The Infrared Medium-deep Survey. IX. Discovery of Two New $z \sim 6$ Quasars and Space Density Down to $M_{1450} \sim −23.5$ mag

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Abstract

We present the result of the Infrared Medium-deep Survey (IMS) $z \sim 6$ quasar survey, using the combination of the IMS near-infrared images and the Canada–France–Hawaii Telescope Legacy Survey optical images. The traditional color selection method results in 25 quasar candidates over 86 deg$^2$. We introduce the corrected Akaike information criterion (AICc) with the high-redshift quasar and late-type star models to prioritize the candidates efficiently. Among the color-selected candidates, seven plausible candidates finally passed the AICc selection, of which three are known quasars at $z \sim 6$. The follow-up spectroscopic observations for the remaining four candidates were carried out, and we confirmed that two out of four are $z \sim 6$ quasars. With this complete sample, we revisited the quasar space density at $z \sim 6$ down to $M_{1450} \sim −23.5$ mag. This result supports the low quasar space density at the luminosity where the quasar’s ultraviolet ionizing emissivity peaks, favoring a minor contribution of quasars to the cosmic reionization.

Unified Astronomy Thesaurus concepts: Quasars (1319); Active galactic nuclei (16); Reionization (1383); Early universe (435); Sky surveys (1464); Observational astronomy (1145)

1. Introduction

As to which objects produced a large amount of ultraviolet (UV) photons that could rapidly ionize the neutral hydrogen in the high-redshift universe ($z \gtrsim 6$; McGreer et al. 2015), the role of high-redshift active galactic nuclei (AGNs) has been under debate. The bright and faint populations have been studied by wide-shallow surveys such as the Sloan Digital Sky Survey (SDSS; Fan et al. 2001, 2006; Jiang et al. 2008, 2009, 2015, 2016; Yang et al. 2019) and narrow-deep surveys like the Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS; Giulalongo et al. 2015; Parsa et al. 2018; Giulalongo et al. 2019; Grazian et al. 2020), respectively. These surveys, however, have not provided a consensus on the number density of intermediate-luminosity AGNs with $M_{1450} \sim −23$ mag (or faint quasars), which make a major contribution to the quasar UV ionizing emissivity (Kim et al. 2020).

In the past decade, there have been various attempts to fill the deficiency of the observed high-redshift faint quasar population based on multiwavelength surveys. The early works with one or two faint quasars over small survey areas ($\lesssim 10$ deg$^2$) showed that the quasar luminosity function (LF) at $z \sim 6$ has a break like the LFs at lower redshifts, but the space number density is somewhat low at a magnitude fainter than the break (Willott et al. 2010; Kashikawa et al. 2015; Kim et al. 2015; Onoue et al. 2017). This implies that the quasars can provide only about 10% or less of the UV ionizing photons required to fully ionize the intergalactic medium (IGM) at $z \sim 6$.

Recently, the Subaru High-z Exploration of Low-Luminosity Quasars (SHELLQs) project based on the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP; Aihara et al. 2018) has found several dozens of faint quasars over 900 deg$^2$ (Matsuoka et al. 2016, 2018a, 2018b, 2019a, 2019b). With this sample, Matsuoka et al. (2018c) derived the quasar LF down to $M_{1450} = −22$ mag, which is extremely suppressed at $M_{1450} > −24$ mag and implies that quasars play only a minor role (~3%) in the cosmic reionization at $z \sim 6$.

Such a low space density, however, is still inconsistent with that from the faint X-ray AGNs with $M_{1450} \sim −22$ mag (Giallongo et al. 2015, 2019), which is an order of magnitude higher than the results from the above studies. Matsuoka et al. (2018c) explained that this discrepancy is due to dust obscuration in the UV by which the X-ray AGNs are not affected (see also Trebitsch et al. 2019). But recently, follow-up spectroscopy reveals that GDS 3073, one of the members of their sample, is identified as an AGN in rest-UV (Grazian et al. 2020), implying that the number density from the quasars identified by rest-UV spectroscopy is still high at $M_{1450} \sim −22.5$ mag, although their
survey area is very small (0.15 deg$^2$). From a different point of view, there are attempts to explain such a discrepancy with a change in the fraction of AGNs outshining their host galaxy at $M_{1450} \gtrsim -24$ mag (Ni et al. 2020; Kim & Im 2021).

We have been performing an independent survey for finding faint $z \sim 6$ quasars with the Infrared Medium-deep Survey (IMS; M. Im et al. 2022, in preparation). This is a moderately deep ($J \sim 22.5-23.5\,\text{mag}$ in 5$\sigma$ depth) near-infrared (NIR) imaging survey with the Wide Field Camera (WFCam; Casali et al. 2007) on the United Kingdom InfraRed Telescope (UKIRT), covering $\sim 120$ deg$^2$. Our main goal is to discover quasars as faint as $M_{1450} \sim -23.5$ mag to figure out the quasar demography in the early universe. Combining the NIR data with the optical data from the Canada–France–Hawaii Telescope Legacy Survey (CFHTLS; Hudelot et al. 2012), we discovered a faint $z \sim 6$ quasar and dozens of $z \sim 5$ quasars (Kim et al. 2015, 2019, 2020) and suggested the minor contribution of quasars to the cosmic reionization; quasars provide only $\sim 3\%$ of the required photons at $z \sim 6$ (up to 15%). In this work, we present an extended result of our $z \sim 6$ quasar survey, over the overlap regions between CFHTLS and IMS, covering $\sim 86$ deg$^2$. Our main goal is to find quasars as faint as $M_{1450} \sim -23.5$ mag and to examine their space density and implications for the cosmic reionization.

We describe our imaging data in Section 2 and quasar candidate selection in Section 3. Our follow-up observations in spectroscopy and the discovery of two new $z \sim 6$ quasars are described in Section 4. In Section 5, we present the $z \sim 6$ quasar space density with our complete sample, and we discuss the results in Section 6. Throughout this paper, all the magnitudes are given in the AB system, and we used the cosmological parameters of $\Omega_m = 0.3, \Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. Imaging Data

2.1. IMS

We use the $J$-band imaging data from the IMS and UKIRT Infrared Deep Sky Survey Deep eXtragalactic Survey (UKIDSS-DXS; Lawrence et al. 2007), obtained with WFCam (Casali et al. 2007) on UKIRT. Each image covers a $13'65 \times 13'65$ area with a pixel scale of 0.22 pixel$^{-1}$ after microstepping (0.24 pixel$^{-1}$ in the original). For simplicity, we hereafter refer to the combination of these two surveys as “IMS.”

As in Kim et al. (2019), we use the images with rescaled zero-points ($zp$) of 28.0 mag in the Vega system, using the bright coordinate-matched sources from the point-source catalog of the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006). Then, we applied the Vega-to-AB correction of 0.938 mag (Hewett et al. 2006) in the following photometric process.

2.2. CFHTLS

In the case of optical data, we used the images from the CFHTLS Wide survey, which were stacked by the TERAPIX processing pipeline.\textsuperscript{12} The images in $u^s$, $g^i, r^i, i^i$, and $z'$ bands were obtained with the MegaCam on the Canada–France–Hawaii Telescope (CFHT), and each image covers a $1 \times 1$ area (hereafter “tile”) with a pixel scale of 0.186. Note that there was a change of $i^i$-band filter during the survey, from the filter number of 9701 (or $i'_1$) to 9702 (or $i'_2$). Unlike stellar sources, it is difficult to constrain well the transition between the $i'_1$ and $i'_2$ magnitudes for high-redshift quasars ($z \sim 6$) because their colors dramatically change with respect to their redshifts. Therefore, we consider the difference between the two $i^i$-band filters in the following sections.

