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The Discovery of a High-redshift Quasar without Emission Lines from Sloan Digital Sky Survey Commissioning Data[1]

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ABSTRACT

We report observations of a luminous unresolved object at redshift $z = 4.62$, with a featureless optical spectrum redward of the Lyman α forest region, discovered from Sloan Digital Sky Survey (SDSS) commissioning data. The redshift is determined by the onset of the Lyman-α forest at $\lambda \sim 6800$ Å, and a Lyman Limit System at $\lambda = 5120$ Å. A strong Lyα absorption system with weak metal absorption lines at $z = 4.58$ is also identified in the spectrum. The object has a continuum absolute magnitude of -26.6 at 1450Å in the rest-frame ($h_0 = 0.5$, $q_0 = 0.5$), and therefore cannot be an ordinary galaxy. It shows no radio emission (the $3\,\sigma$ upper limit of its flux at 6 cm is 60μJy), indicating an radio-to-optical flux ratio at least as small as that of the radio-weakest known BL Lacs. It is also not linearly polarized in the observed I band to a $3\,\sigma$ upper limit of 4%. Therefore, it is either the most distant BL Lac object known to date, with very weak radio emission, or a new type of unbeamed quasar, whose broad emission-line region is very weak or absent.

Subject headings: quasars: individual (SDSS 1533-00) — BL Lacertae objects: individual (SDSS 1533-00) — radio continuum: galaxies — X-rays: galaxies

1. Introduction

The Sloan Digital Sky Survey (SDSS; Gunn & Weinberg 1995; York et al. 1999[19]) is using a dedicated 2.5m telescope at Apache Point Observatory, New Mexico and a wide-field camera with 54 CCDs (Gunn et al. 1998), to obtain CCD images in five broad optical bands (u', g', r', i', z', centered at 3540Å, 4770Å, 6230Å, 7630Å and 9130Å, Fukugita et al. 1996) over 10,000 deg^2 of the high Galactic latitude sky centered approximately on the North Galactic Pole. The multicolor data allow objects of spectral energy distribution distinct from that of stars to be easily selected as outliers from the stellar locus in color-color space. In particular, the SDSS has proven to be a successful source of discoveries of high-redshift quasars, selected by their distinctive colors in the redder filters. Fan (1999) has shown that for redshifts greater than 2, the colors of quasars in the SDSS filter system are a strong function of redshift, as first the Lyman-α forest, and then the Lyman Limit Systems (LLSs), move through the filter system. For redshifts appreciably above 4, quasars are essentially

[19]see also `http://www.astro.princeton.edu/PBOOK/welcome.htm`

invisible in the SDSS u' and g' filters, and thus must be selected from their $r' - i'$ and $i' - z'$ colors. In the redshift range from 3.6 to 5, the distinction between the stellar and quasar loci is quite sharp, and follow-up spectroscopy of early SDSS imaging commissioning data has revealed 40 previously unknown quasars in this redshift range (Fan et al. 1999a, b, Schneider et al. 1999).

Spectroscopic follow-up of outliers from the stellar locus has allowed the discovery of objects other than ordinary quasars. In this paper, we present the discovery of a luminous point source at $z = 4.62$, which in contrast to ordinary quasars, shows no emission lines.

2. Observations

The object SDSSp J153259.96–003944.1 (which we refer to hereafter as SDSS 1533–00 for brevity) was selected from SDSS Photometric Run 77 (observed on 27 June 1998) as a high-redshift quasar candidate. The photometric observations and target selection of this run are described in detail in Fan et al. (1999b). This region of the sky was re-imaged in Run 752 (21 Mar 1999). Photometric calibration for these data was provided by an auxiliary 24″ telescope (now decommissioned) at the same site. The survey data processing software carries out astrometric and photometric calibrations, and finds and measures properties of all detected objects in the data (Pier et al. 1999[20], Lupton et al. 1999[21]).

