NEWLY DISCOVERED $z \sim 5$ QUASARS BASED ON DEEP LEARNING AND BAYESIAN INFORMATION CRITERION

SUHYUN SHIN$^1$, MYUNGSHIN IM$^1$, YONGJUNG KIM$^{2,3}$, AND LINHUA JIANG$^3$

$^1$SNU Astronomy Research Center, Astronomy Program, Dept. of Physics & Astronomy, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea; suhyun.shin.s2@gmail.com, myungshin.im@gmail.com
$^2$Department of Astronomy and Atmospheric Sciences, College of Natural Sciences, Kyungpook National University, Daegu 41566, Republic of Korea
$^3$Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, People’s Republic of China

Abstract: We report the discovery of four quasars with $M_{1450} \gtrsim -25.0$ mag at $z \sim 5$ and supermassive black hole mass measurement for one of the quasars. They were selected as promising high-redshift quasar candidates via deep learning and Bayesian information criterion, which are expected to be effective in discriminating quasars from the late-type stars and high-redshift galaxies. The candidates were observed by the Double Spectrograph on the Palomar 200-inch Hale Telescope. They show clear Lyα breaks at about 7000-8000 Å, indicating they are quasars at $4.7 < z < 5.6$. For HSC J233107-001014, we measure the mass of its supermassive black hole (SMBH) using its CIVA1549 emission line. The SMBH mass and Eddington ratio of the quasar are found to be $\sim 10^9 M_\odot$ and $\sim 0.6$, respectively. This suggests that this quasar possibly harbors a fast growing SMBH near the Eddington limit despite its faintness ($L_{\text{bol}} < 10^{46}$ erg s$^{-1}$). Our 100 % quasar identification rate supports high efficiency of our deep learning and Bayesian information criterion selection method, which can be applied to future surveys to increase high-redshift quasar sample.

Key words: galaxies: active, galaxies: quasars: general, methods: data analysis, methods: observational, techniques: spectroscopic

1. INTRODUCTION

Quasars are one of the most powerful astrophysical sources in the universe with a bolometric luminosity, $L_{\text{bol}} \gtrsim 10^{45}$ erg s$^{-1}$ (e.g., Hickox & Alexander 2018). Owing to their high luminosities, we can find them even in the distant universe ($z > 7$; Mortlock et al. 2011; Bañados et al. 2018; Matsuoka et al. 2019; Yang et al. 2020). The discovery of quasars in the early universe enables us to investigate how the in-tergalactic medium (IGM) was ionized and supermas-sive black holes (SMBHs) grew (e.g., Fan et al. 2006; Akiyama et al. 2018; Matsuoka et al. 2018; McGreer et al. 2018; Kim et al. 2020; Shin et al. 2020). Given the short time available for SMBHs to grow beyond the birth of seed BHs and the age of the universe where the highest redshift known quasars reside, examining the properties of the early universe quasars can give us insights on how the SMBH became to exist (e.g., Bañados et al. 2018; Yang et al. 2020).

Although the expected contribution to the UV background at $z \sim 5$ of quasars with the rest-frame absolute magnitude at 1450 Å ($M_{1450}$) between $-25$ and $-22$ mags are comparable to or greater than that of brighter quasars (Kim et al. 2020), the number of the currently identified faint quasars with $-25 < M_{1450} < -22$ is much less than the number of brighter quasars so far. This is because previous quasar searches have mostly relied on wide-field surveys with shallow depths. The situation is improving with deeper data becoming available for high-redshift quasar search: the Canada–France–Hawaii Telescope Legacy Survey (CFHTLS; Gwyn 2012); the Dark Energy Survey (DES: Dark Energy Survey Collaboration et al. 2016); the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP; Aihara et al. 2019); the Infrared Medium-deep Survey (IMD; M. Im et al. 2022, in preparation).

