinsic QSO flux would be 2 times higher, leading to a correspondingly lower amplification.

It is clear that this estimate is essentially statistical in nature. Barring systematic effects (discussed in the next section), the major source of statistical uncertainty is the variance of the Lyα lines statistical distribution. We have estimated it using a standard χ^2 error analysis on the maximum-likelihood parameters, obtaining a 2 σ upper limit of $F_{\rm PE} = 7.5 \times 10^{-28}$, corresponding to a 2 σ lower limit on the amplification of $A > 4.4$ when a value of $J = 5J_{-22}$ is used.

We therefore conclude that this result provides further support both to the gravitational lens hypothesis and to the photoionization model for the proximity effect, where it is expected to be weaker in low-luminosity QSOs. As an alternative hypothesis, the absorption systems in the environment of Q1208+1011 could be more gas rich than on average; in this case, however, we would expect the detection of the corresponding metal lines as well.

3. DISCUSSION

The reliability of the large amplification factor derived in § 2 from the proximity effect analysis on Q1208+1011 depends on how the estimates of both the UV background and the ionizing flux of the QSO 1208+1011 are unbiased.

Recent estimates of the UVB at $z \sim 3.5$ derived from the proximity effect range from the value used in the present paper, $J_{-22} = 5 \pm 1$ (or $5^{+2.5}_{-1}$ if we allow for asymmetric errors), to the value $J_{-22} \sim 10$ derived by Cooke, Espey, & Carswell (1997). In fact, the UVB estimate from the proximity-effect analysis depends on the slope of the column density distribution of the weaker lines. Giallongo et al. (1996) used the flat slope ~ 1.4 derived from their data. This value is in good agreement with the recent Keck results (Kim et al. 1997). The analysis by Cooke et al. (1997), based on lower resolution and/or lower S/N data, assumes a single steep power-law distribution with a slope of ~ 1.7, resulting in a higher J value.

Thus, an unbiased J value definitely lower than 10^{-21} is found (Giallongo et al. 1997), in agreement with what is expected from the QSO contribution at $z \sim 2$–3 (Haardt & Madau 1996). There is also no indication of any appreciable redshift evolution of the UVB in the redshift interval $z = 1.7$–4.1.

Gravitational lensing can also bias the estimate of the ionizing UVB. If lensing brightens the QSO continuum, then the QSOs are intrinsically fainter than they appear, and J is overestimated. However, the fact that the deficiency of lines in QSOs of different redshifts is correlated with luminosity but not with redshift suggests that the statistical weight of the gravitational lensing effect is small (Bechtold 1994).

The estimate of the ionizing flux of the QSO 1208+1011 can be affected by variability (Hjorth et al. 1995). This implies that an accurate measure of the amplification factor can only be obtained by monitoring the luminosities of various images on a time interval of at least a few years.

In summary, the unbiased statistical estimate of the UVB at $z \sim 3.5$, together with its image splitting in two components, strongly support the gravitational lensing hypothesis for Q1208+1011.

Since the very limited spatial separation of the two components prevents the detection of the lensing galaxy, hints as to its redshift have been sought from the heavy-element systems in the QSO spectrum. Early investigations at low resolution (Steidel 1990) revealed the existence of an unusually crowded series of C IV absorption systems at $z \simeq 2.8$–2.9. The identification of one of these high-z absorption systems with the lensing galaxy is not straightforward. Indeed, the small angular separation of the lens corresponds to an impact parameter of ~ 2 kpc at $z = 2.9$.

However, C IV systems are expected to arise preferentially at large impact parameters, while the very small impact parameters implied for this lens should favor the detection of low-ionization species. In addition to the cluster of absorption systems at $z \geq 2.8$, another interesting candidate for the lensing galaxy is the $z = 1.13$ Mg II absorption system (Fig. 2) that we discovered from an analysis of our high-resolution spectrum (Fontana et al. 1997; see also Siemiginowska et al. 1998). As can be seen from Figure 2, the identification relies not simply on the wavelength coincidence, but also on the good agreement in the relative intensities of the lines. This Mg II complex has been fitted with six components, which is the minimum number required to give a satisfactory fit.

The total equivalent width is $\simeq 0.7$ Å. Several systems with this equivalent width have been detected in Mg II surveys at a very small impact parameter (e.g., Steidel 1995).

Several arguments indicate that the $z = 1.13$ Mg II absorption system may be connected with the lensing galaxy. As shown by Kochanek (1992), statistical arguments favor intermediate redshifts for the lensing galaxy. The probability distribution of the redshift of the lensing galaxy is a strongly peaked function, which in the case of Q1208+1011 has a maximum at $z = 1$–1.15, depending on cosmology. At larger redshift, this probability becomes rapidly smaller, being about 0.008 at $z \sim 2.8$. Great care must be taken in applying this statistical approach to a single object, to avoid the pitfalls of a posteriori statistics. We note, however, that these models have a direct physical basis; lenses are most efficient when placed at half-way along the light path.

