SIX MORE QUASARS AT REDSHIFT 6 DISCOVERED BY THE CANADA–FRANCE HIGH-\(z\) QUASAR SURVEY

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ABSTRACT

We present imaging and spectroscopic observations for six quasars at \(z \geq 5.9\) discovered by the Canada–France High-\(z\) Quasar Survey (CFHQS). The CFHQS contains subsurveys with a range of flux and area combinations to sample a wide range of quasar luminosities at \(z \sim 6\). The new quasars have luminosities 10–75 times lower than the most luminous Sloan Digital Sky Survey quasars at this redshift. The least luminous quasar, CFHQS J0216–0455 at \(z = 6.01\), has absolute magnitude \(M_{1450} = -22.21\), well below the likely break in the luminosity function. This quasar is not detected in a deep \(XMM-Newton\) survey showing that optical selection is still a very efficient tool for finding high-redshift quasars.

Key words: cosmology: observations – quasars: emission lines – quasars: general

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1. INTRODUCTION

Observations of distant galaxies and quasars give us a direct view of the past because of the finite speed of light. We can now discover these objects at redshifts \(z > 6\), revealing the nature of the universe during the first billion years.

Quasars are particularly useful because their high intrinsic ultraviolet luminosities can be used as a background light source to be absorbed by intervening gas. Studies of quasars out to redshifts of \(z = 6.4\) have put the strongest constraints yet on when the universe was reionized (Fan et al. 2006a). The absence of Gunn–Petersen troughs along most lines of sight (LOS) at \(z < 6\) shows that cosmic reionization was just about complete by \(z = 6\). The high electron scattering optical depth of microwave background photons shows that the first phase of reionization occurred significantly earlier than \(z = 6\) (Dunkley et al. 2008). The reionization history at \(z > 6\) is still quite uncertain. Spectroscopy of quasars at redshifts between \(z = 6\) and \(z = 6.5\) provides the most detailed information currently available on this period (White et al. 2003; Wyithe et al. 2008).

It is now widely believed that the high luminosities of quasars are generated via gravitational potential energy released as matter falls toward supermassive black holes. Reverberation mapping has shown the existence of a relationship between broad emission line velocity, luminosity, and black hole mass which allows black hole masses to be estimated for all quasars (Kaspi et al. 2005; Peterson et al. 2004). Studies of the highest redshift quasars therefore allow inferences on the growth of the most massive black holes in the early universe (Willott et al. 2003; Jiang et al. 2007; Kurk et al. 2007). The black hole masses implied lead to strong constraints on theories for the early growth of supermassive black holes in galaxies (e.g., Volonteri & Rees 2005; Li et al. 2007).

The Canada–France High-\(z\) Quasar Survey (CFHQS) is a survey based on multicolor optical imaging at the Canada–France–Hawaii Telescope (CFHT) to discover quasars at redshifts \(5.8 < z < 6.5\) much less luminous than those discovered by the Sloan Digital Sky Survey (SDSS). The CFHQS quasars are 10–75 times less luminous than the main SDSS sample (Fan et al. 2006b) and 5–25 times less luminous than the SDSS deep stripe sample (Jiang et al. 2008). The range in luminosity is essential for an accurate determination of the quasar luminosity function and for studying lower mass black holes than those powering SDSS quasars. We have previously reported the discovery of four quasars at \(z > 6\) by the CFHQS (Willott et al. 2007; hereafter W07). In this paper, we present the discovery of further six quasars bringing the total of CFHQS quasars at \(z \geq 5.9\) to ten.

All optical and near-infrared (near-IR) magnitudes in this paper are on the AB system. Cosmological parameters of \(H_0 = 70\ \text{km s}^{-1} \text{Mpc}^{-1}\), \(\Omega_M = 0.28\), and \(\Omega_\Lambda = 0.72\) (Komatsu et al. 2008) are assumed throughout.