For accurate photometry to find faint quasars, we reestimated the $zp$ values of the CFHTLS images. We first selected the objects that also appear in the point-source catalog of the first data release of the Panoramic Survey Telescope and Rapid Response System (PS1; Kaiser et al. 2002; Chambers et al. 2016). Note that we used the point-spread function (PSF) magnitudes from the StackObjectThin table. The PS1 magnitudes of the selected sources were converted to the MegaCam magnitude system using a conversion relation.\textsuperscript{13} For the $zp$ calculation, we use only the sources within a magnitude range of 17.5–21.0 mag to avoid saturated or low signal-to-noise ratio (S/N) objects that could bias the result. Then, we compared the PSF magnitudes of the PS1-selected sources with those of the sources extracted from the CFHTLS images using Sextractor (Bertin & Arnouts 1996) with PSFEx (Bertin 2011) to determine the $zp$ value of each image in each band. Most of the offsets from the original $zp$ values provided by Hudelot et al. (2012) are less than 0.1 mag in all bands, but these updated $zp$ values result in point-source colors that are better in line with the synthetic stellar loci of Covey et al. (2007), including IMS $J$-band magnitudes. Thus, these reestimated $zp$ values improve the removal of stars during the quasar selection.

2.3. CFHTLS-IMS Overlap

There are four extragalactic fields in the CFHTLS-IMS overlap area: the XMM-Large Structure Survey region (XMM-LSS), the CFHTLS Wide survey second region (CFHTLS-W2), the Extended Groth Strip (EGS), and the Small Selected Area 22h (SA22). We resampled the overlap area between CFHTLS and IMS images using the SWarp software (Bertin 2010). If a region was observed in both the $i'_1$ and $i'_2$ bands, we used the former one. The four fields cover 8.7, 22.0, 34.4, and 21.1 deg$^2$, respectively, and the total sky coverage is 86.2 deg$^2$. The area sizes were calculated from the mosaicked images undersampled to a pixel scale of 1$'$ pixel$^{-1}$ using SWarp.\textsuperscript{14} Note that such undersampling is due to the consideration of computing time not only for this area size calculation but also for the survey completeness calculation in Section 5.1.

Using the updated $zp$ values mentioned above, we estimated the limiting magnitudes of each field for point sources, including the PSF correction for an aperture that we used for source extraction (Section 2.4). In Figure 1, we show the histogram of the limiting magnitudes in $i'_1, i'_2, z'$, and $J$-band images. The detailed information of the four fields, including typical image depths, is listed in Table 1. Note that the image depth in a given filter varies between tiles, giving the limiting depth histogram distributions with widths between a few tenths to a couple of magnitudes (Figure 1). The optical images in the four fields have homogeneous imaging depths of $u^s = 25.6$ mag, $g^i = 26.1$ mag, $r = 25.5$ mag, $i'_1 = 25.3$ mag, $i'_2 = 25.5$ mag.

\textsuperscript{12} T0007; http://terapix.iap.fr/epht/T0007/doc/T0007-doc.html.

\textsuperscript{13} http://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/megapipe/docs/filt.html

\textsuperscript{14} The area size was updated from that of Kim et al. (2020; 85 deg$^2$) with a slight increase.
and $z' = 24.2$ mag, with a standard deviation of $\sim 0.2$ mag in all bands. On the other hand, the $J$-band imaging depths show more variations; the depths of the XMM-LSS and SA22 field images are $\sim 0.8$ mag deeper than those of the other field images, while portions of the CFHTLS-W2 and EGS fields have shallower depths owing to the shorter exposure times. We consider this difference when we calculate the survey completeness (Section 5.1). The median seeing sizes in the $(u^*, g', r', i', z', J)$ band images are ($0.86, 0.80, 0.71, 0.65, 0.60, 0.68, 0.86$) in units of arcsec, respectively, and those in each field are listed in Table 1.

2.4. Source Extraction

With SExtractor, the source detection was performed first in the $z'$-band images, at which the Ly$\alpha$ $\lambda 1216$ (Lya) emission of a $z \sim 6$ quasar is expected to be located. We set the detection criteria for the SExtractor parameters to $\text{DETECT\_MINAREA}=9$ pixels and $\text{DETECT\_THRESH}=1.3\sigma$, allowing us to catalog only the sources with significant ($\gtrsim 4\sigma$) signals in $z'$ band. Note that this affects the photometric completeness estimation in Section 5.1.

For the $z'$-band-detected sources, we performed aperture photometry with an aperture of $2 \times \text{FWHM}_{z'}$ diameter, where $\text{FWHM}_{z'}$ is the full width at half-maximum of point sources in $z'$-band images ($\sim 0.7$), by using dual-image mode in SExtractor (called forced photometry). The aperture size is determined to maximize $S/N$ (or $\text{FLUX}/\text{FLUXERR}$) of the $z'$-band detection with comparable seeing sizes in the other bands. The aperture fluxes in each band were converted to the total fluxes by adopting the aperture correction factors derived from bright point sources in the same field, so that differences in seeing values in different bands are taken care of. Note that we use aperture instead of PSF because the PSF flux tends to be overestimated if there is no detection when doing forced photometry.

To correct for the galactic extinction (minor in our extragalactic fields; $<0.05$ mag), we used the extinction map of Schlafly & Finkbeiner (2011) with an assumption of $R_V = 3.1$ (Cardelli et al. 1989).

3. Quasar Candidate Selection

3.1. Point-source Selection

Under the imaging resolution of our data, most of the high-redshift quasars with $M_{1450} < -23.5$ mag are classified as point sources ($\gtrsim 90\%$; Bowler et al. 2021). Previous studies often used the magnitude differences (e.g., PSF magnitude vs. aperture magnitude) to avoid the extended-source contamination. In this work, we adopt the $\text{SPREAD\_MODEL}$ parameter, a star—galaxy classifier in SExtractor, which denotes how the source morphology is different from the input PSF model.15 This method offers a better performance to separate point sources from not only the extended sources but also the glitch-like spikes, compared to the previous stellarity index (CLASS\_STAR) in SExtractor, especially at faint magnitudes (Annunziatella et al. 2013). The $\text{SPREAD\_MODEL}$ is defined as

$$\text{SPREAD\_MODEL} = \frac{G^T W_p - G^T W\hat{\phi}}{\phi^T W_p - \phi^T W\hat{\phi}},$$

where $p$ is the image vector centered on the source and $W$ is a weight matrix (diagonal) related to the pixel noises. $\hat{\phi}$ and $\hat{G}$ represent the point source and the galaxy model vectors at the current position, respectively. They are based on the resampled local PSF model generated with PSFEx, while the latter ($\hat{G}$) is obtained by convolving an additional circular exponential model. Since the functional form is normalized by the local PSF model, sources having different PSFs in various fields can be compared to each other.

The average $\text{SPREAD\_MODEL}$ value of point sources is expected to be zero regardless of flux or $S/N$, but its scatter mildly increases as $S/N$ goes lower. Therefore, we used the $\text{SPREAD\_MODEL}$ value in the $z'$ band ($S_\alpha$) as a reference, considering the high $S/N$ of $z \sim 6$ quasars in $z'$ band with Lya emission. Figure 2 shows the $S_{\alpha}$ values of the sources. There is a clear trend of point sources with $S_\alpha = 0$, distinguished from the extended sources ($S_\alpha > 0$) and the glitch-like sources ($S_\alpha < 0$; unremarkable in this figure with their small numbers).

