

# DETECTION OF INTERGALACTIC He II ABSORPTION AT REDSHIFT 3.5<sup>1</sup>

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## ABSTRACT

The large number of quasars found in the Sloan Digital Sky Survey has allowed searches for elusive, clear lines of sight toward He II Ly $\alpha$  absorption, a sensitive probe of the intergalactic medium. The few known systems indicate that He II reionization occurs at  $z > 3$ . We report the detection of a He II Ly $\alpha$  absorption edge in a quasar spectrum at  $z = 3.50$ , the most distant such feature found to date. The candidate quasar was selected from a  $z \sim 3$  sample in the Sloan Digital Sky Survey spectroscopic quasar survey and confirmed as part of an *HST* Space Telescope Imaging Spectrograph SNAP survey. We discuss the general characteristics of the absorption feature, as well as the probability for the discovery of additional such objects.

**Key words:** dark matter — intergalactic medium — quasars: individual (SDSS J2346–0016) — surveys — ultraviolet: general

## 1. INTRODUCTION

Much of the intergalactic hydrogen exists in a highly ionized state, as evidenced by the lack of H I Gunn-Peterson troughs in the optical spectra of high-redshift quasars (Gunn & Peterson 1965). The first presence of a Gunn-Peterson trough was detected in He II absorption, in a quasar at  $z = 3.28$  (Jakobsen et al. 1994). Follow-up observations at a higher signal-to-noise ratio level and spectral resolution (Hogan et al. 1997; Heap et al. 2000) found an average He II optical depth  $\tau = 4.0 \pm 0.5$  at  $z \sim 3$  and at least  $\tau = 5$  at  $z \sim 3.2$ . He II absorption displays significant structure, consisting of unabsorbed void regions and deep absorption troughs (Reimers et al. 1997). When contrasted with the low He II opacity measured at  $z \sim 2.5$  (Davidsen et al. 1996; Kriss et al. 2001; Zheng et al. 2004), these findings indicate a sudden increase in optical depth. While the large opacity at  $z \sim 3.2$  is conceivably related to a fluctuation in the number of local ionizing sources, it may instead (e.g., if confirmed in multiple additional independent lines of sight) more generally signal an epoch in which intergalactic helium is not fully ionized.

Recently, a similar pattern for intergalactic hydrogen has been observed in the  $z > 6$  quasars. Becker et al. (2001) and Fan et al. (2002) report a H I optical depth of at least  $\tau = 15$  at  $z \sim 6.2$ , signaling the late stages of reionization of the intergalactic medium (IGM). The recent *WMAP* results (Spergel et al. 2003) suggest that the IGM reionization may have started at  $z \sim 17$ , and there may have been a second

stage of hydrogen reionization that took place at  $z \sim 6$  (Cen 2003).

The reionization of intergalactic hydrogen and helium are cosmic milestones. As the early universe cooled and evolved, neutral hydrogen atoms in the IGM gradually became bathed in the ionizing ultraviolet background radiation produced by the first stars and quasars. With increasing UV background radiation, the IGM eventually became fully ionized. Atomic hydrogen and helium are affected by the same ionizing UV radiation in the distant universe—but because the He II Ly $\alpha$  transition is related to the number of ionizing photons at 4 ryd (generally smaller than the number at 1 ryd), the reionization of intergalactic helium is expected to occur later than hydrogen, approximately at  $z \sim 3$ –5 (Haardt & Madau 1996; Madau, Haardt, & Rees 1999; Wyithe & Loeb 2003). Indirect evidence (Theuns et al. 2002) suggests that the final stage of He II reionization may take place at  $z \sim 3.2$ –3.4, but only a very small number of independent lines of sight have thus far been identified that are suitable to probe He II even to  $z \sim 3$ . Moreover, each such line of sight is potentially susceptible to systematic bias; these lines of sight are, by selection, the most unobscured of all known quasar lines of sight to high redshift. It is therefore important to find additional lines of sight (to average over possible systematics in global conclusions) and also to extend He II studies to higher redshift. Higher redshift lines of sight are, of course, potentially the most useful, as each such object may provide a measure of He II absorption spanning the full redshift range likely to be most of interest. Our knowledge of the intergalactic helium has been derived from only four lines of sight, and only two are between  $3.0 < z < 3.3$ . More such examples are needed to establish the statistics and evolution of intergalactic helium at redshift  $z > 3$ . The discovery of any bright, UV-unobstructed quasar in this redshift range is therefore interesting.

