Discovery of a new high redshift QSO at z=5.96 with the Subaru telescope

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ABSTRACT

We report a discovery of a new high redshift quasar at z = 5.96, observed with the FOCAS long-slit spectrograph on board the Subaru telescope. The spectrum shows strong and broad Ly$\alpha$+NV emission lines with a sharp discontinuity to the blue side. A Ly$\beta$+OVI emission line is also detected, providing a consistent redshift measurement with the Ly$\alpha$+NV emission. The QSO has an absolute magnitude of $M_{AB,1450} = -26.9 \left( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Delta = 0.5 \right)$. The spectrum shows significant flux in the region 8000-8300 Å and thus does not show a complete Gunn-Peterson trough in the redshift range 5.58 to 5.82, along the line of sight to this z = 5.96 QSO. Therefore the Universe was already highly ionized at z = 5.82.

Key words: quasars:individual, cosmology:early universe, black hole physics.

1 INTRODUCTION

High-redshift QSOs are highly important objects in various scientific aspects. They provide direct probes of the epoch when the first generation of galaxies and QSOs formed. The absorption spectra of these QSOs reveal the state of the intergalactic medium (IGM) close to the reionization epoch (Haiman & Loeb 1999; Madan & Rees 2000; Cen & Haiman 2000). The lack of a Gunn-Peterson trough (Gunn & Peterson 1965) in the spectrum of the luminous QSO at $z = 6.43$ (Fan et al. 2003; White et al. 2003; Goto 2004, 2005) indicates that the universe was already highly ionized at that redshift. Assuming that the QSO is radiating at the Eddington luminosity, this object contains a central black hole of several billion solar masses. The assembly of such massive objects in a timescale shorter than 1 gigayear yields constraints on models of the formation of massive black holes (e.g., Haiman & Loeb 2001). The abundance and evolution of such QSOs can provide sensitive tests for models of QSO and galaxy evolution.

The Sloan Digital Sky Survey (SDSS, York et al. 2000) uses a dedicated 2.5m telescope and a large format CCD camera to obtain images in five broad bands (u, g, r, i and z) centred at 3551, 4686, 6166, 7480 and 8932 Å, respectively. Fukugita et al. 1996 over 10,000 deg$^2$ of high Galactic latitude sky. This unprecedented large sky coverage provides us a unique opportunity to find a very rare class of objects such as highest redshift QSOs, passive spiral galaxies (Goto et al. 2003), and E+A galaxies (Goto et al. 2003; Goto 2004, 2005). The inclusion of the reddest band, z, in principle enables the discovery of QSOs up to $z \sim 6.7$ from the SDSS data as a z-band only detection (Fan et al. 2003). In this work, we have used the fourth public data release of the SDSS (Adelman-McCarthy et al. 2006).

Here we report our pilot search for high redshift QSOs with the Subaru telescope and a successful discovery of a new QSO at $z = 5.96$.

2 TARGET SELECTION

Our target selection is similar to that is used by Fan et al. 2000, 2001, 2003. At $z > 5.7$, Ly$\alpha$ emission of QSOs moves out of the i-band and into z-band, the reddest filter of the SDSS, and no flux shall be found in bluer u, g, r, and i-bands. Therefore, we specifically target faint point sources detected only in z-band in the SDSS imaging data ($i_{AB} > 22.0$ and $z_{AB} < 20.7$)$^1$. In addition, we require targets to have $i_{AB} - z_{AB} > 2.2$ to avoid contamination from late-type stars (Strauss et al. 1999; Tsvetanov et al. 2000). Previously, such a target selection successfully found the currently highest redshift QSO at $z = 6.43$ (Fan et al. 2003), and is known to work quite well (Zheng et al. 2000; Fan et al. 2001; Chiu et al. 2005).