To test how many point sources can be selected by the arbitrary $S_\alpha$ cut, we performed a simulation by adding artificial stars to the $z'$-band images. The artificial stars are based on the sampled stars by PSFEx in each image and scaled to match the arbitrary magnitudes that we set for the simulation. The number of the artificial stars is 100 per 0.5 mag per deg$^2$. Then, we repeated the source extraction described in Section 2.4. The red circles in Figure 2 show the $S_\alpha$ distribution of the artificial stars, with $1\sigma$ (68\%) and $2\sigma$ (95\%) levels, shown as the red and gray colors, respectively. The widening of the $S_\alpha$ selection range decreases the number of missing point sources, but not surprisingly, the numerous contamination by extended sources also increases. With several tests, we set the criterion for the point-source selection as $-0.006 < S_\alpha < 0.006$ (dashed lines) to balance between them down to $z' = 23.5$ mag. With this $S_\alpha$ criterion, 96\% of point sources are recovered at $z' < 23.5$ mag, while the rate in the faintest magnitude bin ($23.0 \leq z' < 23.5$) drops to 83\%.

15 https://sextractor.readthedocs.io/en/latest/Model.html
The coordinates indicate the approximate center of each field. The numbers in parentheses are the areas observed in $i'$ and $i'$ bands, respectively. The limiting magnitude is given in a median value for point sources after the PSF correction for an aperture with a diameter of $2 \times$ FWHM.$^\dagger$

### 3.2. Initial Color Selection

The Ly$\alpha$ break of a $z \sim 6$ quasar is located at $\lambda_{\text{obs}} \sim 8500$ Å, giving a very red $i'$ – $z'$ color with (almost) no detection at the shorter wavelengths. On the other hand, at wavelengths longer than the Ly$\alpha$ emission, the quasar’s color (e.g., $z' - J$) tends to be blue according to the quasar continuum emission. Such colors are distinguished from those of late-type stars that are the main contaminants. Lyman break galaxies (LBGs) can also be interlopers at $z \sim 6$ (Matsuoka et al. 2016, 2018c), but their expected number over our survey area is very small.$^{16}$ Hence, we ignore them in this study.

Figure 3 shows the color distributions of the point sources in our survey (gray contours). Following Kim et al. (2015), we set the color and magnitude selection criteria as follows:

1. $i' - z' > 2.0$
2. $z' - J < 0.625 \times ((i' - z') + 0.1)$
3. $u' > u_{3\sigma}'$, $g' > g_{3\sigma}', r' > r_{3\sigma}'$

$^{16}$The expected number density is calculated by integrating the LBG LF of Harikane et al. (2021) down to $M_{1450} = -24$ (23.5 mag), corresponding to $z' \sim 23$ (23.5 mag). If we assume 100% completeness, we obtain the expected number of 0.7 (4.8) by multiplying the cosmic volume of our survey area. Like quasars, however, the survey completeness for LBGs is also expected to be very low at $-24$ mag $< M_{1450} < -23.5$ mag. Therefore, we ignore them in the selection process.

Note that the magnitude with a subscript of $3\sigma$ ($5\sigma$) is the $3\sigma$ ($5\sigma$) limiting magnitude. The first two color criteria are shown as the black solid lines in Figure 3. If a source is not detected at the $3\sigma$ level (e.g., $i' > i_{3\sigma}'$), then the limiting magnitude is used for the color selection instead. Considering the point-source completeness (Section 3.1) and the $i$-band limiting magnitude, we set the fourth criterion in terms of $z'$-band magnitude. In addition, taking account of the variance in the $J$-band imaging depths (Figure 1), the $J$-band magnitude cut (the fifth criterion) is set at the $5\sigma$ detection limit of the tiling image.

Among 404 color-selected objects, there are many spurious ones with bad image quality; most of them are located in the bad pixel regions in the image of at least one filter (e.g., at the
edge of the image). We automatically reject such cases, resulting in the 64 sources. Then, we performed an additional visual inspection of the remaining sources to reject obvious artifacts, cosmic rays, etc. We also cross-check the ones rejected by the above-automated process, and no object deserves to be selected through the visual inspection process. We finally have 25 candidates, which are listed in Table 2.

3.3. AICc Selection

It has been known that the observational properties of high-redshift quasars are slightly different from those of low-redshift ones. For instance, the EW values of $z \sim 6$ quasars tend to be smaller than those of low-redshift ones (Bañados et al. 2016). Previous studies, however, used the low-redshift quasar templates, which are redshifted to higher redshifts for statistical methods represented by the Bayesian approach to find high-redshift quasars (e.g., Mortlock et al. 2012; Matsuoka et al. 2016). Concerned that this issue may miss plausible candidates, we here prefer to use the models whose parameters can be easily tuned to fit the observed properties. Unlike when using observation-based templates, the complexity of the model and its potential for overfitting must be taken into account when using such models with multiple parameters. We selected models that can represent the photometric characteristics of high-redshift quasars and late-type stars well with minimal parameters, which are described below. Each model has a different number of free parameters, so we introduced an information criterion that prioritizes models for a given data set by giving an additional penalty based on the number of free parameters. This approach is known to be effective in selecting the promising high-redshift quasar candidates by comparing models of different types of celestial objects (Shin et al. 2020). Moreover, we chose this method over the well-known Bayesian approach because it takes into account the ideal characteristics and distributions of the models, unlike observation-based templates.

In this study, we introduce the Akaike information criterion (AIC: Akaike 1974), which is based on the Kullback–Leibler discrepancy (Kullback & Leibler 1951). For a model $m$, AIC is given by

$$AIC_m = 2k_m - 2\ln(L_m),$$

where $k_m$ is the number of free parameters and $L_m$ is the likelihood. The first term gives an additional penalty, allowing us to compute the model priority with not only $L_m$ but also $k_m$. Using such an AIC value, we can compute the model priority with not only $L_m$ but also $k_m$. We also consider the modified AIC (AICc), which adjusts for small sample sizes and is given by

$$AICc_m = AIC_m + \frac{2k_m(k_m + 1)}{N - k_m - 1},$$
We have photometric information only in six bands, so a corrected version of AIC for small sample sizes (AICc; Sugiura 1978) works better than Equation (2) (Burnham & Anderson 2002), which is given by

$$\text{AICc}_m = \text{AIC}_m + \frac{2k_m(k_m + 1)}{n - k_m - 1},$$

where $n$ is the number of filters (or photometric data) to calculate $L_m$. By comparing the AICc values from different models, we can determine which model traces the observed data more closely. Here we introduce the two models: high-redshift quasars and late-type stars.

### 3.3.1. High-redshift Quasar Model

We use the model of Kim et al. (2019) based on the quasar composite spectrum of Vanden Berk et al. (2001), including the IGM attenuation effect (Madau et al. 1996). It has four parameters of $(z, M_{1450}, \alpha_p, EW)$, where $z$ is the redshift, $M_{1450}$ is the monochromatic magnitude at 1450 Å, $\alpha_p$ is the slope of the quasar power-law continuum, and $EW$ is the equivalent width of the composition of Ly$\alpha$ and N V emissions (see Kim et al. 2019 for details). Instead of letting the parameters be free, we generated 0.1 million mock quasars that reflect the observational properties of real quasars at $z \sim 6$. The redshift and the magnitude are uniformly distributed (but randomly generated) in the range of $5.5 < z < 7.0$ and $-28 < M_{1450} < -22$. On the other hand, the other two parameters are randomly given by Gaussian distributions (mean ± standard deviation): $\alpha_p = -1.6 \pm 1.0$ (Mazzucchelli et al. 2017) and $\log EW = 1.542 \pm 0.391$ (Bañados et al. 2016). As in Kim et al. (2020), the Baldwin effect (Baldwin 1977) is also included when we generate the EW distribution, by giving the shift to the mean value using the relation between EW of Ly$\alpha$ and continuum flux in Dietrich et al. (2002). Although the relation is from low-redshift AGNs, we use it under the assumption of no redshift evolution in the quasar broad-line properties in rest-UV (Shen et al. 2019; Schindler et al. 2020). From these model spectra, broadband magnitudes are calculated by integrating the mock quasar spectra convolved with the filter transmission curves.