However, finding faint quasars is more challenging than bright quasar search, even with deeper images. High-redshift quasars can be identified by the strong break in their spectral energy distributions (SEDs) caused by the redshifted Lyman break (Jiang et al. 2016; Jeon et al. 2017; McGreer et al. 2018; Kim et al. 2019; Shin et al. 2020). However, as we go fainter in magnitude, there is a rapid increase in the number of other types of objects, such as primarily late-type stars and high redshift galaxies, which mimic this break. Conventional color selection considering only a few broadband colors is not enough to reject lots of contaminant sources in faint quasar candidates (Matsuoka et al. 2018; Niida et al. 2020, hereafter, N20).

SED model fitting is a physically meaningful approach...
for searching quasars \cite{reed17}. However, it would require a considerable amount of computing resources if one hopes to find faint quasars among many contaminants.

In our previous work \cite{shin22}, we developed a novel method for selecting quasar candidates adopting the deep learning and the Bayesian information criterion (BIC). We applied this method to the HSC-SSP data that reaches a 5-σ depth of $i \sim 26$ mag for point source detection \cite{aihara19} which corresponds to $M_{1450} \sim -20$ mag for $z \sim 5$ quasars. We identified 35 faint quasar candidates, five being previously known quasars.

In this paper, we report our spectroscopic observation of four quasar candidates with $i < 23$ mag as an attempt to further confirm the effectiveness of our new quasar selection method. In Section 2, we describe the photometric selection process for quasars at $z \sim 5$ in brief. The specification for the spectroscopic observation is explained in Section 3. Section 4 includes the spectral fitting procedure and black hole (BH) mass measurement from CIV emission line. The efficiency of our quasar selection is addressed in Section 5. Section 6 summarizes our findings. We assume cosmological parameters $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ throughout the paper. We adopted the AB magnitude system for representing a flux measured in each filter \cite{oke83} and used the dust map of \cite{schlegel98} to correct fluxes for the Galactic extinction.

2. QUASAR SELECTION

Faint quasar candidates at $z \sim 5$ were selected in our previous work \cite{shin22}. Here, we briefly explain how the quasar candidates were selected.

2.1. Photometric data

The HSC-SSP has Wide, Deep, and UltraDeep layers. Taking advantage of deep images ($i \sim 26$ mag) and moderate survey area (27 deg$^2$), we choose the Deep layer to search quasars among the layers. The Deep layer consists of four fields covered by five broadbands ($g,r,i,z,y$) and two narrow-bands ($NB_816, NB_921$). The 5-σ image depths of broadbands ($g,r,i,z,y$) are (27.3, 26.9, 26.7, 26.3, and 25.3). For $NB_816$ and $NB_921$, the depths are 26.1 and 25.9 mag, respectively.

We retrieved a source catalog of the public data release (PDR2) of the HSC-SSP. To exclude objects with unreliable photometry, we adopted flags evaluating influences from the bad pixel, cosmic ray, saturation at the center of an object, abnormal background level, and the location of an object on an image. Also, we constrained that a source should be a primary object with detection in the $i$-band. After excluding the flagged objects, the resulting effective survey area of the Deep layer for our quasar search became $\sim 15.5$ deg$^2$ based on a random source catalog in HSC-SSP data archival system \cite{convon13}, somewhat smaller than the nominal HSC-SSP Deep survey area of 27 deg$^2$. The number of sources in the catalog is 3.5 million. In this study, we use two magnitude systems: the point-spread function (PSF) magnitude and the CModel magnitude (CModel).

2.2. SED models

Due to the small sample size of spectroscopically confirmed quasars at $z \sim 5$ in the Deep layer of the HSC-SSP (< 10), quasar SED models were used for training deep learning models and calculating BIC. Stellar SED models are also necessary to do SED fitting. Since these SED models were introduced in detail in \cite{shin22}, we explained them in brief.

Our quasar SED models have four free parameters: redshift ($z_{\text{SED}}$), continuum slope ($\alpha_{\lambda}$), equivalent width of Lyo and N V $\lambda 1240$ (EW), and $M_{1450}$. We created a composite SED by adopting the SED at $\lambda < 1450$ Å from \cite{lusso15} and the redder part from \cite{selsing16}. Then, the Lyo+N V equivalent width and the continuum slopes are adjusted. The IGM attenuation model of \cite{inoue14} was adopted.