For these candidates, we have obtained J-band imaging using one night of the UKIRT and three half nights of the APO3.5m telescope time to further remove contaminations from cosmic-rays and late-type stars. We have selected our targets from the fourth public data release of the SDSS (Adelman-McCarthy et al. 2006, 6670 deg$^2$ in total). In total, 131 candidates were observed in J-band. The $z - J$ colour is a powerful separator of high-$z$ QSOs (blue in $z - J$) from late-type stars (red in $z - J$; Fan et al. 2001).

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$^1$ We express $u, g, r, i$ and $z$ magnitudes in AB system, and $J$ magnitude in Vega system throughout this paper.
Figure 1. The Subaru/FOCAS spectrum of a QSO, SDSSJ084119.52+290504.4, at z=5.96. The spectrum is smoothed using a 10 Å box. Expected locations of various emission lines at $z = 5.96$ are indicated with the dotted line.

Figure 2. The sky-subtracted two-dimensional spectrum of the QSO. The width of the vertical axis is 30 pixel or 9 arcsec. The vertical axis is expanded by 50% for clarity.

since the continuum shape of QSOs is relatively flat toward near infrared, while the flux of late-type stars continues to rise toward longer wavelengths. We only target those candidates whose $z - J$ colour is consistent to be high-$z$ QSOs ($z_{AB} - J_{Vega} \leq 1.7$) for spectroscopic follow-up with the Subaru telescope.

3 OBSERVATION

We have spectroscopically observed 26 candidates that satisfied the criteria in Section 2 with the FOCAS (The Faint Object Camera and Spectrograph, Kashikawa et al. 2002) mounted on the Subaru telescope on the night of February 3rd, 2006. The weather was fine all through the night except for relatively strong wind that blurred the seeing to be $\sim 1.5$ arcsec. We used 300 lines mm$^{-1}$ grating and the 058 order cut filter with 0.8” wide slit, giving a spectroscopic resolution of $R \sim 600$. This setting will give us wavelength coverage of 6000Å to 10000Å. The spatial resolution used was 0.3” pixel$^{-1}$ by 3-pixel, on-chip binning. Data reduction was carried out using the standard IRAF routines. We have used the Ar lamp to calibrate wavelength. We observed standard stars, G191B2B and HZ44, with the 2” slit-width for a flux calibration. Under the condition of 1.5” seeing, we estimate that the slit-loss of the 0.8” slit is 47% compared to the 2” slit assuming the Gaussian PSF, and corrected the flux calibration by this factor. However, we caution readers not to strongly interpret the flux calibration due to the uncertainties from the telescope pointing, tracking, time-variability of the seeing size and so on.
Out of the 26 candidates, we have found one QSO. The rest of the targets were either M or L dwarf stars. We discuss the details of this QSO in the next section.

4 A NEW QSO AT z=5.96

We present the basic information of the QSO in Table 1. We show the observed spectrum in Figure 1. Three exposures of 1200 sec each were combined. The spectrum is smoothed using a 10 Å box. The spectrum shows an unambiguous signature of a high redshift QSO. The broad and strong Lyα+NV emission lines are present at 8465Å with a sharp discontinuity to the blue side due to the strong absorption by neutral hydrogen. The Lyα and NV emission lines are blended. A straight Gaussian fit to the line suggests that this QSO is at $z = 5.96$. The Lyα shows self-absorption at 8478Å. Lyβ+OVI emission lines are detected at 7141Å providing a consistent redshift measurement of $z = 5.96$. This is the 11th highest redshift QSO known to date. The spectrum shows no detectable flux at $\lambda < 6350$Å because of the Lyman limit system. At the redward of the Lyα, there is a slight sign of OI+SiII(λ1302) and SiIV+OIV(λ1400) emissions. They are, however, not clearly detected partly due to the increased noise on the spectrum, and possibly because of the metals are not produced yet at this high redshift. The equivalent width measurement of Lyα+NV line is difficult due to the uncertain continuum level. Using the continuum level determined from the redward of the line, we measured restframe equivalent width of $\sim 58$Å, quite typical of lower redshift QSOs. The measurement of Lyβ+OVI line is difficult as well. We measure restframe equivalent width of $\sim 46$Å. However, these numbers are highly uncertain. The extinction corrected absolute magnitude at 1450Å is $M_{AB,1450} = -26.86$ (We used $H_0 = 50$ and $q_0 = 0.5$ for comparison purpose), assuming that the QSO is not gravitationally magnified. This is a typical luminosity of $z \sim 6$ QSOs (c.f., Fan et al. 2001b). It is important to test the gravitational amplification with a high-resolution imaging (see Shioya et al. 2002). The QSO is not detected in the FIRST radio survey (Becker, White, & Helfand 1995) at the 1mJy level in 20cm. The features around 9300Å are affected by the residuals in background sky subtraction and are not real. There are possible signs of absorption lines at 8810,8946,9509 Å. However, the locations of these lines coincides with strong atmospheric features, and thus, the detection is questionable.

