OBSERVATIONS OF QSO J2233–606 IN THE SOUTHERN HUBBLE DEEP FIELD

K. M. Sealey, M. J. Drinkwater, and J. K. Webb

Department of Astrophysics and Optics, School of Physics, University of New South Wales, Sydney 2052, Australia

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ABSTRACT

The Hubble Deep Field South (HDF-S) Hubble Space Telescope (HST) observations are expected to begin in 1998 October. We present a composite spectrum of the QSO in the HDF-S field covering UV/optical/near-IR wavelengths, obtained by combining data from the Australian National University 2.3 m telescope with STIS on the HST. This intermediate-resolution spectrum covers the range 1600–10000 Å and allows us to derive some basic information on the intervening absorption systems which will be important in planning future higher resolution studies of this QSO. The QSO J2233–606 coordinates are \( \alpha = 22^\text{h}33^\text{m}37^\text{s}.6, \rightdelta = -60^\circ33'29'' \) (J2000), the magnitude is \( B = 17.5 \), and its redshift is \( z_{\text{em}} = 2.238 \), derived by simultaneously fitting several emission lines. The spectral index is \( \alpha = -0.7 \pm 0.1 \), measured between the Ly\( \alpha \) and Mg \( \text{II} \) emission lines. Many absorption systems are present, including systems with metal lines redward of the Ly\( \alpha \) emission line at \( z_{\text{abs}} = 2.077, 1.928 \), without similarly strong metal lines. There is a conspicuous Lyman limit (LL) absorption system that is most likely associated with the \( z_{\text{abs}} = 1.942 \) system with a neutral hydrogen column density of \( N_{\text{HI}} = (3.1 \pm 1.0) \times 10^{17} \text{cm}^{-2} \). There is some evidence for the presence of a second LL absorber just to the blue of the conspicuous system at \( z = 1.870 \). We have employed a new technique, based on an analysis of the shape of the observed spectrum in the region of the LL absorption, to explore the properties of the gas. We tentatively conclude that this system might have suitable characteristics for measuring the deuterium-to-hydrogen (D/H) ratio.

Subject headings: quasars: absorption lines — quasars: emission lines

1. INTRODUCTION

Compared to the original studies of the Hubble Deep Field (HDF), scientific studies of the Hubble Deep Field South (HDF-S) may benefit from the additional information provided by a bright high-redshift \( z > 2 \) QSO lying close to (but not within) the targeted WFPC2 imaging area. Initially 12 small (\( 1^\circ \times 1^\circ \)) fields were selected as candidate target fields. While no known high-\( z \) QoSs were present in any of the possible fields, Hewett and Irwin, using a UK Schmidt Telescope IIIa-J objective-prism plate scanned by the Automated Plate Measuring facility in Cambridge, found a high-\( z \) QSO candidate in one of the fields. Follow-up observations of the candidate at the Anglo-Australian Telescope confirmed the object to be a QSO (J2233–606; \( \alpha = 22^\text{h}33^\text{m}37^\text{s}.6, \rightdelta = -60^\circ33'29'' \) [J2000], \( B = 17.5 \)) with a redshift \( z > 2 \) (see Boyle 1997 for details). We note for completeness that 20 cm radio observations have been made (R. Norris 1997, private communication reported in Boyle 1997) that give an upper limit on the radio flux as \( S_{20 \text{ cm}} < 3 \text{ mJy} \). There is a strong radio source 10' from the QSO (\( S_{20 \text{ cm}} = 146 \text{ mJy} \)).

We present here a low-resolution spectrum of the HDF-S QSO taken with the Australian National University (ANU) 2.3 m telescope and combined with the publicly available STIS spectrum providing wide spectral coverage. The QSO has an optically thin Lyman limit (LL) which is a possible candidate for measuring the deuterium-to-hydrogen (D/H) ratio. The QSO also has several strong absorption features redward of the Ly\( \alpha \) emission line, to which we assign tentative identifications.

2. OBSERVATIONS AND DATA REDUCTION

The ANU 2.3 m observation of the QSO was taken on 1997 October 21 at Siding Spring in clear conditions with \( \pm 2'' \) seeing.