For the stellar SED models, we used the BT-Settl models \cite{allard13} which have five free parameters: effective temperature ($T_{\text{eff}}$), surface gravity ($\log(g)$), metallicity ($[M/H]$), alpha-element enrichment ($[\alpha/M]$), and a normalization factor ($f_N$).

2.3. Quasar selection process

We applied multiple criteria sequentially. Figure 1 shows the sequence of our selection.

First, we selected objects with $19 < i_{\text{PSF}} < 25$ and magnitude error < 0.2 mag (the process (1)). Then, we...
The magnitude errors are mostly less than 0.03 mag.

eliminated extended sources by applying the extendedness cut of $i_{PSF} - i_{Model} < 0.2$ (the process (2)). With this procedure, we could include about 98.4 % of point sources identified by an $I$-band catalog of the Hubble Space Telescope (HST) Advanced Camera for Surveys (Leauthaud et al. 2007). The number of candidates satisfying the process (1) and (2) was 333,780. Among them, there are six spectroscopically confirmed quasars at $4.5 < z < 5.5$ (McGreer et al. 2013; Pâris et al. 2018; Shin et al. 2020).

Since faint quasars at $z \sim 5$ have the strong IGM absorption lines in the blueward of the Lyα emission line, they tend to show a weak signal to noise ratio (SNR < 3) in the $g$-band or large $g - r$ color. To focus on the quasars at $4.5 < z < 5.5$, we limited the $g - r$ color to 0.987, which is the minimum $g - r$ value for quasar models at the redshift range. The number of candidates was 125,644.

After choosing the red objects, we performed classification using deep learning. We trained 100 models to predict a class of an object based on its HSC-SSP photometry information. Our trained models assume that the red objects belong to one of two classes: quasars at $z \sim 5$ (‘qso’) or non-quasar sources (‘nqso’). Training set for the ‘qso’ comprised of 100,000 randomly sampled quasar models at $4.5 < z < 5.5$. For training ‘nqso’ class, 100,000 randomly sampled point sources with $19 < i < 25$ and $\sigma_i < 0.2$ were used. Combining results of 100 deep learning models, we achieved an average accuracy larger than 99 % for the ‘qso’ class. 1,599 candidates were selected in our ensemble learning.

To compensate for the simple approximation used in the deep learning and deal with possible misclassified ‘nqso’ objects, we carried out SED fitting of 1,599 deep-learning-selected candidates using quasar and stellar SED models and compare the best-fit models by adopting the BIC. For each best-fit model, the BIC value can be calculated as,

$$\text{BIC} = \chi^2 + k \times \ln n,$$

where $k$ is the number of free parameters in the model, $n$ is the number of the data, and $\chi^2$ is the chi-square value for the model. The BIC imposes the penalty term to the model with a large $k$, so a fair comparison between given models becomes possible. The difference between the BIC values, $\Delta \text{BIC}$, is defined as

$$\Delta \text{BIC} = \text{BIC}_{\text{qso}} - \text{BIC}_{\text{quasar}}.$$

The larger $\Delta \text{BIC}$ is, the more likely it is a quasar. We considered the minimum value of the $\Delta \text{BIC}$ as 10 (Liddle 2007). The number of the BIC-selected candidates was 78.

We visually inspected multi-band HSC-SSP images to remove candidates for which the photometry could be affected by satellite tracks, nearby bright stars, optical ghosts, and scattered lights. Among the 78 BIC-selected candidates, 53 candidates passed the visual inspection.

Finally, we restricted the $M_{1450}$ of the candidate to be brighter than $-22.0$ mag where the number density of quasar candidates can dramatically increase due to the galaxy contamination (N20 Shin et al. 2022, accepted). The number of the final quasar candidates is 35. Five out of 35 candidates are known quasars at $z \sim 5$ (McGreer et al. 2013; Shin et al. 2020). Another four candidates were selected to be promising candidates selected in McGreer et al. (2018), Chaves-Montero et al. (2017) and Shin et al. (2020). Among these four candidates, a spectrum of one candidate (Shin et al. 2020) was obtained in this study.