Table 1 gives the results of the astrometry and photometry in these two observations of SDSS 1533–00. As this table shows, the photometry is consistent between two dates separated by 9 months in the bands in which it was detected at high signal-to-noise ratio. The absolute calibration of the photometry is uncertain at the 5% level, as the primary standard star network had not been completely established when these data were taken; for this reason, we indicate our photometry with asterisks rather than the primes of the final system, although we continue to refer to the filters themselves with the prime notation. A finding chart for SDSS 1533–00 in the i' band is given in Fan et al. (1999b). The object was undetected in u' and g', and has colors $r^* - i^* \sim 1.4$, $i^* - z^* \sim 0.2$, typical for a quasar at $z \sim 4.7$ (see Figure 1 of Fan et al. 1999b).

We obtained optical spectra of SDSS 1533–00 on 13 March 1999 UT using the Double Imaging Spectrograph on the Apache Point 3.5m telescope, with the same instrumental configuration used by Fan et al. (1999a,b). The resolution is 13Å, and the spectral coverage

[20]see also `http://www.astro.princeton.edu/PBOOK/astrom/astrom.htm`

[21]see also `http://www.astro.princeton.edu/PBOOK/datasys/datasys.htm`

is 4000–10,000Å. Observations of the spectrophotometric standard BD +33°2642 (Oke 1990) provided flux calibration and allowed removal of the atmospheric absorption bands. The seeing was about 1.4″ on this photometric night, and the observations were carried out at low airmass. The resulting spectrum, a co-addition of three 30 minute exposures, is shown in Figure 1; this spectrum also appears in Fan et al. (1999b).

The optical spectrum of this object is very unusual; it has no emission lines, and possesses two distinct breaks. The first break is at $\sim$ 6800Å. Redward of this break, the spectrum shows only a smooth power-law-like continuum, with no obvious emission line or strong absorption features. Blueward of this break, it shows numerous strong absorption lines typical of the Lyman α forest region in high-redshift quasars. The second break is at 5120 Å, blueward of which there is no detectable flux. If these two breaks are the onset of Lyman α and a strong LLS respectively, they give a consistent redshift of 4.62. Furthermore, a damped Lyα system candidate at $z = 4.58$ is identified by the strong Lyα and Lyβ and weak Lyγ absorption lines in the spectrum, as indicated in the figure. The redshift determination of SDSS 1533–00 and the nature of the Lyα system is further discussed in §3.

Given the unusual nature of the spectrum, we immediately obtained additional observations. We obtained deep VLA imaging of the field of SDSS 1533–00 on 3 April 1999 in the D array. These observations used two circular polarizations and two 50 MHz IF's at 4860 MHz separated by 50 MHz, for a total effective bandwidth of 100 MHz in two orthogonal polarizations. The total integration time was 72 minutes. The image was CLEANed with a Gaussian restoring beam of $20'' \times 14''$ at PA = 34°. The resulting map has a $1\,\sigma$ noise level of 20μJy per beam; no source is detected above $3\,\sigma$ at the position corresponding to our object. Moreover, this object is also not detected on the ROSAT full-sky pixel images (W. Voges, private communication, Voges et al. 1999), implying a $3\,\sigma$ upper limit of X-ray flux of 3×10^{-13} erg cm^{-2}s^{-1} in the 0.1 – 2.4 keV band.

We obtained optical polarimetric observations of SDSS 1533–00 using the Steward Observatory 2.3m Bok telescope and imaging/spectropolarimeter (Schmidt, Stockman & Smith 1992) on the night of 18 May 1999. The instrument images both polarized beams simultaneously; chopping was done via rotation of a half-waveplate every 60 sec. Our total integration was 3840 sec. The Hoya R72 filter used cuts off at the blue end at $\approx$ 7200Å; the red end of the passband was defined by the CCD sensitivity function, which declines very quickly beyond $\approx$ 8000Å. The seeing on this night varied between 1.0 and 1.5 arcsec. Our final result is a linear polarization of $P = 0.7\% \pm 1.3\%$, after correction for the uncertainty bias in polarization measurements; the uncertainty was estimated from the variance in results from four independent measurements. We conclude that the object is unpolarized to a $3\,\sigma$ upper limit of 4%.