The Double Beam Spectrograph (DBS) was used with a 300 line mm\(^{-1} \) grating in the blue arm (binned by 2 in the dispersion direction), and a 158 line mm\(^{-1} \) grating in the red, giving a resolution of 8 Å in each arm. A dichroic was used to split the light at \( \approx 5400 \text{ Å} \). Because of the difficulty in combining the red and blue spectra around the dichroic wavelength, there is some uncertainty in our spectrum in the wavelength region 5400–5600 Å. The data were reduced using standard procedures with the IRAF\(^2 \) image analysis software. The resulting spectrum (3300–10000 Å) is the weighted combination of two exposures (1200 and 900 s).

We combined our ground-based 2.3 m spectrum with the HST/STIS spectrum taken on 1997 October 30 with the G230L grating for 3700 s (1600–3100 Å, resolution \( \approx 3.4 \text{ Å} \)) and the G430L grating for 2200 s (2900–5700 Å, resolution \( \approx 6 \text{ Å} \)). Our 2.3 m spectrum was not spectrophotometric (we used a narrow slit), so we scaled it before combining to have the same flux level as the STIS spectrum in the overlapping region of the two spectra. In order to preserve the higher resolution of the STIS data and because of uncertainties in the flux calibration of the ground-based data in the blue, we only used data redward of the Ly\( \alpha \) emission (4170 Å) from the 2.3 m data in the combined spectrum. A comparison of the 2.3 m spectrum and the STIS spectrum in the overlap region made by cross-correlating the two spectra does not show any significant wavelength shifts, with a typical uncertainty of 40 km s\(^{-1} \) (0.5 Å). This is consistent with the rms residuals obtained for the comparison lamp exposures for the 2.3 m blue DBS spectrum, which were around 0.6 Å.

The final composite spectrum (shown in Fig. 1) has been rebinned to the dispersion of the UV STIS component of the

\(^2\) IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under cooperative agreement with the National Science Foundation.
spectrum ($\lambda < 2900$ Å), 1.55 Å pixel$^{-1}$. The signal-to-noise ratio per pixel is $\approx 5$ below the LL break ($\lambda < 2700$ Å), $\approx 20$ in the Ly$\alpha$ forest, and up to $\approx 40$ around 7000–8000 Å.

3. Results

3.1. Emission Lines and QSO Continuum

We measured the redshift of each of the emission lines in the QSO independently and also determined the QSO redshift by simultaneously fitting some of the emission lines using VPFIT (Webb 1987; Carswell et al. 1992). Table 1 shows, for each of the emission lines, the redshift, the equivalent width (EW), and the velocity width. The four lines used in the simultaneous measurement were C iv + Al iii, C iv, and Mg ii. The individual redshifts for each line are listed in Table 1. The redshift from the simultaneous fit is $z = 2.238$. The difference of 1390 km s$^{-1}$ between the (C iv and C iii) + Al iii) and the Mg ii redshifts is not unusual (Espey et al. 1989). The observed EWs lie in the ranges given by the composite QSO spectra of Francis et al. (1991) and Boyle (1990).

The spectral index of the combined spectrum is $\alpha = -0.7 \pm 0.1$ (where $f_{\nu} \propto \nu^\alpha$), consistent with values derived for optically selected QSOs (e.g., the LBQS survey yields $0.0 < \alpha < -0.8$; Francis 1996). The measurement was made by fitting to three sections of the spectrum between 4000 and 9000 Å free of detectable emission lines. Our estimate of the uncertainty in $\alpha$ was derived by fitting the combined spectrum and the 2.3 m data alone and hence is approximate.

3.2. Absorption Systems

An initial investigation of the QSO reveals that there is complex absorption present from intervening systems. The absorption system details are tabulated in Table 2. There are four systems with metal lines and two systems with no detectable metals (at the signal-to-noise ratio and resolution of these data) redward of the Ly$\alpha$ emission line.

There is a Ly$\alpha$ line at $z = 1.870$ (L3) with associated metal lines (C ii, Si iii, and strong C iv). If N v is present, it is blended with the stronger ($z = 1.928$) of the 2 Ly$\alpha$ lines at $z = 1.928$ (L1) and $z = 1.942$ (L2) (see Fig. 2, top panel). We note that the C iv absorption line associated with L3 ($z = 1.870$) line falls blueward of the Si iv emission line, so a Si iv identification is also feasible. However, this seems unlikely because there is no corresponding Ly$\alpha$ absorption line for a Si iv identification.