## 3. Spectroscopy

We conducted spectroscopic observations for four candidates with $i_{PSF} < 23$ mag between 2020 November and 2021 July. Note that one of the targets, IMS J161827+551748 was also selected using a different selection method that included medium-band data (Shin et al. 2020). We utilized the Double Spectrograph (DBSP) on the 200-inch Hale Telescope in the Palomar Observatory (PID: CTAP2020-B0043 and CTAP2021-A0032, PI: Y.Kim). Using the dichroic filter, the DBSP can observe the red and blue channels simultaneously. The dichroic filter we used was D55. We set a long-slit mode with a slit of which the width and length correspond to 1.5 and 128 arcseconds. The 316 (600) lines/mm grating with a wavelength of 7500 (4000) Å was chosen for the red (blue) channel. The exposure time was $\sim 1200$ to 1800 seconds. The typical seeing during the observing period was $\sim 1.1$ to 1.5 arcseconds.

After acquiring the spectroscopic data, we preprocessed the data with a python package, PypeIt (Prochaska et al. 2020). Owing to the expected IGM absorption in the blue channel, we only considered the red channel in this study. The PypeIt can automatically subtract bias, perform flat-fielding, give a wavelength solution, and model the sky background. To do wavelength calibration, we used a HeNeAr lamp. Since

### Table 1

General information of the targets and spectroscopic observations

| ra (J2000) | dec (J2000) | $g$ [mag] | $r$ [mag] | $i$ [mag] | $NB816$ [mag] | $z$ [mag] | $NB921$ [mag] | $y$ [mag] | Date         | ExpTime [sec] |
|-----------|------------|----------|----------|----------|--------------|---------|--------------|---------|--------------|--------------|
| 02:17:33:44 | -4:44:44:32 | 25.7     | 23.7     | 22.2     | 22.4         | 22.1    | 22.1         | 22.3    | 2020 Nov 19  | 1500          |
| 16:18:27:28 | 55:17:48:51 | 25.3     | 22.7     | 21.1     | 21.1         | 20.9    | 20.9         | 20.8    | 2021 Jul 13  | 600           |
| 23:27:13:22 | 0:05:47:92  | > 27.3   | 25.1     | 22.3     | 21.3         | 22.0    | 21.7         | 21.8    | 2020 Nov 19  | 1800          |
| 23:31:07:00 | -0:10:14:52 | > 27.3   | 24.4     | 22.6     | 23.2         | 22.6    | 21.8         | 22.7    | 2020 Nov 19  | 1800          |

| ra (J2000) | dec (J2000) | $g$ [mag] | $r$ [mag] | $i$ [mag] | $NB816$ [mag] | $z$ [mag] | $NB921$ [mag] | $y$ [mag] | Date         | ExpTime [sec] |
|-----------|------------|----------|----------|----------|--------------|---------|--------------|---------|--------------|--------------|
| 02:17:33:44 | -4:44:44:32 | 25.7     | 23.7     | 22.2     | 22.4         | 22.1    | 22.1         | 22.3    | 2020 Nov 19  | 1500          |
| 16:18:27:28 | 55:17:48:51 | 25.3     | 22.7     | 21.1     | 21.1         | 20.9    | 20.9         | 20.8    | 2021 Jul 13  | 600           |
| 23:27:13:22 | 0:05:47:92  | > 27.3   | 25.1     | 22.3     | 21.3         | 22.0    | 21.7         | 21.8    | 2020 Nov 19  | 1800          |
| 23:31:07:00 | -0:10:14:52 | > 27.3   | 24.4     | 22.6     | 23.2         | 22.6    | 21.8         | 22.7    | 2020 Nov 19  | 1800          |
our targets are too faint to be detected with a default algorithm, we manually extracted the fluxes of a standard star and the targets. We adjusted the spatial and spectral locations of the extraction window and its size to maximize the signal-to-noise ratio of each spectrum. After reducing the data, we calculated a sensitivity function by comparing the observed fluxes of a standard star, Feige110, with its actual fluxes. After the sensitivity correction, we rescaled the spectrum using HSC-SSP i-band magnitude to correct for a possible flux loss due to the finite size of the slit width.