2. OBSERVATIONS

2.1. Imaging

The six quasars whose discovery we present in this paper were found from several different optical imaging surveys which all form part of the CFHQS. The CFHQS uses several data sets with different magnitude limits to sample a range of quasar luminosities. Because ultracool brown dwarfs are also found from this type of optical imaging, the CFHQS shares imaging data with the Canada–France Brown Dwarf Survey (CFBDS). Further details on the imaging and data processing can be found in W07 and Delorme et al. (2008). A plot showing the sky locations of all the fields observed to the end of 2007 can be found in Delorme et al. (2008). We give here a brief description of each data set.

It is important to note that CFHQS/CFBDS follow-up is still ongoing and there are likely many more quasars to be found in this survey over the next couple of years. For this reason, we defer the discussion of the \(z = 6\) quasar luminosity function to a future publication when there will be some areas of the CFHQS with well defined selection criteria and completeness.
The majority of the sky area in the CFHQS (∼550 deg²) is part of the RCS-2 survey (Yee et al., 2007). These data consist of MegaCam g′r′i′z′ imaging with exposure times in each filter of 240 s, 480 s, 500 s, 360 s, respectively. The RCS-2 data contain four of the quasars presented in this paper, CFHQS J0055+0146, CFHQS J0102−0218, CFHQS J2318−0455, and CFHQS J2329−0403 and three of the quasars presented in W07.

2.1.2. CFHTLS Very Wide

The CFHT Legacy Survey (CFHTLS) Very Wide is the shallowest component of the CFHTLS and covers several hundred square degrees. The CFHQS contains ∼150 deg² of data from the Very Wide. The total exposure times for the Very Wide are comparable to RCS-2 with 540 s at i′ and 420 s at z′. To date only one high-redshift quasar has been discovered in the CFHTLS Very Wide, CFHQS J1509−1749 from W07.

2.1.3. CFHTLS Deep

The CFHTLS Deep is the intermediate depth/area component of the CFHTLS. It consists of 171 deg² at u′g′r′i′z′ with typical MegaCam integration times of 4300 s at i′ and 3600 s at z′. CFHQS J0227−0605, presented in this paper, is the first high-redshift quasar from the CFHTLS Wide.

2.1.4. CFHQS J1509−1749

The CFHQS Deep consists of four MegaCam pointings each of ∼1 deg² at u′g′r′i′z′. Typical final integration times are 250,000 s at i′ and 200,000 s at z′. The negative results of a search for high-redshift quasars in the first release of the Deep (T0001 with ≈20% of the final integration time) were presented.

2.1.1. Red-Sequence Cluster Survey 2 (RCS-2)

The CFHQS consists of four MegaCam pointings each of ∼1 deg² at u′g′r′i′z′ with typical MegaCam integration times of 4300 s at i′ and 3600 s at z′. CFHQS J0227−0605, presented in this paper, is the first high-redshift quasar from the CFHQS Wide.

Notes.
All magnitudes are on the AB system.
* Not detected at >2σ significance, a 2σ lower limit is given.

Table 2
Optical Spectroscopy Observations of the New CFHQS Quasars

| Quasar      | Redshift | Date                  | Resolving Power | Slit Width (arcsec) | Exp. Time (s) | Seeing (arcsec) | M1450 |
|-------------|----------|-----------------------|-----------------|---------------------|---------------|----------------|-------|
| CFHQS J0055+0146 | 6.02     | 2007 Dec 14 + 2008 Jan 05 + 2008 Jan 07 | 1300            | 1.0                 | 5400          | 0.7            | −24.54 |
| CFHQS J0102−0218 | 5.95     | 2007 Dec 08           | 1300            | 1.0                 | 1800          | 0.8            | −24.31 |
| CFHQS J2318−0246 | 6.05     | 2008 Jun 11           | 1300            | 1.0                 | 5400          | 0.8            | −24.83 |
| CFHQS J0102−0218 | 5.95     | 2007 Dec 14 + 2008 Jan 05 + 2008 Jan 07 | 1300            | 1.0                 | 1800          | 0.8            | −24.31 |

Notes.
Absolute magnitudes (M1450) are calculated using the measured J-band magnitudes and assuming a template quasar spectrum. Note that this is slightly different to the method used in W07, which was based on measuring the continuum redward of Ly α in the spectrum and assuming a spectral index.
by Willott et al. (2005). No high-redshift quasars have yet been discovered in the CFHTLS Deep.