In the left panels of Figure 4, we show the color distributions of these mock quasars across the redshift. As a function of redshift, they show good agreements with the confirmed quasars not only in this work (red circles) but also from the Canada–France–Hawaii Quasar Survey (CFHTQS; Willott et al. 2007, 2009, 2010; blue circles). This implies that the mock quasars emulate the real quasars at $z \sim 6$ well.

### 3.3.2. Late-type Star Model

We use the BT-Settl model (Allard et al. 2012) for late-type stars, which is publicly available on the Theoretical Spectra Web Server. The model has four parameters: effective temperature ($T_{\text{eff}}$), surface gravity ($g$), metallicity ([M/H]), and $\alpha$-element enhancement ($\alpha_E$). We choose the templates in the ranges of $1000 \leq T_{\text{eff}} \leq 3000$ K and $3.5 \leq \log(g) \leq 5.5$ with step sizes of $\Delta T_{\text{eff}} = 100$ K and $\Delta \log(g) = 0.5$, respectively. Since the low-$T_{\text{eff}}$ ($\leq 2500$ K) stars have a fixed value of $[\text{M/H}] = 0$ and $\alpha_E = 0$, we only used the templates with those values. Note that there is no template for a star with $T_{\text{eff}} = 1000$ K and $\log(g) = 3.5$, resulting in the $20 \times 5 + 4 = 104$ templates. In addition, we used a normalization factor $f_N$ as a free parameter. Like the quasar model, their magnitudes were obtained by integrating fluxes within each band.

The right panels of Figure 4 show the color distribution of our late-type star model. For comparison, we sourced the photometry of late-type stars from the Pan-STARRS1 3π Survey (PS1) late-type star catalog (Best et al. 2018). The PS1 stellar spectral types were converted to $T_{\text{eff}}$ using the relations between them (Pecaut & Mamajek 2013; Bailey 2014). We also converted the PS1 magnitudes into the CFHTLS photometric system, shown as the blue circles, except for the L- and T-dwarf stars without $g_{\text{PS1}}$-band photometry information. The filter systems between the two surveys are only slightly different, so we also show the colors in PS1 as blue circles in order to see the trend of such L- and T-dwarf stars. As in this figure, our late-type star models are broadly consistent with the real stars.

17 http://svo2.cab.inta-csic.es/theory/newov2/index.php
18 http://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/megapipe/docs/filt.html
3.3.3. SED Fitting and AICc-based Criterion

We performed the fitting for the spectral energy distributions (SEDs) of the 25 color-selected candidates in Section 3.2 with the above high-redshift quasar and late-type star models. As in Kim et al. (2019), for a model, we find the best-fit solution that minimizes the modified χ² statistic:

\[
\chi^2_m = \sum_d \chi^2_{m,d} + \sum_u \chi^2_{m,u} = \frac{(F_{o,d} - F_{m,d})^2}{\sigma_{o,d}^2},
\]

where \(F_{o,d}\) is the observed flux in the \(d\)th band, \(F_{m,d}\) is the model flux, and \(\sigma_{o,d}\) is the uncertainty of \(F_{o,d}\). On the other hand, the second term gives an additional penalty for the cases of upper limit, defined by Sawicki (2012):

\[
\chi^2_{m,u} = -2 \ln \int_{F_{lim,u}}^{\infty} \exp \left[ -\frac{1}{2} \left( \frac{F_{o,u} - F_{m,u}}{\sigma_{o,u}} \right)^2 \right] dF
\]

\[
= -2 \ln \left( \frac{\sqrt{2 \pi} \sigma_{o,u}}{2} \left[ 1 + \text{erf} \left( \frac{F_{lim,u} - F_{m,u}}{\sqrt{2} \sigma_{o,u}} \right) \right] \right),
\]

where \(F_{lim,u}\) is the upper limit of flux in the \(u\)th band, while \(F_{o,u}\) and \(F_{m,u}\) are the observed flux, model flux, and sensitivity in the same band, respectively. Parameter \(\text{erf}(x)\) is the error function of \((2/\sqrt{\pi}) \int_0^x e^{-t^2} dt\), for the numerical calculation.

We calculate \(\chi^2_m\) (=−2ln \(L_m\)) for the SEDs of the color-selected candidates. For example, if a candidate is detected in the \(i'\), \(z'\), and \(J\) bands, we calculate \(\chi^2_{m,d}\) for these bands and \(\chi^2_{m,u}\) for the other bands. The best-fit quasar and star models, which minimize \(\chi^2_m\) values, are shown as the blue and orange lines, respectively, in Figure 5.

Using Equations (2) and (3), we compute AICc\(_q\) and AICc\(_s\), where the subscripts \(q\) and \(s\) denote the high-redshift quasar and late-type star models, respectively. Since our purpose is to determine whether a candidate is more likely to be a quasar or not, we only compare the best-fit cases from the two models. To prioritize the models, we introduce the weights of AICc (Burnham & Anderson 2002), given by:

\[
w_m(\text{AICc}) = \frac{I_m}{I_q + I_s},
\]

where

\[
I_m = \exp \left( -\frac{1}{2} (\text{AICc}_m - \text{AICc}_{\text{min}}) \right)
\]

and AICc\(_{\text{min}}\) is the minimum of the AICc values (\(\text{min}[\text{AICc}_q, \text{AICc}_s]\)). This weight can be interpreted as the probability that the given model is the best one. For the color-selected candidates, we listed their \(w_q\) values in Table 2.

We set a very strict criterion of \(w_q > 0.99\). This corresponds to the fraction of the weights of \(w_q/w_s \geq 100\), meaning that the high-redshift quasar model is 100 times more likely to be the best model than the late-type star model (Burnham & Anderson 2002). This choice is because our late-type star model has a very small scatter in colors, compared to the observed ones, as shown in Figure 4. There are seven candidates satisfying this criterion, shown as the orange filled circles in Figure 3.

3.4. Photometric Cross-check with HSC

Several parts of our survey area overlap with the area of the Wide Survey of HSC-SSP. On average, the optical images from the HSC-SSP Public Data Release 3 (PDR3; Aihara et al. 2022) are ~1 mag deeper than those from CFHTLS. Therefore, we expect more accurate photometry for the overlapping targets.

We found that 14 of the color-selected candidates are in the overlapping area, by matching our candidates to the sources in the HSC-SSP PDR3 catalog. We adopted the HSC-SSP PDR3’S PSF magnitudes in the \(i'\)-HSC and \(z'\)-HSC bands, listed in Table 2 in the \(i'\)-HSC – \(z'\)-HSC form. Note that the filter systems of CFHTLS and HSC are slightly different from each other, especially in the \(z'\) and \(z'\)-HSC bands. While their central wavelengths are similar to each other (8815 and 8908 Å, respectively), the former has a broader bandwidth of 1040 Å than the latter, which has a bandwidth of 781 Å. This makes different color trends of quasars on the color–color diagram, as shown in Figure 6. For our quasar model, the \(i'\)-HSC – \(z'\)-HSC color (yellow diamonds) is redder at \(z < 6\) and becomes bluer at \(z > 6.5\) than \(i' - z'\) (blue and purple diamonds).

Most of the HSC-overlapped candidates (12/14) have blue colors of \(i'\)-HSC – \(z'\)-HSC < 1.5. If we use \(i'\)-HSC and \(z'\)-HSC instead of \(i'\) and \(z'\), respectively, the 12 candidates move toward the stellar locus in the color–color diagram (yellow circles), meaning that they are unlikely to be \(z < 6\) quasars or even galaxies at that redshift (Harikane et al. 2021). It is remarkable that all of them are also rejected by our AICc selection using the CFHTLS optical photometry. On the other hand, the colors of the other two candidates, highlighted by red circles, are still likely to be those of the high-redshift quasar models even if using the HSC colors. We note that they satisfy our AICc selection criterion and were also identified as high-redshift quasars by spectroscopy (Kim et al. 2015; Matsuoka et al. 2016). This demonstrates that our AICc selection, even under shallower imaging data, is an effective method to exclude nonquasar objects.