From the full width at half maximum (FWHM) of sky emission lines, we estimated a spectral resolution, $R = 800 - 1300$, which varied depending on the observed wavelength and the observation date. Table 1 shows the coordinate, HSC-SSP photometry, observation date, and exposure time for the candidates.

4. Result

4.1. Spectral fitting

To increase the SNR of each spectrum, the spectrum was binned at intervals of $6 \sim 9$ Å ($5 \sim 6$ pixels), corresponding to FWHM from its $R$. Each flux in each bin was weighted by the inverse of its squared flux uncertainty. The weighted mean flux is calculated to be a representative value of each bin. After binning, the SNRs of the spectra reach 5 to 15 at their emission lines, and 2 to 3 at their continua. Figure 2 shows the binning spectra of the four objects. All four objects show predominant and broad Lyα emission lines with sufficient SNR $\sim 10$ and sharp breaks at the blueward of the line due to the IGM absorption, confirming their nature as high-redshift quasars.

To estimate the spectroscopic redshift ($z_{\text{spec}}$), we performed a spectrum fitting based on quasar SED models to the binned spectra (please refer to Section 2.2). The best-fit model was obtained by using Markov Chain Monte Carlo (MCMC) method [Foreman-Mackey et al. 2013]. From the sampled posterior distribution of the parameter, we obtained the best-fit parameter and its error as the median and the 68% equal-tailed interval of the distribution (Table 2). Due to the low SNR of the continuum, the uncertainties of the parameters are somewhat large except for $z_{\text{spec}}$, implying the role of the clear Lyα emission line in constraining the $z_{\text{spec}}$. These quasars have $M_{1450} = -23.0$ to $-25.2$ mag at $z_{\text{spec}} = 4.7$ to 5.6.

In addition to the best-fit $z_{\text{spec}}$, we calculated the $z_{\text{Ly}α}$ by comparing the location of the strongest point in the Lyα emission line to the rest wavelength of the line (1216 Å). Although the blueward of the Lyα emission line was attenuated by the neutral hydrogen in the IGM, the $z_{\text{Ly}α}$ is still consistent with the locations of the strong emission lines such as Lyβ and C IV, especially for HSC J233107-001014. The $z_{\text{Ly}α}$ values are also provided in Table 2.

4.2. BH mass and Eddington ratio

One interesting question is whether high-redshift quasars are more vigorously growing than lower-redshift quasars [Willott et al. 2010; Kim et al. 2018; Onoue et al. 2019; Shen et al. 2019]. Recent studies of quasars at $z \geq 6$ have found that SMBHs in the bright quasars are vigorously growing with the Eddington ratios ($\lambda_{\text{Edd}}$) of $\lambda_{\text{Edd}} \sim 1$ [Mortlock et al. 2011; Bañados et al. 2018].

| id            | $z_{\text{Ly}α}$ | $z_{\text{spec}}$ | $\alpha_λ$ | log($E/W$) | $M_{1450}$ [mag] |
|---------------|------------------|------------------|------------|------------|-----------------|
| HSC J021733-044444 | 4.07 | 4.783$^{+0.003}_{-0.003}$ | -1.58$^{+0.37}_{-0.37}$ | 2.38$^{+0.05}_{-0.05}$ | -23.88$^{+0.06}_{-0.06}$ |
| HSC J161827+551748  | 4.75 | 4.726$^{+0.005}_{-0.005}$ | -1.94$^{+0.52}_{-0.52}$ | 2.41$^{+0.12}_{-0.12}$ | -25.13$^{+0.06}_{-0.06}$ |
| HSC J232713+000547  | 5.59 | 5.561$^{+0.008}_{-0.008}$ | -1.40$^{+0.32}_{-0.32}$ | 2.51$^{+0.16}_{-0.16}$ | -24.44$^{+0.16}_{-0.16}$ |
| HSC J233107-001014  | 4.97 | 4.950$^{+0.004}_{-0.004}$ | -0.58$^{+0.56}_{-0.56}$ | 2.62$^{+0.10}_{-0.10}$ | -23.03$^{+0.16}_{-0.16}$ |
Figure 3. Spectral modeling for the CIV emission line. We plot the binned spectrum of HSC J233107-001014 in the gray bar. The thick line indicates the best-fit model which is the summation of the power-law continuum and CIV emission line modeled as a single Gaussian distribution. The former and latter is plotted in the dot-dashed line and the dashed line, respectively.