Finally, we obtained higher signal-to-noise ratio (S/N) spectroscopy of SDSS 1533–00 with the Keck II telescope. The object was observed with the Low Resolution Imaging Spectrograph (LRIS, Oke et al. 1995) on the night of 13 May 1999. The resolution was roughly 7Å, and the spectra covered the range from 5100-9000Å. We obtained a 2700 second exposure, under photometric skies and good seeing. The spectrum is shown in Figure 2. The Keck spectrum is consistent with the APO spectrum, with all the spectral features in this wavelength range reproduced.

3. Discussion

3.1. Redshift Determination

The interpretation of object SDSS 1533–00 as a high-redshift object is unambiguous. In addition to the presence of two breaks in the spectrum representing the onset of the Lyman α forest and the LLS absorption, the properties of the absorption lines are consistent with our interpretation. We calculate the flux decrement parameters D_A and D_B (Oke & Korycansky 1982), the average flux depression due to absorption lines in the rest-frame wavelength ranges 1050-1170 Å, and 920–1015Å. We determine the continuum level by fitting a power law for $\lambda > 7200$Å. Assuming $z = 4.62$, we get $D_A = 0.63$ and $D_B = 0.69$, very typical values for objects at similar redshift (e.g., Schneider, Schmidt & Gunn 1991, Storrie-Lombardi et al. 1994, Kennefick, Djorgovski & de Carvalho 1995).

In Figure 2, we examine the property of the Lyα absorption system at $z = 4.58$ in detail, using the Keck spectrum. A Voigt profile with $N_{HI} = 2.5 \times 10^{20}$ cm^{-2} is overplotted on the observed Lyα absorption line. Although the shape of the red wing of the absorption line matches the damped wing of the Voigt profile, the core of the line is wider, and it rises much more steeply than does the Voigt profile. Furthermore, the core of the Lyβ absorption line does not reach zero flux. These facts indicate the absorption system has more complicated velocity structure, rather than being a single damped Lyα absorber. Weak metal absorption lines of Si IIλ 1260.4 and C IIλ 1334.5 are tentatively detected in the spectrum. The Si IV and C IV absorption lines would be in the more noisy part of the spectrum and are not clearly detected. Future observations with higher resolution and S/N are needed to fully understand this absorption system and whether it is physically related to SDSS 1533–00 itself. We also note a broad "emission" feature at ~ 5800 Å in Figures 1 and 2. This wavelength coincides with that of O VIλ 1034 at $z \sim 4.6$, but this may just be a void in the Lyα forest.

Because of the absence of emission lines, determination of the exact redshift of SDSS 1533–00 is not straightforward. The existence of the Lyα absorption system at $z_{\rm abs} = 4.58$

suggests that the intrinsic redshift $z \gtrsim 4.58$. The presence of the LLS at 5120Å indicates $z \gtrsim 4.62$. The number density of LLSs increases with redshift. For quasars at this redshift, the redshift of the LLS is typically within 0.1 of the emission line redshift (Schneider, Schmidt & Gunn 1991, Storrie-Lombardi et al. 1994, Fan et al. 1999a,b). The high S/N Keck spectrum shows no obvious absorption due to Lyman α forest lines beyond 6900 Å, indicating that the redshift is smaller than 4.67. We therefore assign a redshift of 4.62 ± 0.04. A more accurate redshift can be determined if emission lines are detected at infrared wavelengths.