On the contrary, there may be objects that have red \(i'\)-HSC – \(z'\)-HSC colors in HSC but not so in our data. From the HSC-SSP PDR3 catalog, we select point sources with \(i'\)-HSC – \(z'\)-HSC > 2 using the selection criteria given in Equation (1) of Matsuoka et al. (2018c), which are also detected in CFHTLS \(z'\)-band images. There are seven isolated point sources at \(z' < 23.5\) mag, while the brightest one among them has \(i' - z' = 1.58\) in our data. This is because of its brighter \(i'\)-band magnitude in IMS \((i' = 24.51 \pm 0.18)\) vs. \(i'\)-HSC = 25.00 ± 0.10), while there is no significant difference in \(z'\)-band magnitudes \((z' = 22.93 \pm 0.05)\) mag vs. \(z'\)-HSC = 22.88 ± 0.03). We note that this object is close to the edge of the CFHTLS image. This implies that 14% (1/7) of red objects could be missed in our imaging data, especially for \(z' < 23.5\) mag objects.

4. Spectroscopic Identification

In previous studies, three of our candidates were already identified as \(z \sim 6\) quasars: J142952+544718 (Willott et al. 2010), J220418+011145 (Kim et al. 2015, 2018), and J221644–001650
For the remaining targets, we additionally obtained their spectra with the Palomar 200-inch and Gemini telescopes.

4.1. P200/DBSP Observation

We carried out spectroscopic observations of the other four AICc-selected candidates with the Double Spectrograph (DBSP) on the Palomar Hale 200-inch telescope (P200) on 2021 July 13 (PID:CTAP2021-A0032), under the seeing condition of $\sim1.5\text{arcsec}$. We used the grating of 316 lines mm$^{-1}$ with a 1.5-width slit, giving the resolution of $R=956$. To avoid the duplication of the zeroth-order spectrum, the D55 dichroic filter ($\lambda_{\text{obs}}>5500\text{\AA}$) was used. The total exposure times were 3600 s for fainter ones ($\text{J140001+554619}$ and $\text{J140121+531434}$) and 1200 s for the other brighter ones ($\text{J140504+542435}$ and $\text{J143055+531520}$).

For data reduction, we used the PypeIt Python package which is an open-source pipeline for the selected instruments, which automatically performs the bias subtraction, flat-fielding, skyline subtractions, and wavelength calibrations (with HeNeAr arc lines). Considering the faintness of our target, we manually extracted fluxes within an optimal aperture with a fixed FWHM that matches the seeing size (1.5 arcsec). The key best-fit parameters of each candidate are marked in each panel. The AICc-selected candidates with $w_q > 0.99$ are highlighted with star symbols.

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19 https://pypeit.readthedocs.io/
done by PypeIt with the standard star, Feige 110. In addition, we scaled the spectra to match with their $z'$-band photometry to compensate for the flux loss by sky fluctuation, as was done in Kim et al. (2019) and Kim et al. (2020). By convolving the $z'$-band transmission curve with the three spectra (except for J140121+531434 without detection), we obtained scaling factors of 1.54–1.78. We applied the average scaling factor of 1.69 to all the DBSP spectra. Note that the limited wavelength coverage of our spectra up to ∼10000 Å may affect the scaling factor. Finally, we binned the spectra in the spectral direction with resolutions of $R = 956$ and 300 by using the inverse-variance weighting method (e.g., Kim et al. 2018).

We show the DBSP spectra of the four candidates in Figure 7. Except for the faintest, J140121+531434, their spectra are marginally detected with low S/N of 2–3. J140001+554619 and J143055+531520 show clear breaks at ∼8400 and 8850 Å, respectively. Such breaks are more clearly visible if we maximize the S/N by binning the data to a low resolution of $R = 300$ (right columns in Figure 7). We provide more detailed individual notes for these targets in Section 4.3.

As mentioned above, J140121+531434 is not detected, even though its $z'$-band magnitude is brighter than J140001+554619. For a high-redshift quasar, the peak of Lyα flux in its spectrum is expected to be brighter than broadband photometry ($z'$ band; purple squares), which is dominantly determined by continuum emission, but this object shows no remarkable feature. On the other hand, the spectrum of J140504+542435 has continuum emissions without any remarkable emission lines or breaks. Therefore, we concluded that J140121+531434 and J140504+542435 are not high-redshift quasars but interlopers like late-type stars or faint galaxies.

### 4.2. Gemini/GMOS Observation

We obtained the spectra of J085550–051346 and J090554–052518 with the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004) on the Gemini-South 8 m Telescope on 2020 February 24 (PID: GS-2020A-Q-219). Note that these observations preceded the AIfc selection. The seeing condition was ~0''7. Since the targets are very faint, we optimized the observing configurations to maximize S/N. The choice of an R150_G5326 grating with a slit width of 1''0 gives a low resolution of $R ∼ 315$, and we set the 4 × 4 binning in the spatial/spectral directions. The nod-and-shuffle mode was used to subtract skylines accurately. The total exposure times are 2904 and 3388 s for J085550–051346 and J090554–052518, respectively.

We followed the general reduction process for the GMOS spectra using the Gemini IRAF package: (1) bias subtraction, (2) flat-fielding, (3) sky line subtraction, (4) wavelength calibration with CuAr arc lines, and (5) flux calibration with a standard star LTT2415. Note that for the extraction process we used a fixed aperture whose size is consistent with the seeing size of ∼0''7. Like DBSP spectra, the GMOS spectra were scaled to match with $z'$-band magnitudes, by a factor of 2.25 on average. Such a large scaling factor might be due to the reported problem on the coefficient of thermal expansion during our observing run.\footnote{https://www.gemini.edu/news/instrument-announcements/gmos-s-data-affected-ccd1-cte-problem} We also binned the spectra along the spectral direction to match the instrument resolution of $R = 315$.

The two spectra are shown in Figure 8. Both show clear continua but without any remarkable emission lines or Lyα break, suggesting that they are not high-redshift quasars. We here emphasize that they satisfy the AIFc criterion, supporting the feasibility of our approach.

### 4.3. Spectral Properties of New Quasars

For J140001+554619 and J143055+531520, which are likely to be high-redshift quasars with clear breaks on their spectra, we measured their $z$ and $M_{1450}$ by finding the best-fit models among our mock quasars in Section 3.3.1. We calculated the reduced chi-square values ($\chi^2_{\text{red}}$) between their spectra and our mock quasar spectra. The wavelength range for the spectral fitting was set as 6500 Å < $\lambda_{\text{obs}}$ < 9500 Å. We chose the best-fit models of J140001+554619 and J143055+531520 with the minimum $\chi^2_{\text{red}}$ values of 1.01 and 1.09, respectively, which are shown as the red lines in Figure 7. The best-fit parameters are listed in Table 3, along with the results from the photometric data (Section 3.3.3). We also list the measurements of the three previously known quasars at $z ∼ 6$ (Willott et al. 2010; Kim et al. 2015; Matsuoka et al. 2016; Kim et al. 2018).