Figure 4. 

The mass scaling relation based on the C IV line (Vestergaard & Peterson 2006) is expressed as,

\[ M_{\text{BH}} = \left( \frac{\text{FWHM}_{\text{CIV}}}{1000 \text{ km s}^{-1}} \right)^2 \left( \frac{\lambda L(1350 \ \text{Å})}{10^{44} \text{ erg s}^{-1}} \right)^{0.53} \times 10^{6.6} M_\odot. \]  

(3) 

\[ L(1350 \ \text{Å}) \] is calculated from the best-fit SED model for the spectrum of HSC J233107-001014. The resulting log \( (M_{\text{BH}}/M_\odot) \) is \( 7.92^{+0.62}_{-0.27} \) for the virial factor of 5.1 (Woo et al. 2013).

We caution that C IV-based \( M_{\text{BH}} \) could be systematically biased than the Balmer line-based \( M_{\text{BH}} \), since the C IV line profile could be seriously affected by non-virial motion (e.g., Sulentic et al. 2017). To correct for systematic bias, some studies have considered the relation between physical parameters (e.g., C IV blueshift, Eddington ratio, C IV line asymmetry, and so on) and the difference between C IV-based and Balmer-based BH masses (Coatman et al. 2017; Marziani et al. 2019; Zuo et al. 2020). Although the corrected FWHM_{CIV} based on the relations could improve the \( M_{\text{BH}} \) estimates, we did not apply the correction due to large uncertainties in the physical parameters caused by the low SNR of the spectra.

Using the bolometric correction derived in (Rummel et al. 2012), which is considered the former only due to the lack of sensitivity in its overall spectrum and an insignificant influence of the Fe II emissions on the C IV line properties (e.g., Shen et al. 2011). We fitted the power-law continuum to the fluxes of which the wavelength range is not close to those of the broad emission lines (e.g., Lya, C IV). To prevent large uncertainty of \( \alpha_\lambda \) caused by poor SNR \( \sim 1 - 3 \) of the binned spectrum, it was inevitable to use global parts of the spectrum corresponding to \( \lambda = 1260 - 1510 \) and \( 1580 - 1660 \), and assume \( \zeta = 1 \). The fitted power-law continuum was subtracted from the spectrum.
The confirmation of 4 new quasars brings the total number of spectroscopically confirmed quasars to 9 among 35 candidates. None of the candidates have been shown to be non-quasars so far, suggesting a very high confirmation rate. In addition, there is one quasar candidate with medium-band data, which can be almost certain to be a quasar (Shin et al. 2020).

To quantitatively evaluate the effectiveness of our selection, we compare it to the traditional color selection of N20. We checked whether the 35 final candidates can be selected by N20 selection. It misses 16/35 (~46%) of the final candidates. Figure 5 shows redshift histograms of the final candidates and the final candidates that meet N20 selection. Since the N20 selection has a high completeness value only when searching for quasars at 4.7 < z < 5.1, it is difficult to select quasars at z < 4.7 or z > 5.1. However, our selection method can find quasar candidates at a broader redshift range than the N20 selection does, allowing us to increase the number of quasar sample at z ~ 5.

We also calculate the recovery rate of known quasars at 4.5 < z < 5.5. Our selection process recovers 5/6 known quasars and 4/4 newly discovered quasars (= 9/10, ~90%). We find that one quasar that has been missed is in the parameter space where the completeness is low (see Shin et al. 2022, accepted), suggesting that our quasar recovery rate is as high as expected. To firmly confirm the effectiveness of our selection, spectroscopic observations for the 26 remaining candidates is required.