2.1.5. Subaru/XMM-Newton Deep Survey (SXDS)

The SXDS is a deep $B V R i' z'$ survey of $\sim 1.2$ deg$^2$ carried out at the Subaru Telescope (Furusawa et al. 2008). With integration times (on the much larger Subaru Telescope) of $\sim 25,000$ s at $i'$ and $13,000$ s at $z'$, these data reach comparable depths to the CFHTLS Deep. Because of its similar depth and similar $i' z'$ filters to the CFHTLS Deep, the SXDS field is combined with the Deep to make up the deepest portion of the CFHQS. CFHQS J0216−0455 which is presented in this paper is located in the SXDS.

2.2. Quasar Selection from Imaging

Candidate quasars are selected from the $i'$ and $z'$ imaging as objects with colors $i' - z' > 2.0$. This is marginally redder than the selection criterion of $i' - z' > 1.7$ used by W07 (but note that all four quasars in W07 have $i' - z' > 2.0$). The new criterion will lower quasar completeness at redshifts $z < 6$, but has little impact on the completeness at higher redshift. The reason for this change in criterion is due to the large number of M dwarfs observed to have $1.7 < i' - z' < 2.0$ due to scattering from the M dwarf locus by photometric errors. Finding all the quasars in this region would be inefficient use of 8 m telescope spectroscopy time.

All candidates with $i' - z' > 2.0$ are observed with pointed observations at the $J$-band (see Delorme et al. 2008 for details). $J$-band data are used to discriminate between high-redshift quasars, which are blue in $z' - J$, and L/T dwarfs, which are red in $z' - J$ (W07; Delorme et al. 2008). Objects lying in the quasar selection region of the $i' z' J$ color–color diagram are selected as quasar candidates for spectroscopy. Figure 1 shows this diagram for the four quasars from W07 and the six new quasars in this paper. Also shown is SDSS J2315−0023, which is a $z = 6.12$ quasar discovered by Jiang et al. (2008) in the SDSS Deep Stripe, which we had identified as a quasar candidate in our CFHQS imaging before it was published by Jiang et al. The quasars are mostly located very close to the redshifted template quasar track.

2.3. Spectroscopy

Optical spectroscopy of candidate quasars was carried out using the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004) at the Gemini South Telescope. These observations led to the discovery of six new high-redshift quasars. Positions and photometry for the quasars are given in Table 1. $20'' \times 20''$ images centered on the quasars are shown in Figure 2. Finding charts in the $z'$-band over a wider field are presented in the Appendix.

GMOS spectroscopy was carried out using the nod-and-shuffle mode. The details of the spectroscopic observations are given in Table 2. The data processing followed an identical method to that described in W07.

The optical spectra of the six quasars are shown in Figure 3. In all cases, there is an unambiguous spectral break close to the Ly $\alpha$ emission line, indicating that the object is a $z \sim 6$ quasar. With the lack of other emission lines in these optical spectra, redshifts for the quasars are estimated using the Ly $\alpha$ lines. The systemic redshift is identified at a location close to the sharp drop on the blue side of broad Ly $\alpha$ or in some cases a narrow Ly $\alpha$ peak, using experience gained from near-IR observations of previous SDSS and CFHQS $z \sim 6$ quasars. Most of these redshifts are uncertain by $\sigma_z \approx 0.03$.

3. NOTES ON INDIVIDUAL QUASARS

3.1. CFHQS J0227−0605

This quasar is the first to be found from the CFHTLS Wide. With $z = 6.20$, it is the second highest redshift quasar in the CFHQS so far and the fifth highest redshift quasar known. It has a fairly strong Ly $\alpha$ emission line. There is an apparent dark region of the intergalactic medium (IGM) at $z \gtrsim 6$, but higher signal-to-noise ratio (S/N) spectroscopy is required...
Figure 3. Optical spectra of the six newly discovered quasars. The expected locations of Ly \( \alpha \), Ly \( \beta \), and Ly \( \gamma \) are marked with dashed lines. All spectra are binned in 10 Å pixels.

to determine whether this region does have a high optical depth.