The clear break of J140001+554619 at ∼8400 Å is consistent with the $z = 5.85$ quasar model. Interestingly, some peaky detections on the spectrum are also in line with the locations of quasars’ high-ionization emission lines: O I 1304 and C II 1335 (red vertical markers in Figure 7). The existence of the probable emission lines may provide additional evidence supporting its nature as a high-redshift quasar. However, since the S/Ns of the two peaky detections are as low as 2.7 and 1.9, respectively, we still have doubts about their reliability. LBGs would have a clear Lyman break on their spectra too, so it is difficult to confidently say that J140001+554619 is not a $z ∼ 6$ LBG, although we have ignored them in our selection process. Further observations are needed to identify the high-ionizing emission lines, which can be a crucial criterion for determining whether this object is a quasar or LBG. In the following sections, we assume that J140001+554619 is a high-redshift quasar, but we here caution that our estimates could be overestimated if this object is actually an LBG.

In the case of J143055+531520, there is a clear Lyα break with a plausible N V λ1240 emission line ($S/N ∼ 7$) calculated from peaky emissions at 9010–9072 Å on the R = 300 spectrum), which is consistent with the $z = 6.29$ quasar model. With little chance of finding LBGs as bright as this target ($M_{1450} = −25.12$ mag; inferred from the LBG LF of Harikane et al. 2021), we conclude that J143055+531520 is a high-redshift quasar.

The photometric redshifts ($z_{\text{phot}}$) of the five spectroscopically identified quasars are well in line with the spectroscopic redshifts ($z_{\text{spec}}$): the standard deviation of $\delta z = (z_{\text{phot}} - z_{\text{spec}})/(1 + z_{\text{spec}})$ is only 0.013. This is much smaller than the value for $z ∼ 5$ quasars using the same model (0.043; Kim et al. 2019), which might be due to the stronger IGM attenuation at higher redshifts, despite the small number statistics. The DBSP spectra with low $S/N$ of 2–3 and limited wavelength ranges of $\lambda_{\text{obs}} < 9500$ Å give a degeneracy of $M_{1450}$, $\alpha_p$, and EW in the fitting at $\lambda_{\text{obs}} \gtrsim 9000$ Å. Meanwhile, our SED fitting for photometry includes $z'$- and $J$-band magnitudes, enabling us to estimate $M_{1450}$ better. Therefore, we use their magnitudes from photometry instead of those from spectra in the following analysis.
5. Quasar Space Density

5.1. Survey Completeness

As mentioned in Section 2.3, the imaging depths of our survey are not uniform (Figure 1). Therefore, we calculated the completeness for every 1 arcmin² area (hereafter “patch”), given as a function of $z$ and $M_{1450}$: $f_X, p(z, M_{1450})$, where $X$ is the type of completeness and $p$ is the index of each patch. We used bin sizes of $dz = 0.05$ and $dM_{1450} = 0.2$ mag, including more than 100 mock quasars (Section 3.3.1) in each bin.

5.1.1. Detection and Point-source Selection Completeness

We first consider the photometric completeness related to the source detection. We used the artificial stars from a simulation described in Section 3.1 to test how many of them can be recovered with our images and methods along with the magnitude (Section 2.4). The resultant completeness is parameterized by the equation of Fleming et al. (1995):

$$c(z') = \frac{1}{2} \left( 1 - \frac{\alpha_{50}(z' - z_{50})}{\sqrt{1 + (\alpha_{50}(z' - z_{50}))^2}} \right).$$

where $\alpha_{50}$ is the slope of the function at the 50% completeness magnitude ($z_{50}$). The results for each CFHTLS tile are shown as the red lines in Figure 9, while the median values are highlighted by the thick solid line.

For comparison, we also parameterized the photometric completeness of Hudelot et al. (2012) with Equation (9), shown...
as the orange lines. Note that the functions were shifted in the magnitude direction by following our new \( z_p \) measurements. Our results show lower \( z_{50}^f \) (\( \leq 24 \) mag) than Hudelot et al. (2012). This is because of our choice of SExtractor parameters for searching high-S/N sources: DETECT_MINAREA = 9 and DETECT_THRESH = 1.3. These are more stringent than DETECT_MINAREA = 3 and DETECT_THRESH = 1.0 used by Hudelot et al. (2012). If we use these values instead, our simulation gives consistent results with Hudelot et al. (2012). But we point out that there is only a negligible difference in detection rate (<1%) between ours and that of Hudelot et al. (2012) at \( z' < 23.5 \) mag.

In addition to the detection completeness, we consider the point-source selection described in Section 3.1. Using Equation (9), we also fitted the binned completeness for the detected sources satisfying our point-source selection criterion. The results are shown as the blue lines in Figure 9, which have \( z_{50}^f \sim 23.5 \) mag on average, which is naturally lower than those of the detection completeness limits. This means that our magnitude cut of \( z' < 23.5 \) mag is very marginal. Using the mock quasar sample described in Section 3.3.1, we converted the completeness for a given patch to a function of \( z \) and \( M_{1450} \):

5.1.2. Color Selection Completeness

Our initial selection is based on the colors, so we calculate the quasar selection efficiency of our color criteria described in Section 3.1. We gave random Gaussian noises to the magnitudes of the mock quasars according to the imaging depths at a given patch. Then, the fraction of quasars satisfying the criteria in each \( (z, M_{1450}) \) bin was calculated, resulting in the color selection completeness of \( f_{\text{c.p}}(z, M_{1450}) \). Note that the difference between the \( i_1 \) - and \( i_2 \)-band images is also considered.

5.1.3. AICc Selection Completeness

We considered the application of the AICc selection for the final candidates. The fraction of the mock quasars satisfying \( w_p > 0.99 \) was calculated patch by patch as in Section 5.1.2. Since the mock quasars have no error information in their magnitudes, we gave appropriate magnitude errors according to their magnitudes and imaging depths in each patch. The resultant completeness, \( f_{\text{AICc}}(z, M_{1450}) \), shows 90% down to \( M_{1450} \sim -23.5 \) mag, meaning that the AICc selection does not reduce the total selection completeness significantly at the magnitude ranges of interest.

5.1.4. Total Selection Completeness

At a given patch, the total selection completeness is calculated by multiplying the above completeness functions because they are independent of each other: \( f_p = f_{\text{DP}} \times f_{\text{c.p}} \times f_{\text{AICc}} \). Then, we combined \( f_p \) in each field to get the average completeness: \( F_{\text{field}}(z, M_{1450}) = \left[ \sum_{\text{field}} f_p(z, M_{1450}) / N_{\text{field}} \right] \), where \( N_{\text{field}} \) is the total number of the patches in the field. Figure 10 shows the resultant completeness \( F_{\text{field}}(z, M_{1450}) \) of each field. As can be inferred from the quasar track in Figure 3, the difference between the \( i_1 \) - and \( i_2 \)-band filters is reflected in the results; the usage of the \( i_2 \)-band filter can catch more quasars at \( z < 5.9 \). The two brighter quasars are in the parameter space where the completeness is ~1, while the remaining three fainter ones have completeness values of 0.1~0.3. But this is because they are found in the survey area of the SA22 and EGS fields, where deeper \( J \)-band images are available. Indeed, \( f_p(z, M_{1450}) \) for the three quasars is 0.2~0.5, which rather deserves to be selected. We also calculated the total completeness \( F(z, M_{1450}) = \sum_{\text{field}} f_p(z, M_{1450}) / N_p \), shown in Figure 11.