6. SUMMARY

We performed spectroscopic observations for four candidates with $M_{1450} \gtrsim -25.0$ mag at z ~ 5 utilizing the DBSP on the 200-inch Hale Telescope in the Palomar observatory. The candidates were selected by deep learning and Bayesian information criterion (Shin et al. 2022, accepted). Each candidate has a strong Lyα emission line and clear break near the line in its spectrum, suggesting all the candidates are quasars at z ~ 5. 4/4 spectroscopic confirmation rate implies the validity of our novel selection approach. Our selection method provides a possible way for efficiently selecting high-redshift quasars at unbiased redshift ranges from future surveys.

Since HSC J233107-001014 has a strong C IV emission line as well among the quasars, we calculated the marginal BH mass for the quasar, resulting in $10^8 M_\odot$. The $\lambda_{Edd}$ of the quasar is ~0.6, although most quasars with a similar luminosity ($L_{\text{bol}} \sim 10^{46}$ erg s$^{-1}$) to the quasar have lower Eddington ratios. To better understand the early growth of SMBHs, more faint quasars with $L_{\text{bol}} \lesssim 10^{46}$ erg s$^{-1}$ should be investigated.

ACKNOWLEDGMENTS

This research was supported by the National Research Foundation of Korea (NRF) grants No. 2020R1A2C3011091 and No. 2021M3F7A1084525, funded by the Ministry of Science and ICT (MSIT). S. S. acknowledges the support from the Basic Science Research Program through the NRF funded by the Ministry of Education (No. 2020R1A6A3A13069198). Y. K. was supported by the NRF grant funded by
the MSIT (No. 2021R1C1C2091550). He acknowledges the support from the China Postdoc Science General (2020M670022) and Special (2020T130018) Grants funded by the China Postdoctoral Science Foundation. This research uses data obtained through the Telescope Access Program (TAP) (PID: CTAP2020-B0043 and CTAP2021-A0032), which has been funded by the National Astronomical Observatories of China, the Chinese Academy of Sciences, and the Special Fund for Astronomy from the Ministry of Finance. Observations obtained with the Hale Telescope at Palomar Observatory were obtained as part of an agreement between the National Astronomical Observations, Chinese Academy of Sciences, and the California Institute of Technology.

The Hyper Suprime-Cam (HSC) collaboration includes the astronomical communities of Japan and Taiwan, and Princeton University. The HSC instrument and software were developed by the National Astronomical Observatory of Japan (NAOJ), the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), the University of Tokyo, the High Energy Accelerator Research Organization (KEK), the Academia Sinica Institute for Astronomy and Astrophysics in Taiwan (ASIAA), and Princeton University. Funding was contributed by the FIRST program from the Japanese Cabinet Office, the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), the Japan Society for the Promotion of Science (JSPS), Japan Science and Technology Agency (JST), the Toray Science Foundation, NAOJ, Kavli IPMU, KEK, ASIAA, and Princeton University.

This paper makes use of software developed for the Large Synoptic Survey Telescope. We thank the LSST Project for making their code available as free software at http://dm.lsst.org.

This paper is based on data collected at the Subaru Telescope and retrieved from the HSC data archive system, which is operated by the Subaru Telescope and Astronomy Data Center (ADC) at National Astronomical Observatory of Japan. Data analysis was in part carried out with the cooperation of Center for Computational Astrophysics (CICA), National Astronomical Observatory of Japan. The Subaru Telescope is honored and grateful for the opportunity of observing the Universe from Maunakea, which has the cultural, historical, and natural significance in Hawaii.

REFERENCES

Aihara, H., AlSayyad, Y., Ando, M., et al. 2019, Second data release of the Hyper Suprime-Cam Subaru Strategic Program, PASJ, 71, 114.

Akiyama, M., He, W., Ikeda, H., et al. 2018, The quasar luminosity function at redshift 4 with the Hyper Suprime-Cam Wide Survey, PASJ, 70, S34.

Allard, F., Homeier, D., Freytag, B., et al. 2013, Progress in modeling very low mass stars, brown dwarfs, and planetary mass objects, Memorie della Societa Astronomica Italiana Supplementi, 24, 128.

Bañados, E., Venemans, B. P., Mazzucchelli, C., et al. 2018, An 800-million-solar-mass black hole in a significantly neutral Universe at a redshift of 7.5, Nature, 553, 473.