CFHQS J0227−0605 has the reddest \( z'-J \) color of the CFHQS quasars discovered so far with \( z'-J = 1.25 \). Partially, this is due to its high redshift. The simulations of quasar colors as a function of redshift from Willott et al. (2005) show that \( z'-J \) typically starts increasing at \( z > 6.1 \) due to the dark, IGM-absorbed region of the spectrum entering the \( z' \) filter bandpass. But CFHQS J0227−0605 is 0.5 mag redder than the typical quasar at its redshift. This could be an indication that the quasar continuum is reddened by dust like several other very high redshift quasars (Maiolino et al. 2004; McGreer et al. 2006; Venemans et al. 2007; W07). Future near-IR spectroscopy will test for this. As shown in Figure 1, quasars much redder than CFHQS J0227−0605 could fall outside our selection box. Most such quasars would still be identified by the CFBDS which obtains near-IR spectra for most T dwarfs (L. Albert et al. 2009, in preparation).

3.2. CFHQS J2318−0246

This quasar was not detected at \( i' \) band and has a color limit of \( i'-z' > 2.74 \). The spectrum shows a typical high-redshift quasar at \( z = 6.05 \) with asymmetric Ly \( \alpha \) line and large continuum break across the Ly \( \alpha \) line.
3.3. CFHQS J0055+0146

The colors and spectrum of this \( z = 6.02 \) quasar are typical of \( z \approx 6 \) quasars. It is located only 12" from a very bright (\( i' \approx 14 \)) star and therefore is well suited to a natural guide star adaptive optics study of its host galaxy.

3.4. CFHQS J0216−0455

This object was first identified by McLure et al. (2006) as a potential \( z \approx 6 \) Lyman Break galaxy based on optical and near-IR photometry (their source name: MCD1). However, the fact that it is unresolved in the \( z' \) band (0′/8 FWHM) and is relatively bright at \( z' \), suggested that it was also consistent with being a \( z \approx 6 \) quasar.

The optical spectrum shows a very strong asymmetric emission line and weak continuum on the red side of the line only. It is at a redshift of \( z = 6.01 \). The emission line contributes about 70% of the flux detected in the \( z' \) band. With an absolute magnitude of \( M_{1450} = -22.21 \), this quasar is the least luminous known quasar at \( z > 6 \) by some margin. Although the luminosity function at \( z = 6 \) is not well constrained (Shankar & Mathur 2007), this quasar is likely well below the break magnitude.

Although the emission line is very narrow by quasar standards, a fit to the red side of Ly \( \alpha \) suggests that an intrinsic symmetric Gaussian would have FWHM \( = 1600 \) km s\(^{-1}\) and in addition there is a residual broader component. These velocities are too great to be caused by normal galactic processes and indicate an active nucleus. Note that if CFHQS J0216−0455 is accreting at the Eddington limit, then its low absolute magnitude implies a black hole mass of \( 2 \times 10^5 M_\odot \). Therefore, it is not too surprising to find a relatively narrow emission line in this quasar. However, near-IR spectroscopy of the Mg \( \beta \) line will be required to derive a virial black hole mass.

3.5. CFHQS J0102−0218

This \( z = 5.95 \) quasar is not detected at \( i' \) band due to the relatively poor sensitivity of the \( i' \)-band observation. The color limit of \( i' − z' > 2.09 \) enabled it to be identified as a quasar candidate and the \( z' − J \) color of \( z' − J = 0.26 \) is typical of \( 5.5 < z < 6.1 \) quasars. The spectrum shows a typical Ly \( \alpha \) line and a break in the continuum across the line.

3.6. CFHQS J2329−0403

This is the lowest redshift CFHQS quasar so far at \( z = 5.90 \). The spectrum shows a typical broad asymmetric emission line and continuum break. This quasar should not be confused with CFHQS J2329−0301 at \( z = 6.42 \) presented in W07, which by chance lies only about 1 deg away.