5.2. Binned Space Density

As listed in Table 3, we have five \( z \sim 6 \) quasars identified by spectroscopy within the IMS survey area, including the two

### Table 3

Best-fit Parameters of IMS \( z \sim 6 \) Quasars

| ID                | \( z \) | \( M_{1450} \) | \( \alpha_p \) | logEW |
|-------------------|-------|----------------|--------------|-------|
| J140001+554619    | 5.85  | -23.25         | -1.49        | 1.54  |
| J143055+531520    | 6.29  | -25.45         | -0.80        | 1.56  |
| J142952+544718    | 6.21  | -25.85         | ...          | ...   |
| J220418+011145    | 5.93  | -23.99         | ...          | ...   |
| J143055+531520    | 6.29  | -25.12         | -0.31        | 1.73  |
| J221644-001650    | 6.10  | -23.56         | -1.58        | 1.61  |

Note. This table provides the parameters of the high-redshift quasar models (Section 3.3.1), which are best-fitted for the spectroscopy and photometry of the IMS \( z \sim 6 \) quasars, respectively.
new quasars in this work. Their $z$–$M_{1450}$ distributions are shown as the orange filled circles in Figure 10. With this complete sample of $z \sim 6$ quasars, we calculate the binned space density using the $1/V_e$ method of Avni & Bahcall (1980), where $V_e$ is the specific comoving volume. For given bin sizes of $\Delta M_{1450}$ and $\Delta z$, $V_e$ can be calculated as

$$V_e = \frac{1}{\Delta M_{1450}} \int F(z, M_{1450}) \frac{dV_e}{dz} \, dz \, dM_{1450},$$

where $dV_e/dz$ is the comoving element of our survey area. Then, we calculate the binned space density ($\Phi_{\text{bin}}$) and its error ($\sigma_{\Phi_{\text{bin}}}$) as follows:

$$\Phi_{\text{bin}}(M_{1450}) = \frac{1}{\Delta M_{1450}} \sum_{i=1}^{N_{\text{bin}}} \frac{1}{V_e},$$

and

$$\sigma_{\Phi_{\text{bin}}}(M_{1450}) = \frac{1}{\Delta M_{1450}} \left[ \sum_{i=1}^{N_{\text{bin}}} \left( \frac{1}{V_e} \right)^2 \right]^{1/2},$$

where $N_{\text{bin}}$ is the number of objects in the given bin. This method critically depends on the choice of the bin. Considering the small number of our sample, we set a single redshift bin of $5.8 < z < 6.4$. The average redshift of our sample is $z = 6.08$. Meanwhile, we took two large $M_{1450}$ bins: $-26.0 < M_{1450} < -24.5$ and $-24.5 < M_{1450} < -23.0$ (red boxes in Figures 10 and 11). Such large bins in $M_{1450}$ were chosen because our sample is small but complete. There are two and three quasars in each bin, and their average magnitudes are $M_{1450} = -25.28$ and $-23.69$ mag, respectively. The resultant $\Phi_{\text{bin}}$ values are listed in Table 4 (top two rows). We note that the average redshifts of the two bins are $z = 6.25$ and 5.97, respectively. The discrepant redshift values reflect the shape of the completeness function and the larger volume available for higher redshifts for the brighter sample. We consider both of the points representing the $z \sim 6$ quasar space density considering the small number statistics and the small redshift difference.

Despite the small number of our sample, we additionally calculated the binned space densities in the three survey fields where the quasars are identified: EGS ($i_1'$), EGS ($i_2'$), and SA22 ($i_1'$). The results are given in the bottom three rows of Table 4, which are higher than the one for the total survey area. We discuss this in the following section.
### Table 4

| Field | $M_{1450}$ (mag) | $\Delta M_{1450}$ (mag) | $N_{\text{bin}}$ | $V_\alpha$ (Gpc$^3$) | $\Phi_{\text{bin}}$ (Gpc$^{-3}$mag$^{-1}$) |
|-------|-----------------|-------------------------|-----------------|----------------------|----------------------------------|
| Total | $-25.28$        | 1.5                     | 2               | $0.31$               | $4.27 \pm 0.02$                   |
|       | $-23.69$        | 1.5                     | 3               | $0.14$               | $13.8 \pm 8.0$                    |
| EGS ($i_1'$) | $-25.28$        | 1.5                     | 2               | $0.10$               | $13.9 \pm 9.2$                    |
| EGS ($i_2'$) | $-23.54$        | 1.5                     | 1               | $0.01$               | $61.9 \pm 61.9$                   |
| SA22 ($i_2'$) | $-23.77$        | 1.5                     | 2               | $0.03$               | $39.3 \pm 27.8$                   |

## 6. Discussion

In Figure 12, we compare our results with those from the literature (Willott et al. 2010; Jiang et al. 2016; Matsuoka et al. 2018c; Giallongo et al. 2019; Grazian et al. 2020), after the correction for the cosmological parameters. For the results from faint X-ray AGNs at $z \sim 5.5$ (Parsa et al. 2018; Giallongo et al. 2019; Grazian et al. 2020), we adopted the density shift to $z = 6$ using the density scaling factor of $10^{-0.723}$ at $z = 5.6$ (Jiang et al. 2016). Note that Matsuoka et al. (2018c) derived their space densities including the samples of Willott et al. (2010) and Jiang et al. (2016). We also show the Matsuoka et al. (2018c) LF in a double-power-law function (blue solid line). Our space densities from the total survey area (red circles) are broadly consistent with those from the previous large surveys for UV quasars (Willott et al. 2010; Jiang et al. 2016; Matsuoka et al. 2018c), despite large errors with the small number statistics. In the intermediate magnitude range of $-24 < M_{1450} < -22$ in question, our result shows the suppressed space density in line with the recent quasar LF of Matsuoka et al. (2018c). Therefore, our result reinforces the suggestion that quasars are not the main contributor to the reionizing process at $z \sim 6$ (e.g., Ricci et al. 2017; Dayal et al. 2020; Jiang et al. 2022), disfavoring the AGN-dominant scenario (e.g., Giallongo et al. 2015; Madau & Haardt 2015).

Our main result, however, is somewhat different from the space densities of Onoue et al. (2017) and Grazian et al. (2020), both from the AGNs identified by rest-UV spectroscopy, favoring a continuous increase in space density from bright to faint AGN populations. But we here point out that the fundamental limitation of these two studies is their small survey areas (6.5 and 0.15 deg$^2$, respectively) and corresponding small $V_\alpha$, which could result in the overestimated space densities. For instance, we show the space densities from our three individual fields where high-redshift quasars are discovered (red hexagons): EGS ($i_1'$), EGS ($i_2'$), and SA22 ($i_2'$). As in the two studies, the results are from one or two quasars in the small survey area (29.2, 5.2, and 16.7 deg$^2$), which may give higher space densities than those from our total survey area.

Grazian et al. (2020) suggest that their higher space density is due to the stringent color selection criteria of the other studies (e.g., $i_{\text{HSC}} - z_{\text{HSC}} > 2$ in Matsuoka et al. 2018c), while the two quasars they used (GDN 3333 and GDS 3073) have moderate ($i' - z'$)-matched colors: 0.12 and 0.69, respectively. But the two quasars are at $z = 5.2$ and 5.6, respectively, so it would be better to check their $i' - i'$ colors instead to see whether they can be selected by the traditional color selection. From the CANDELS catalogs (Guo et al. 2013; Barro et al. 2019), we found that their ($i' - i'$)-matched colors\(^{21}\) are 2.11 and 3.03, respectively. These are red enough to be selected as a quasar candidate with a color selection (e.g., $r' - i' > 1.2$ for $z > 5$ quasars; Kim et al. 2020), so the strict color selection cannot solely explain the discrepancy clearly.

From a different point of view, such high densities can be explained with the recent quasar LF model by Kim & Im (2021). This model is based on the empirical scaling relations of dark matter halos, galaxies, and black holes, while the key idea is that an AGN outshining its host galaxy can be observed as a point-source-like quasar. In Figure 12, we show the model with/without the outshining effect as the black solid/dashed line, respectively. Note that we show the models including the gravitational lensing effect of Pacucci & Loeb (2020). These models suggest that the discrepancy in space density between rest-UV quasars (e.g., Matsuoka et al. 2018c; this work) and faint X-ray AGNs from some previous works (e.g., Giallongo et al. 2019) can be explained if a large fraction of AGNs become dimmer in UV than its host galaxy.