Chaves-Montero, J., Bonoli, S., Salvato, M., et al. 2017, ELDAR, a new method to identify AGN in multi-filter surveys: the ALHAMBRA test case, MNRAS, 472, 2085.

Coatman, L., Hewett, P. C., Banerji, M., et al. 2017, Correcting C IV-based virial black hole masses, MNRAS, 465, 2120.

Couzon, J., Czakon, N., Bosch, J., et al. 2018, The bright-star marks for the HSC-SSP survey, PASJ, 70, S7.

Dark Energy Survey Collaboration, Abbott, T., Abdalla, F. B., et al. 2016, The Dark Energy Survey: more than dark energy - an overview, MNRAS, 460, 1270.

De Rosa, G., Decarli, R., Walter, F., et al. 2011, Evidence for Non-evolving Fe II/Mg II Ratios in Rapidly Accreting z ~ 6 QSOs, ApJ, 739, 56.

Fan, X., Strauss, M. A., Richards, G. T., et al. 2006, Constraining the Evolution of the Ionizing Background and the Epoch of Reionization with z ~ 6 Quasars. II. A Sample of 19 Quasars, AJ, 131, 1203.

Foreman-Mackey, D., Hong, S. W., Lang, D., et al. 2013, emcee: The MCMC Hammer, PASP, 125, 306.

Greene, J. E., Strader, J., & Ho, L. C. 2020, Intermediate-Mass Black Holes, ARA&A, 58, 257.

Gwyn, S. D. J. 2012, The Canada-France-Hawaii Legacy Survey: Stacked Images and Catalogs, AJ, 143, 38.

Hickox, R. C. & Alexander, D. M. 2018, Obscured Active Galactic Nuclei, ARA&A, 56, 625.

Ikeda, H., Nagao, T., Matsuoka, K., et al. 2017, An Optically Faint Quasar Survey at z ~ 5 in the CFHTLS Wide Field: Estimates of the Black Hole Masses and Eddington Ratios, ApJ, 846, 57.

Inoue, A. K., Shimizu, I., Ita, H., et al. 2014, An updated analytic model for attenuation by the intergalactic medium, MNRAS, 442, 1805.

Jeon, Y., Im, M., Kim, D., et al. The Infrared Medium-deep Survey. III. Survey of Luminous Quasars at 4.7 ≤ z ≤ 5.4, 2017, ApJS, 231, 16.

Jiang, L., Fan, X., Vestergaard, M., et al. 2007, Gemini Near-Infrared Spectroscopy of Luminous z ∼ 6 Quasars: Chemical Abundances, Black Hole Masses, and Mg II Absorption, AJ, 134, 1150.

Jiang, L., McGreer, I. D., Fan, X., et al. 2016, The Final SDSS High-redshift Quasar Sample of 52 Quasars at z > 5.7, ApJ, 833, 222.

Jun, H. D., Im, M., Lee, H. M., et al. 2015, Rest-frame Optical Spectra and Black Hole Masses of 3 < z < 6 Quasars, ApJ, 806, 109.

Kaiser, N., Burgett, W., Chambers, K., et al. 2010, The Pan-STARRS wide-field optical/NIR imaging survey, Proceedings of the SPIE, 7733, 77330E.

Kim, Y., Im, M., Jeon, Y., et al. 2018, The Infrared Medium-deep Survey. IV. The Low Eddington Ratio of A Faint Quasar at z ∼ 6: Not Every Supermassive Black Hole is Growing Fast in the Early Universe, ApJ, 855, 138.

Kim, Y., Im, M., Jeon, Y., et al. 2019, The Infrared Medium-deep Survey. VI. Discovery of Faint Quasars at z ~ 5 with a Medium-band-based Approach, ApJ, 870, 86.

Kim, Y., Im, M., Jeon, Y., et al. 2020, The Infrared Medium-deep Survey. VIII. Quasar Luminosity Function at z ~ 5, ApJ, 904, 111.

Leauthaud, A., Massey, R., Kneib, J.-P., et al. 2007, Weak Gravitational Lensing with COSMOS: Galaxy Selection and Shape Measurements, ApJS, 172, 219.