We report here the detection of a He II absorption feature in the spectrum of quasar SDSS J234625.67–001600.4 (hereafter abbreviated as SDSS J2346–0016), the highest-redshift He II feature found to date. This new quasar sight line potentially will allow a measure of He II absorption from  $z = 2.8$  to  $z = 3.5$  in a single object, efficiently sampling the full redshift range commonly suggested for the epoch of helium reionization. We describe the method of selection,

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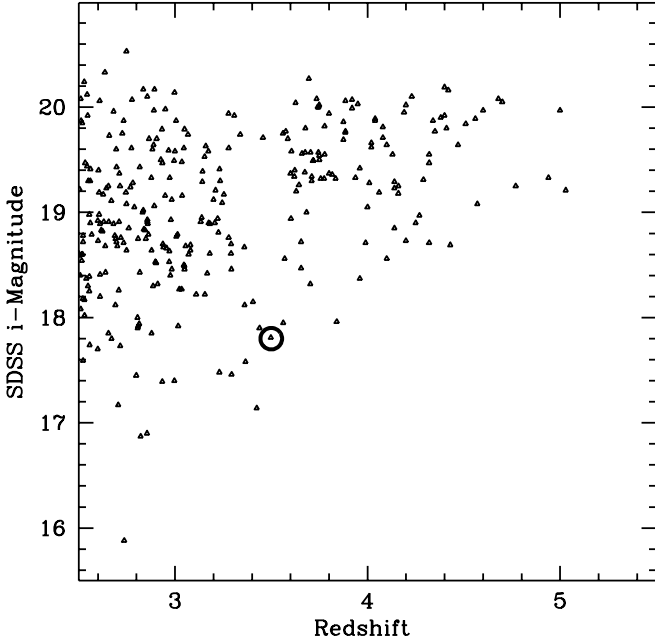


FIG. 1.—Plot of 302 quasars at  $z > 2.5$  found in the SDSS EDR (Schneider et al. 2002). The circle marks the position for the newly discovered quasar SDSS J2346-0016.

preliminary observations from *HST*/Space Telescope Imaging Spectrograph (STIS), and the probability for further discovery of similar objects.

## 2. CANDIDATE SELECTION AND OBSERVATIONS

At redshift  $z \gtrsim 2.8$  the He II Ly $\alpha$  feature becomes observable with *HST*. However, the observed UV flux of most high-redshift quasars is strongly suppressed by absorption from intergalactic H I along the line of sight. For objects at  $z \sim 3$ , attenuation by individual Ly $\alpha$  forest lines is moderate at rest-frame wavelengths shortward of  $\sim 600$  Å, but Lyman-limit systems (LLSs) can remove a significant amount—and frequently most—of the UV flux in high-redshift quasars (Møller & Jakobsen 1990). Not until recently have quasar catalogs provided sufficient numbers of bright, high-redshift candidates to begin to outweigh these difficulties. To date extensive searches have revealed only four such quasar sight lines with He II absorption features. Such a sample is too small to confidently understand the possible systematic uncertainties in the resulting cosmological inferences.

The Sloan Digital Sky Survey (SDSS; York et al. 2000) plans to image a quarter of the sky through five broadband filters (Fukugita et al. 1996) and to obtain spectra of approximately 1 million galaxies and 100,000 quasars. The survey employs a dedicated 2.5 m telescope at Apache Point Observatory to obtain images (Gunn et al. 1998), and automated pipelines (Pier et al. 2003; Smith et al. 2002; Stoughton et al. 2002) process the data. Objects were selected based on their broadband SDSS colors (Hogg et al. 2001). Richards et al. (2002) describe the SDSS quasar selection algorithm. The spectrophotometric calibration includes scaling by wider aperture “smear” exposures to the photometry from the imaging data. Details regarding the spectroscopic system and analysis pipelines may be found in Stoughton et al. (2002) and Blanton et al. (2003). The Early Data Release (EDR) Quasar

Catalog contains 3814 quasars (3000 discovered by the SDSS; Schneider et al. 2002). The redshift-magnitude distribution of the 302 EDR quasars at  $z > 2.5$  are shown in Figure 1.

The SDSS provides an excellent sample in which to search for quasar candidates with He II absorption features. We selected a sample of optically bright ( $i < 18.5$ ) quasars at redshift  $z > 2.9$  for an *HST* snapshot survey to search for He II absorption edges in the UV. The snapshot program used the STIS; only one out of the 24 candidates observed by the programs exhibited flux at the expected location of He II absorption.