3.2. Could This be a BL Lac Object?

The absolute AB magnitude of SDSS 1533–00 at 1450Å (rest-frame) is $M_{1450} = -26.59$ (for $q_0 = 0.5$, $h_0 = 0.5$, after correcting for Galactic extinction using the reddening map of Schlegel, Finkbeiner, & Davis 1998). Thus, although the S/N of our optical spectrum is probably not high enough to rule out the presence of stellar absorption lines, this object is much too luminous to be an ordinary galaxy. It shows no broad emission lines in its optical spectrum, and therefore is not a typical quasar. A Lyα emission with rest-frame equivalent width of 5Å would be easily detected in our spectrum. For comparison, the typical quasar at $z \sim 4.6$ has a Lyα rest-frame equivalent width of $\sim$ 60Å (e.g., Fan et al. 1999a,b); the lowest equivalent width of Lyα in a high-redshift quasar of which we are aware is PSS 1435+0357 at $z = 4.35$ (Kennefick, Djorgovski & de Carvalho 1995), which has a 10Å line in the rest frame. It is also unlikely that the emission lines are severely affected by the $z = 4.58$ absorption system. Even if the Lyα emission were partly absorbed, the absorption lines associated with Si II and C II are weak, arguing that the effect of the absorption due to C IV and Si IV on any putative emission lines there would be weak.

There is no indication that SDSS 1533–00 is extended beyond the point spread function of the 1.3″ FWHM SDSS image. Thus this object cannot be a normal galaxy amplified by gravitational lensing. Therefore SDSS 1533–00 is either an AGN whose emission lines have been swamped by a relativistically beamed continuum (i.e., a BL Lac or Blazar), or there is simply no broad emission line region at all.

A BL Lac object shows no or very weak emission lines (Urry & Padovani 1995). It is also characterized by strong radio and X-ray emission, optical variability, and strong and variable optical polarization due to the synchrotron radiation from the relativistic jet. No radio-quiet BL Lac has ever been found (Stocke et al. 1990, Jannuzi, Green & French 1993), in the sense that every BL Lac for which mJy level radio data exist has been detected. The highest redshift BL Lac in the literature is at $z < 2$ (Laurent-Muehleisen et al. 1999).

However, other than the absence of optical emission lines, SDSS 1533–00 exhibits none of the properties that define a BL Lac object, although the current observations cannot definitively rule out that it is a BL Lac: (1) it is radio-quiet at low flux level. The $3\,\sigma$ limit at 6 cm is 60 μJy. The i^* magnitude of 19.7 corresponds to a flux of 48 μJy at $\lambda_{\rm eff} = 7600$Å. This implies a radio-optical spectral index in the observed frame $\alpha_{\rm ro} < 0.02$ at $3\,\sigma$. Classical radio-selected BL Lacs have $\alpha_{\rm ro} > 0.3$ (Stocke et al. 1990), and X-ray-selected BL Lacs can have $\alpha_{\rm ro}$ as small as ~ 0.1 (Laurent-Muehleisen et al. 1999). This indicates an radio-to-optical flux ratio of SDSS 1533–00 smaller than that of BL Lacs with the weakest known radio emission. However, the radio K-correction of BL Lacs is completely unknown at this redshift. Therefore, it is still possible that the radio-to-optical flux ratio of SDSS 1533–00 is comparable to that of a low-redshift BL Lac with very weak radio emission. Yet deeper radio imaging is needed to put further constraints on its radio properties. (2) It is not optically polarized (the $3\,\sigma$ limit on its linear polarization is 4%). BL Lacs have maximum linear polarization of order 10%, and the duty cycle for polarization (i.e., the fraction of the time that any given object has a polarization greater than 4%) is 40–60% (Kühr & Schmidt 1990, Jannuzi, Smith & Elston 1994), so it is possible that we have observed it on its off cycle. (3) The photometry of SDSS 1533–00 at two epochs separated by 9 months (1.5 months in the rest-frame of the object) is consistent to within 0.05 mag in r', i' and z' bands. Further long-term monitoring of SDSS 1533–00 is needed to put a stronger constraint on its polarimetric and photometric variability. (4) It is not detected in ROSAT X-ray full-sky images. The optical-X-ray index in the observed frame is $\alpha_{\rm ox} > 1.10$ at $3\,\sigma$ (assuimg an X-ray spectral index $\alpha_{\rm x} = 1$). This lower limit is in the middle of the distribution of $\alpha_{\rm ox}$ in the samples of Stocke et al. (1990), and values of $\alpha_{\rm ox}$ as large as ~ 2 are seen in radio-selected BL Lac samples (e.g. Laurent-Muehleisen et al. 1999). Therefore, the X-ray upper limit is not a strong constraint.