Identifications of other metal systems are less secure because there are fewer metal lines. Prominent Ly$\alpha$ absorption features at $z = 1.942$ (L2), $z = 1.787$, and $z = 2.204$ all appear to have C iv absorption. Also, there are absorption lines lying at the midpoint between the Ly$\alpha$ and N v emission lines, which may be due to N v absorption corresponding to the $z = 2.204$ system.

There appear to be no detectable metal lines associated with the strong Ly$\alpha$ line ($z = 2.077$), or with L1 ($z = 1.928$). The strong line at 3003.9 Å is due at least in part to Ly$\beta$ associated with L1 ($z = 1.928$).

If the identifications above are correct, we are seeing a rich complex of C iv absorption spread over the redshift range 1.787–2.204 corresponding to a scale $\sim 100$ Mpc, if interpreted as a spatial separation. Detailed studies of this QSO and the region of the sky around it, particularly photometric redshift analyses, should reveal whether we have discovered a huge structure formed at an early epoch or whether the line of sight to this QSO happens to intersect multiple isolated galaxies or clusters.

The STIS spectrum can be used to explore the properties of the LL absorption system to determine the neutral hydrogen column density, $N_{H,1}$, and to constrain the velocity width of the absorbing gas. This is of particular interest from the point of view of seeing whether the system has suitable characteristics for measuring the deuterium-to-hydrogen ratio (D/H). The important requirement, apart from having a sufficiently high $N_{H,1}$ for D i to be detectable, is that the D i feature is not broad.

| N v Identification | $\lambda$ (Å) | $\sigma(\lambda)$ (Å) | $z_{\text{abs}}$ | EW$_{\text{abs}}$ (Å) | $\sigma$(EW) (Å) |
|--------------------|--------------|----------------------|----------------|------------------|------------------|
| Ly$\alpha$         | 1.870        | 1.5                  | Ly$\alpha$     | 1.787            | 1.7              |
| Ly$\alpha$         | 1.942        | 3.0                  | Ly$\beta$      | 1.928            | 7.3              |
| Ly$\alpha$         | 2.077        | 2.0                  | Ly$\alpha$     | 1.928            | 5.1              |
| Ly$\beta$          | 1.924        | 1.6                  | Ly$\alpha$     | 1.922            | 2.2              |
| Ly$\alpha$         | 1.942        | 1.8                  | Ly$\alpha$     | 1.942            | 3.3              |
| Ly$\alpha$         | 2.077        | 1.9                  | Ly$\alpha$     | 2.077            | 4.9              |
| Ly$\alpha$         | 2.204        | 1.6                  | Ly$\alpha$     | 2.204            | 2.0              |
| Ly$\alpha$         | 2.204        | 0.9                  | N v            | 2.204            | 0.9              |
| Ly$\alpha$         | 2.204        | 1.7                  | C iv           | 2.204            | 2.7              |
To identify the Lyα line associated with the LL, we used the wavelength (2685 Å) of the LL to estimate where the associated Lyα line would fall. Figure 2 shows that there are two candidate lines, one at \( z = 1.928 \) (L1) and the other at \( z = 1.942 \) (L2). They are sufficiently close to each other that it is unclear which is associated with the LL.

In order to explore whether L1 or L2 is associated with the LL, we generated a series of simulated spectra at the column density derived above, for a range of velocity dispersion parameters \( (b = 10, 30, \text{and } 60 \text{ km s}^{-1}) \) at the two redshifts of L1 and L2. We then compared the agreement between the model and observed spectra in the LL region. The low spectral resolution makes it difficult to derive useful information by comparing model and observed individual Lyman series lines. Instead, a more promising method is to look explicitly at the wavelength and shape of the LL drop, at and around the point at which the flux falls to roughly a constant level. The second and third panels of Figure 2 show the two possible systems associated with the LL, with the models overlaid.

Figure 2 shows that it is still difficult to unambiguously determine whether the actual LL absorber is associated with L1 or L2. However, if it is associated with L2, the \( b = 30 \text{ and } 60 \text{ km s}^{-1} \) models are inconsistent with the data, and we can only get a reasonable fit to the LL for \( b \approx 10 \text{ km s}^{-1} \). The L1 system requires a higher effective \( b \) parameter, suggesting that H i has complex velocity structure, so that it would not be suitable for a D/H study.