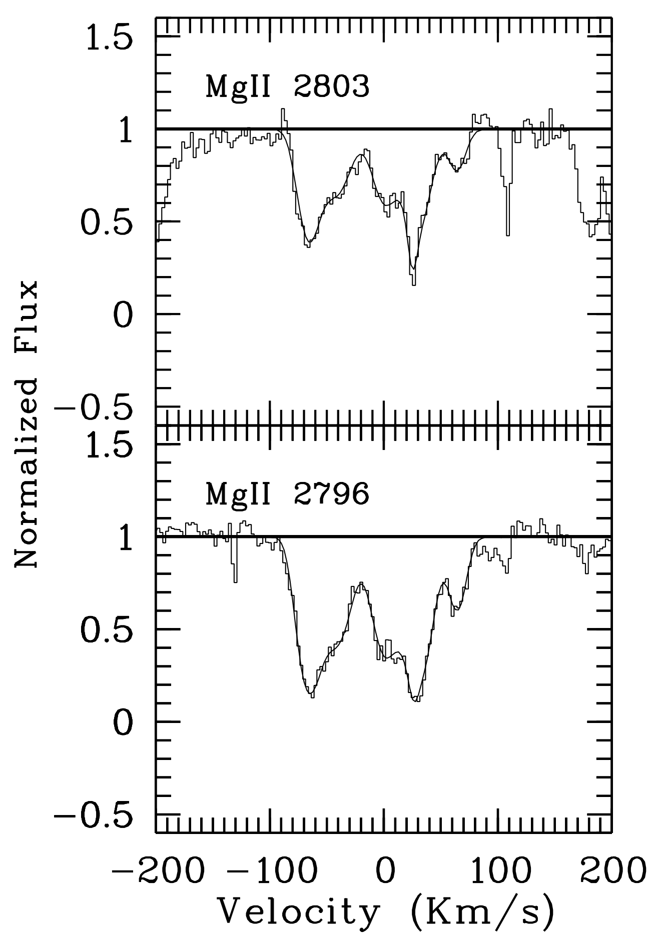

FIG. 2.—Mg II doublet at $z = 1.13$. Six components have been fitted.

In a simple isothermal model for the lensing galaxy, the one-dimensional velocity dispersion can be computed from the image separation $\Delta\theta$ alone, as (Turner, Ostriker, & Gott 1984) $\sigma_{\parallel} = c[\Delta\theta S/(8\pi)]^{1/2}$, where S accounts for the cosmology and is weakly dependent on Ω. At $z = 2.9$, we derive a one-dimensional dispersion of $\sigma_{\parallel} \sim 300$ km s^{-1}, to be compared with an observed value in the C IV absorption systems of about 240 km s^{-1}. The corresponding dynamical mass enclosed in the impact parameter $\sim\Delta\theta/2 \simeq 1.75$ kpc is $M \sim 10^{11}\ M_{\odot}$, and the corresponding virial mass is $M_L \sim 3 \times 10^{12}\ M_{\odot}$. These values are hardly credible at $z \simeq 2.9$ in any cosmological scenario for galaxy formation. The $z = 2.9$ C IV systems could provide a mass overdensity (extended over several hundreds of kpc) not related to the split of the QSO images, but able to provide a further luminosity amplification at most.

Alternatively, the velocity dispersion expected at $z = 1.13$ is $\sigma_{\parallel} = 140$ km s^{-1}, the same as observed in the Mg II system (Fig. 2) with an enclosed mass of $M \sim 3 \times 10^{10}\ M_{\odot}$ in a radius of ~ 2 kpc, and a virial mass of $M_L \sim 7 \times 10^{11}\ M_{\odot}$.

The comparison between predicted and observed velocity dispersions assumes that the observed gas velocity spread is representative of the galaxy velocity dispersion. Although there are hints favoring this association from Mg II absorptions detected both in the halos of external galaxies and in our own Galaxy (e.g., Lanzetta & Bowen 1992; Bowen, Blades, & Pettini 1995), there are also examples of strong absorptions spanning ~ 300 km s^{-1} that seem unrelated to the velocity dispersion within galaxies (Bowen et al. 1996).

In conclusion, the $z = 1.13$ galaxy giving rise to the Mg II absorption system appears to be the best candidate for the lensing galaxy. In the same simple isothermal model used above, the total amplification A is a simple function of the observed brightness ratio between the two components R: $A = 2 \times (R + 1)/(R - 1)$, yielding $A \simeq 3(4)$ if $R \sim 4(3.3)$, as found in the two available measurements of Q1208+1011, i.e., a value that is near the 2 σ lower limit derived from an analysis of the proximity effect, leaving the possibility that an additional magnification mechanism exists.

Finally, we would like to point out two opportunities for future work.

Q1208+1011 and its surrounding field deserve more in-depth investigations, to search for the lensing galaxy and other foreground structures. The *HST* or a ground-based telescope equipped with adaptive optics could be used to provide evidence for the faint lensing galaxy at $z \sim 1$. The observations should be carried out at wavelengths shorter than 580 nm, where the continuum of the QSO is depressed by the intergalactic-medium absorption.

There are seven lensed QSOs known to date at $z > 2.5$ that are within the observing capabilities of high-resolution spectrographs at very large telescopes; these could be used to confirm on a statistical basis the validity of this approach and to provide further constraints on the lensing mechanism.

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