Thus, three interpretations present themselves. First, SDSS 1533–00 could be the most distant BL Lac object known to date. If this is true, it is unusually radio weak, but is likely to show a faint radio counterpart with further observing. It should also show signatures of relativistic beaming such as strong photometric and polarimetric variability. A population of high-redshift BL Lacs has in fact long been speculated by Stocke & Perrenod (1981) and Stocke (1989). Second, it is conceivable that dust simply extincts the broad-line region of a normal quasar in this object, but the continuum slope of this object, as measured from the $i^* - z^*$ color, is comparable to other quasars at a similar redshift (Fan et al. 1999a,b), and thus shows no obvious sign of reddening. Moreover, resonant scattering of the Lyα line to reduce the requirement on the dust column density would not effectively extinct the broad wings of the line. Finally, SDSS 1533–00 could be a new kind of quasar with no or very weak broad emission line region. Such objects are clearly very rare; broad-band color selection of high-redshift objects is not very sensitive to the emission line strength (Fan 1999), yet SDSS 1533–00 is the only quasar without emission lines among the 80 or so $z > 4$ quasars found in multicolor surveys (Schneider 1999, Fan et al. 1999a,b). Further observations, including spectroscopy in the infrared to determine the UV/optical/IR spectral energy distribution of the object and to look for other emission lines, HST imaging to look for extended emission from the object, even deeper radio imaging, deep X-ray observations with XMM or AXAF, and long term optical monitoring for photometric and polarimetric variability will help us to understand the physical nature of SDSS 1533–00.

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Table 1. Optical Positions and SDSS Photometry of SDSS 1533-00

Position (J2000)	u^*	g^*	r^*	i^*	z^*	Date
15:32:59.96 –00:39:44.1	24.60 ± 0.46	23.18 ± 0.27	21.19 ± 0.06	19.73 ± 0.03	19.54 ± 0.11	27 June 1998
15:32:59.93 –00:39:43.9	23.70 ± 0.39	23.81 ± 0.30	21.15 ± 0.05	19.75 ± 0.03	19.57 ± 0.07	21 Mar 1999

Photometry is reported in terms of *asinh magnitudes* on the AB system. The asinh magnitude system is defined in Lupton, Gunn & Szalay (1999); it becomes a linear scale in flux when the absolute value of the signal-to-noise ratio is less than about 5. In this system, zero flux corresponds to 24.24, 24.91, 24.53, 23.89, and 22.47, in u^*, g^*, r^*, i^*, and z^*, respectively; larger magnitudes refer to negative flux values.