A further possibility we considered was that neither L1 nor L2 was responsible for the LL, but that L3, (see Fig. 2), was responsible for the depression. In order for its LL to cut in at the observed wavelength, \( N_{\text{H i}} \) would have to be sufficiently high that the high-order Lyman lines were strong enough to blend together, forming a substantial drop in the transmitted flux redward of 912 Å in the rest frame. However, this would require a high neutral hydrogen column density, which would leave no residual flux at wavelengths shorter than the LL, which in turn would require the zero level of the spectrum to be incorrect. We nevertheless explored this possibility further by using the EW of L3 to estimate \( N_{\text{H i}} \), and then comparing its associated LL with the observed spectrum. This procedure should provide an upper limit on \( N_{\text{H i}} \), since in reality L3 is probably composed of multiple components. We found that the \( N_{\text{H i}} \) derived in this way did not produce a large enough flux decrement in the wavelength region shortward of the observed drop at 2680 Å.

Careful examination of Figure 2 also suggests that the residual flux in the data between 2650 and 2680 Å is slightly higher than the synthetic LL from L2 (or L1) alone. The spectrum appears to drop to a lower average flux below ~2640 Å implying the possible presence of an additional high \( N_{\text{H i}} \) cloud.

This suggests two steps in the LL, one associated with L2 (\( z = 1.942 \)) and one with L3 (\( z = 1.870 \)). We again used VPFIT to model the data with a two-component LL system, fixing the two redshifts (\( z = 1.942 \) and \( z = 1.870 \), allowing \( N_{\text{H i}} \) to vary. The resulting fit can be seen in panel 4 of Figure 2. This procedure results in a good fit to the data, suggesting that the observed LL is associated with L2 and that there is indeed a further weak LL absorption associated with L3.

The VPFIT estimate of the L2 column density is \( N_{\text{H i}} = 3.1 \pm 1.0 \times 10^{17} \text{ cm}^{-2} \). A 2 \( \sigma \) upper limit was also obtained for the \( N_{\text{H i}} \) of system L3. This was determined to be \( N_{\text{H i}} = 3.2 \times 10^{17} \text{ cm}^{-2} \). If the LL is associated with L2, this system may

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**Fig. 2.—**Models of the Lyman limit absorption. The top panel illustrates the three candidate Lyα lines that may be associated with the LL. The second and third panels show the LL region with our models overlaid to determine the velocity structure of the system associated with the LL. \( N_{\text{H i}} \) was calculated as described in the text, and three values of the \( b \) parameter were used \((A = 10, B = 30, \text{ and } C = 60 \text{ km s}^{-1}) \) for each of the two redshifts. From the fits we can see that either L1 (\( z = 1.928 \)) with a high \( b \) parameter or L2 (\( z = 1.942 \)) with a low \( b \) parameter will fit the data. The bottom panel shows the LL region with a model overplotted including the combined effect at the LL from systems L2 and L3.
turn out to be suitable for measuring D/H, because the (tentatively) low effective $b$ parameter suggests simple velocity structure and a small velocity dispersion.

Using the two QSO continua described above, we estimated the parameter representing the flux decrement between the Ly$\beta$ and the Ly$\alpha$ emission lines, $D_A = 1 - (f_{\text{obs}}/f_{\text{cont}}) = 0.14 \pm 0.04$.

### 4. DISCUSSION

We have reported the results of a study of a low/intermediate-resolution spectrum covering the UV/optical/near-IR of the HDF-S QSO J2233-606, formed by combining HST/STIS observations with higher wavelength data from the ANU 2.3 m telescope. The intrinsic QSO spectral characteristics have been measured from these data.

A study of the absorption properties have revealed multiple C iv absorption systems, suggesting that either a large structure or multiple galaxies or clusters intersect the sightline to this QSO. Structure in the LL absorption is probably caused by the presence of at least two high N(H i) systems, one of which may have properties that make it suitable for studying D/H.

Despite the low spectral resolution, we have been able to derive reasonably detailed characteristics of the absorption systems. Future high-resolution spectra will of course yield far more information. However, it is already clear from our results that this QSO and the HDF-S studies of its environs will reveal a host of fascinating new information about the $z \sim 2$ universe.

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