4. MULTIWAVELENGTH DATA

We have searched the NASA/IPAC Extragalactic Database (NED) at the locations of the six new quasars and found no coincident objects from any other survey. Only CFHQS J0227−0605 is located in a region covered by the FIRST radio survey (Becker et al. 1995) and it is not detected to a flux limit of \( \approx 0.5 \) mJy.

CFHQS J0216−0455 is located within the footprint of several deep multicolor surveys. It is not detected at 1.4 GHz by the 100 μJy VLA survey of Simpson et al. (2006). It is also not detected in the deep XMM-Newton survey of Ueda et al. (2008) which reaches a typical flux limit of \( 2 \times 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\) in the 0.5–4.5 keV band corresponding to \( L_{0.5−4.5} < 5 \times 10^{44} \) erg s\(^{-1}\).

This X-ray nondetection is not surprising considering that CFHQS J0216−0455 is a very faint quasar. The typical X-ray luminosity for a quasar with \( M_{1450} = -22.41 \) is only \( L_{0.5−4.5} = 10^{44} \) erg s\(^{-1}\), adopting the luminosity-dependent X-ray-optical relationship of Vignali et al. (2003). CFHQS J0216−0455 is detected by the deep Spitzer UDS survey with AB magnitudes of \( 24.10 \pm 0.25 \) at 3.6 \( \mu \)m and \( 23.18 \pm 0.15 \) at 4.5 \( \mu \)m. The color \( J − 3.6 = 0.1 \) is typical of quasars at this redshift (Jiang et al. 2006). The 3.6–4.5 \( \mu \)m color is redder than all the more luminous quasars studied by Jiang et al. (2006) and may be due to a very high equivalent width H\( \alpha \) line in CFHQS J0216−0455.

5. CONCLUSIONS

We have presented the discovery of six high-redshift quasars from the CFHQS. These quasars span a wide range in luminosity including the lowest luminosity quasar known at \( z > 6 \): CFHQS J0216−0455. Future near-IR spectroscopy will test whether lower-luminosity quasars are powered by lower mass black holes accreting at the Eddington limit.

The CFHQS has now discovered a total of 10 quasars at redshifts \( z \geq 5.9 \). Work is underway to complete follow-up of quasar candidates and determine the completeness of the sample. A future publication will use these quasars to determine the bright-end slope of the \( z = 6 \) quasar luminosity function.

The CFHQS continues to discover quasars at redshifts \( z > 6 \) which allow us to probe the ionization state of the IGM. The discovery spectra presented here are not sensitive enough for these faint quasars to allow an investigation of this issue. We are carrying out higher S/N and higher resolution spectroscopy to probe the IGM along these LOSs.

This study is based on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada–France–Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de l’Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. This work is based in part on data products produced at TERAPIX and the Canadian Astronomy Data Centre as part of the Canada–France–Hawaii Telescope Legacy Survey, a collaborative project of NRC and CNRS. Based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Particle Physics and Astronomy Research Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil), and CONICET (Argentina). This paper uses data from Gemini programs GS-2007A-Q-24 and GS-2007B-Q-15. Based on observations made with the ESO New Technology Telescope at the La Silla Observatory. This work is based in part on data obtained as part of the UKIRT Infrared Deep Sky Survey. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Thanks to Howard Yee and the rest of the RCS2 team for sharing their data and to the queue servers at CFHT and Gemini who obtained data for this project. Thanks to the anonymous referee for comments to improve the manuscript.
APPENDIX
FINDING CHARTS

Figure 4 presents $3' \times 3'$ finding charts for the CFHQS quasars. All images are centered on the quasars and have the same orientation on the sky. These are the CFHT MegaCam or Subaru SuprimeCam $z'$-band images in which the quasars were first identified. MegaCam has gaps between the CCDs and these data were not dithered so the gaps remain and are evident in three images where the quasars lie close to the edge of a CCD. For CFHQS J2318−0246, CFHQS J0055+0146, CFHQS J0102−0218, and CFHQS J2329−0403, the Megacam data are a single exposure leading to many cosmic rays in the final images.

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