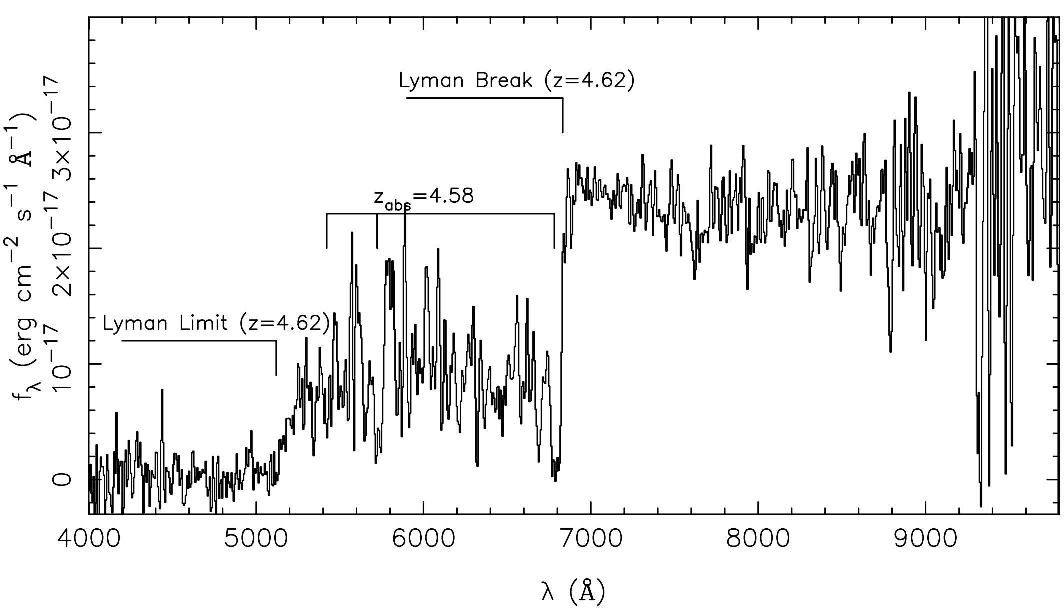

Figure 1. Optical spectrum of SDSS 1533–00 obtained by the DIS spectrograph on the ARC 3.5m telescope. The total exposure time is 5400 sec. The spectral resolution is about 12 Å in the blue and 14 Å in the red. Each pixel represents 6.2 Å. The position of the Lyman break, Lyman limit, and the Lyα, β, and γ lines of an absorption system at $z = 4.58$ are indicated.

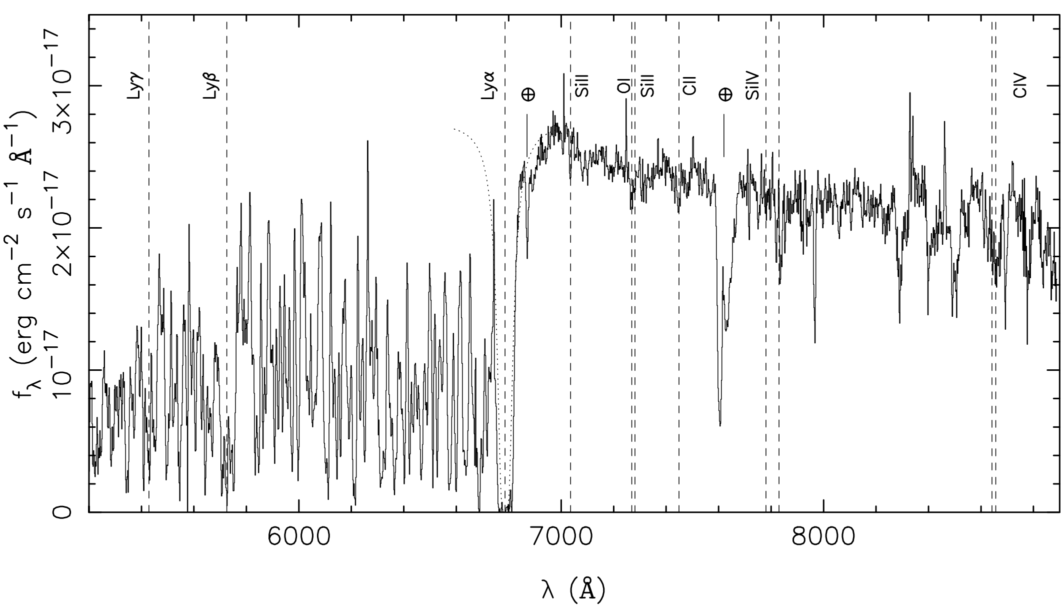

Figure 2. Optical spectrum of SDSS 1533–00 obtained by the LRIS spectrograph on Keck II. The total exposure time is 2700 sec. The spectral resolution is about 7Å, and the dispersion is 1.9Å per pixel. No atmospheric absorption bands were removed from the spectrum. Expected centroids of Lyα, Lyβ, Lyγ and metal absorption lines from the absorption system at $z = 4.58$ are indicated. The wing of the Lyα line is matched by a Voigt profile with $N_{HI} = 2.5 \times 10^{20}$ cm^{-2}.