The optical spectrum of SDSS J2346-0016 ( $i = 17.8$ ) was processed using the standard SDSS spectroscopic data reduction pipeline and is shown in Figure 2. The redshift is measured using the peak of several emission lines: C IV  $\lambda 1549$ , O I  $\lambda 1304$ , C II  $\lambda 1334$ , Si IV+O IV  $\lambda 1400$ , and Ly $\alpha$ , and the averaged value is  $z = 3.49 \pm 0.03$ . The Ly $\alpha$  forest lines set in at 5476.2 Å, corresponding to  $z = 3.5047$ .

The ultraviolet *HST*/STIS spectroscopic snapshot of SDSS J2346-0016 was performed on 2002 May 18. The data were obtained with the G140L grating and a  $52'' \times 0.5''$  slit, covering the wavelength range of 1150 to 1700 Å. The spectral resolution was approximately 1 Å, and the exposure time was 600 s. The *HST* spectrum extraction was done manually and processed using the standard STIS pipeline for wavelength and flux calibration. Figure 3 shows the spectrum binned by 9 pixels ( $\sim 2.7$  Å). It was fitted with a power-law continuum, a Ly $\alpha$  emission line, and an absorption edge. The fitted absorption edge is at  $1369 \pm 2$  Å, with a longward continuum level at  $f_\lambda \sim 10^{-16}$  ergs s $^{-1}$  cm $^{-2}$  Å $^{-1}$ . No flux is detected at the wavelengths below 1360 Å. Between 1330 and 1360 Å, the average flux is  $(0.05 \pm 0.8) \times 10^{-17}$  ergs s $^{-1}$  cm $^{-2}$  Å $^{-1}$ , corresponding to an optical depth of  $6_{-3}^{+\infty}$ .

The match between the redshifts of H I Ly $\alpha$  and the He II Ly $\alpha$  features strongly suggests, at a 98% level, that the observed UV absorption edge is not merely coincidental. The

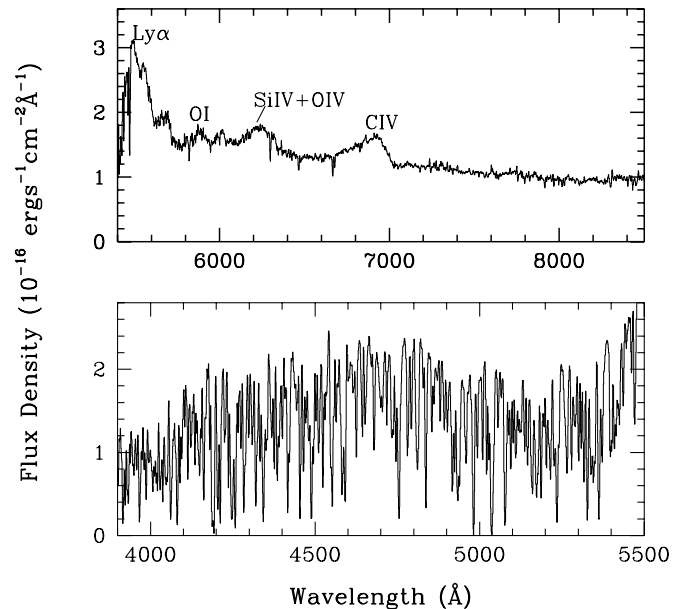


FIG. 2.—Optical spectrum of SDSS J2346-0016. The spectral resolution is approximately 1900. The top panel displays the spectral region longward of 5400 Å, and the bottom panel for the Ly $\alpha$  forest region. Major emission lines are indicated in the figure.