The high space densities of Onoue et al. (2017) and Grazian et al. (2020) are in line with the model without the outshining effect. It is worth noting that the AGNs used in these studies have distinct properties from typical bright quasars. For example, ELAIS 109100446, one of the two AGNs in Onoue et al. (2017), has only a narrow Ly$_\alpha$ line without any other emission lines on its rest-UV spectrum, which indicates that it could be an Ly$_\alpha$ emitter galaxy (Kashikawa et al. 2015). GDN 3333 in Grazian et al. (2020) shows similar features on its spectrum (Barger et al. 2002), while it is classified as an AGN with strong X-ray detection (Alexander et al. 2003; Giallongo et al. 2019); GDS 3073, another quasar in Grazian et al. (2020), is likely a Seyfert galaxy based on the morphological decomposition, while it has no X-ray detection. Taken together, their observational properties appear to be a mixture of AGNs and UV-bright galaxies, so their presence is consistent with the framework of Kim & Im (2021).

It has recently been claimed that the $M_{1450}$ boundary between AGN and star-forming galaxy (represented by an LBG) is blurred, i.e., the AGN fraction of UV sources changes smoothly at $-24 < M_{1450} < -22$ (Adams et al. 2020; Bowler et al. 2021; Harikane et al. 2021). In Figure 12, we show the LF of UV dropout objects at $z \sim 6$ (gray crosses; Harikane et al. 2021). Compared to their best-fit result (gray dotted line), our faint bin gives an AGN fraction of $\sim$30% at $M_{1450} = -23.7$ mag, which is lower than those at lower redshifts (e.g., $\sim$80% at $z \sim 4$; Bowler et al. 2021). This is naturally explained by the more dramatic changes in AGN numbers between $4 \lesssim z \lesssim 7$ (Matsuoka et al. 2018c; Akiyama et al. 2018; Wang et al. 2019; Kim et al. 2020; Niida et al. 2020) than galaxy numbers in UV (Song et al. 2016; Ono et al. 2018; Behroozi et al. 2019; Harikane et al. 2021).

## 7. Summary

In this work, we present the final result of the IMS $z \sim 6$ quasar survey. Over the 86 deg$^2$ sky area of CFHTLS-IMS overlap regions, 25 candidates satisfying the traditional color selection criteria were picked up. We additionally applied the AICc selection based on the SED fitting, resulting in the seven credible candidates. While three of them are known $z \sim 6$ quasars, our follow-up spectroscopy for the remaining candidates leads us to discover two new $z \sim 6$ quasars. Such a high success rate (5/7) proves that our new approach with the AICc method allows us to find plausible candidates efficiently.

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\(^{21}\) F606W–F775W color in the Hubble Space Telescope/Advanced Camera for Surveys (HST/ACS) filter system.
With the complete sample of five quasars, we estimated the quasar space density down to $M_{1450} = -23.5$ mag at $z \sim 6$: $\Phi_{\text{bin}} = 4.3$ and $14 \text{ Gpc}^{-3} \text{mag}^{-1}$ at $M_{1450} = -25.3$ and $-23.7$ mag, respectively. These low numbers are consistent with the recent estimates from other large surveys, which endorses the minor role of quasars in the ionizing process in the reionization era.

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Figure 12. Quasar space densities at $z \sim 6$. The red circles represent our results from the total survey area, while the red hexagons are from the three individual fields where high-redshift quasars are identified. The other symbols represent those in the literature (Willott et al. 2010; Jiang et al. 2016; Onoue et al. 2017; Matsuoka et al. 2018c; Parsa et al. 2018; Giallongo et al. 2019; Grazian et al. 2020). The filled (open) symbols are from the surveys based on rest-UV photometry (X-ray detection). The blue line shows the parametric LF of quasar (Matsuoka et al. 2018c). The black solid (dashed) line represents the quasar LF model with (without) the outshining effect (Kim & Im 2021). The parametric LF of UV dropout objects (or AGN+galaxy; Harikane et al. 2021) is auxiliary, shown as the gray crosses with dotted line.
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Facilities: CFHT (MegaCam), Hale (DBSP), Gemini:South (GMOS-S), UKIRT (WFCAM).
Software: PSFEx (Bertin 2011), PypeIt (Prochaska et al. 2020a, 2020b), SExtractor (Bertin & Arnouts 1996), SWarp (Bertin 2010).

Appendix

Quasar Candidate Selection without J-band Detection

The fifth criterion of our initial color selection ($J < J_{sp}$ in Section 3.2) allows us to select only the sources with significant $J$-band detections. But we may miss many quasars owing to this criterion. For example, a $z = 6.0$ quasar at $z' = 23.0$ mag is expected to have $J = 22.8$ mag, inferred from the quasar track in Figure 3, which is beyond the J-band $5\sigma$ depth of many of the survey areas (especially for those in CFHTLS-W2 and EGS fields; see Figure 1).

We performed the same selection process as in the main text except for the fifth criterion. An additional 1563 sources were color-selected, and 899 sources remain after the automatic process to reject sources on the bad pixels. Visual inspection of the images of the remaining sources showed that most of them are cosmic rays and diffraction spikes. Hence, we finally have 31 sources after the visual inspection. Interestingly, 23 of 31 objects have $w_\alpha > 0.99$ with our AICc method, meaning that they are likely to be high-redshift quasars rather than late-type stars. However, we note that their best-fit models correspond to extreme cases. Figure 13 shows the EW and $\alpha_\gamma$ distributions of the candidates without J-band detection. Compared to the five quasars in this work (red circles; Table 3) and the reported distributions of $z \sim 6$ quasars (blue diamond; Bañados et al. 2016; Mazzucchelli et al. 2017), they have much higher EW values and steeper continuum slope, so they are unlikely to be high-redshift quasars.

Recent high-redshift quasar survey studies with deep HSC data have discovered some $z \sim 6$ quasars with a strong but narrow Ly$\alpha$ line (EW > 200 Å; Matsuoka et al. 2018a, 2018b, 2019a, 2022), but most of them are fainter than our survey limit ($M_{1450} > -23.5$ mag). Matsuoka et al. (2022) also showed that such faint quasars tend to have a strong Ly$\alpha$ line (or a high EW compared to continuum). Note that the EW values are estimated with the fixed continuum slope of $\alpha_\gamma = -1.5$ in those studies, so our EW values will increase if we assume the same condition. In addition, we cross-checked the reliability of the 31 candidates with deep HSC images. Only six of them are located in the HSC PDR3 survey area (teal crosses in Figure 13), but five of them have no matched sources even though they are bright enough to be detected in the HSC images. This means that such sources in our survey may be noncelestial bodies or artificial objects just detected in the $z'$-band images. Even for the matched one ($\log EW = 1.9$ and $\alpha_\gamma = -4.5$), it has a very blue color of $\epsilon_{\text{HSC}} - \zeta_{\text{HSC}} = 0.38$. Therefore, we conclude that these additional candidates without J-band detection are unlikely to be real high-redshift quasars.
Figure 13. EW and $\alpha_P$ distributions of the candidates without $J$-band detection. The gray circles are the color-selected candidates, while the orange circles are the ones satisfying the AICc criterion ($w_q > 0.99$). Several candidates matched to the same quasar model were overlaid, so they appear to have low transparency on the diagram. The candidates covered by the HSC survey are marked by teal crosses. The five quasars in this work are shown as red circles. The blue diamond (and blue lines on the histograms) represents the reported normal distribution of $z \sim 6$ quasars: $\log EW = 1.542 \pm 0.391$ (Bañados et al. 2016) and $\alpha_P = -1.6 \pm 1.0$ (Mazzucchelli et al. 2017), in the form of mean $\pm$ standard deviation. Note that the correlation between the reported EW and $\alpha_P$ is not reflected in this figure.