We show the sky-subtracted two-dimensional spectrum in Figure 2. In the spectrum, there remains detectable flux blueward of the Lyα emission ($7300Å < \lambda < 8300$Å). (For example, the fluxes around 8226,8109 and 7612Å are at the relatively clear regions of the spectrum). This suggests that the Gunn-Peterson trough is not complete and the universe is already highly ionized at $z = 5.96$.

5 CONCLUSIONS

We have found a new QSO at $z = 5.96$ from the SDSS data. The object was selected for a spectroscopic follow-up with the Subaru telescope as a $z$-band only detection with blue $z - J$ colour. The broad Lyα+NV emission and the Lyβ+OVI emission provides a consistent redshift measurement of $z = 5.96$, making this the 11th highest redshift QSO to date. The spectrum shows significant flux in the region 8000-8300 Å and thus does not show a complete Gunn-Peterson trough in the redshift range 5.58 to 5.82, along the line of sight to this $z = 5.96$ QSO. Therefore the Universe was already highly ionized at $z = 5.82$. It is an important future work to compute surveyed area and space density of high redshift QSOs once we finish observing all the selected targets.

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REFERENCES

Adelman-McCarthy J. K., et al., 2006, ApJS, 162, 38
Becker R. H., White R. L., Helfand D. J., 1995, ApJ, 450, 559
Cen R., Haiman Z., 2000, ApJ, 542, L75
Chiu K., et al., 2005, AJ, 130, 13
Fan X., et al., 2003, AJ, 125, 1649
Fan X., et al., 2000, AJ, 120, 1167
Fan X., et al., 2001a, AJ, 122, 2833
Fan X., et al., 2001b, AJ, 121, 31
Fukugita M., Ichikawa T., Gunn J. E., Doi M., Shimasaku K., Schneider D. P., 1996, AJ, 111, 1748
Goto T., 2005, MNRAS, 357, 937
Goto T., 2004, A&A, 427, 125
Goto T., et al., 2003, PASJ, 55, 757
Goto T., et al., 2003, PASJ, 55, 771
Gunn J. E., Peterson B. A., 1965, ApJ, 142, 1633
Haiman Z., Loeb A., 1999, ApJ, 519, 479
Haiman Z., Loeb A., 2001, ApJ, 552, 459
Kashikawa N., et al., 2002, PASJ, 54, 819
Madau P., Rees M. J., 2000, ApJ, 542, L69
Shioya Y., et al., 2002, PASJ, 54, 975
Strauss M. A., et al., 1999, ApJ, 522, L61
Tsvetanov Z. I., et al., 2000, ApJ, 531, L61
White R. L., Becker R. H., Fan X., Strauss M. A., 2005, AJ, 129, 2102
White R. L., Becker R. H., Fan X., Strauss M. A., 2003, AJ, 126, 1
York D. G., et al., 2000, AJ, 120, 1579
Zheng W., et al., 2000, AJ, 120, 1607