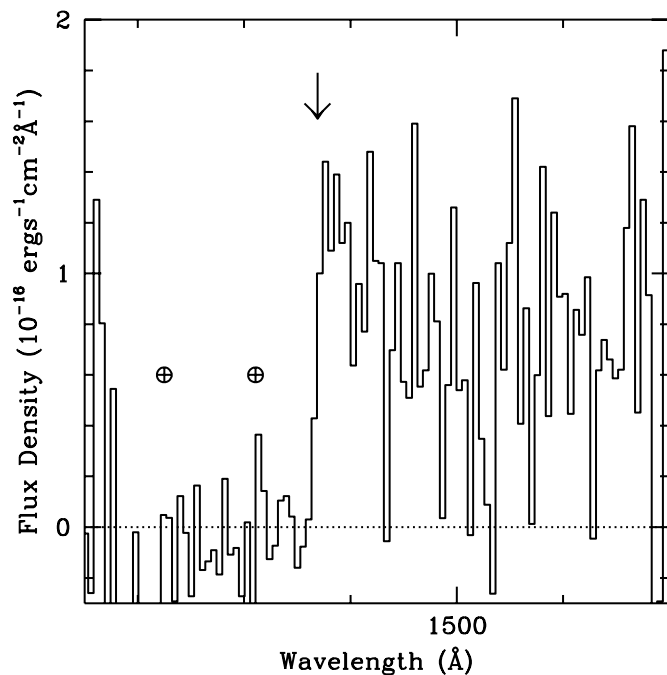


FIG. 3.—*HST*/STIS spectrum of quasar SDSS J2346–0016. The G140L data are binned by nine pixels ( $\sim 5.2$  Å). The He II Ly $\alpha$  absorption edge is near the expected wavelength of 1370 Å. The circled plus signs mark the wavelengths of two strong airglow lines: Ly $\alpha$  and O I  $\lambda$ 1304.

2% probability is based on the expected number of LLSs per redshift interval (Storrie-Lombardi et al. 1994). If this observed break is a LLS, the rest-frame cutoff wavelength is at 920 Å or longer, as a result of the combined effect of high-order Lyman-series lines. Such a system would be at  $z \sim 0.49$ , and a pair of Mg II lines may be expected around 4163.7/4174.4 Å. Between 4160 and 4180 Å there are three absorption lines in the SDSS spectrum: 4180.6 Å (EW  $\sim 2.4$  Å), 4167.3 Å (EW  $\sim 1.5$  Å), and 4161.9 Å (EW  $\sim 4.4$  Å). If any of them is Mg II  $\lambda$ 2803, a counterpart feature is expected approximately at the wavelength 10.5 Å shortward. No such lines are identified within 2 Å at the expected wavelength and within 30% of the expected intensity (50%).

### 3. IMPLICATIONS

The study of He II absorption in this new unobscured quasar sight line (and others extending to similarly high redshifts) will allow significant progress in IGM studies. For example, if helium in the IGM is not fully ionized at  $z = 3.50$ , the high He II opacity would result in a damping profile, which may be detected even at low spectral resolution (Miralda-Escudé 1998). This profile is characterized by a redward wavelength shift of a trough from the expected position of He II Ly $\alpha$  emission, on the order of 2–10 Å. The limited signal-to-noise level of our detection spectrum is insufficient to accurately measure such a feature; future observations with STIS or COS (Cosmic Origins Spectrograph) with significantly longer exposures may establish conclusive evidence. The diagnosis of such a feature may be complicated by the proximity effect (Madau & Rees 2000), and residual infall of matter into the deep potential well of the quasar host galaxy may also give rise to such absorption features (Barkana & Loeb 2002).

However, previous observations of He II absorption in other  $z > 3$  quasars suggest that these effects may not always be present, as high-opacity clouds near the quasar may block the ionizing radiation from the quasar itself (Heap et al. 2000).

Should future observations of this object reveal the proximity effect, the data are useful to estimate the intensity of the metagalactic UV background radiation (Zheng et al. 2003; Miralda-Escudé 1998) and the baryon density of the IGM (Hogan et al. 1997; Anderson et al. 1999). It is known that He II absorption at  $z > 3$  is represented by a high opacity of  $\tau > 3$ . The wavelength baseline between 1050 and 1370 Å in a *HST* spectrum will be the longest to reveal the ionization history of intergalactic helium.

This detection strengthens our confidence in future discoveries of similar features at higher redshifts. Model simulations of the IGM (Møller & Jakobsen 1990) suggest a success rate of approximately 7% in finding a  $z > 3$  quasar whose flux at 300 Å (rest frame) may be detected. This appears to be consistent with our detection rate of 4% (one in 24 objects) and that of a similar program (*HST* GO 8287; one detection in 26 objects). While the lines of sight toward objects at even higher redshifts will encounter more intervening LLSs, these additional systems will not affect the He II detection in a significant manner—they set in at long wavelengths ( $\geq 4100$  Å), and their optical depths recover quickly with  $\tau \propto \lambda^3$ . Therefore, the effect on He II detection at  $z > 3.5$  is determined mainly by the LLSs at  $z < 3.5$ . The large number of SDSS quasars should provide several hundreds of quasars at  $z > 3.5$  that are sufficiently bright for future study. The cases confirmed to be unobscured will be studied with *HST*'s STIS and/or COS with significantly higher sensitivity.

The large span in IGM redshift accessible to He II studies in each such suitable high-redshift quasar will provide critical information on the reionization history of the IGM. The anticipated large sample size will allow assessment of, and averaging over, potential systematic biases that may be present in the current critically small sample, as well as the cosmological inferences obtained therefrom.

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