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Subaru High-z Exploration of Low-luminosity Quasars (SHELLQs). X. Discovery of 35 Quasars and Luminous Galaxies at $5.7 \leqslant z \leqslant 7.0$

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Abstract

We report the discovery of 28 quasars and 7 luminous galaxies at $5.7 \leqslant z \leqslant 7.0$. This is the tenth in a series of papers from the Subaru High-z Exploration of Low-Luminosity Quasars (SHELLQs) project, which exploits the deep multiband imaging data produced by the Hyper Suprime-Cam (HSC) Subaru Strategic Program survey. The total number of spectroscopically identified objects in SHELLQs has now grown to 93 high-z quasars, 31 high-z luminous galaxies, 16 [O III] emitters at $z \sim 0.8$, and 65 Galactic cool dwarfs (low-mass stars and brown dwarfs). These objects were found over 900 deg^2, surveyed by HSC between 2014 March and 2018 January. The full quasar sample includes 18 objects with very strong and narrow Lyα emission, whose stacked spectrum is clearly different from that of other quasars or galaxies. While the stacked spectrum shows N V $\lambda 1240$ emission and resembles that of lower-z narrow-line quasars, the small Lyα width may suggest a significant contribution from the host galaxies. Thus, these objects may be composites of quasars and star-forming galaxies.

Key words: dark ages, reionization, first stars – galaxies: active – galaxies: high-redshift – intergalactic medium – quasars: general – quasars: supermassive black holes

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1. Introduction

Quasars in the high-z universe[25] have been used as an unique probe into early cosmic history. The progress of cosmic reionization can be measured from H I absorption imprinted on the rest-frame ultraviolet (UV) spectrum of a high-z quasar; this absorption is very sensitive to the neutral fraction of the foreground intergalactic medium (IGM; Gunn & Peterson 1965; Fan et al. 2006). The luminosity and mass functions of quasars reflect the seeding and growth mechanisms of supermassive black holes, which can be studied through comparison with theoretical models (e.g., Volonteri 2012; Ferrara et al. 2014; Madau et al. 2014). Measurements of quasar host galaxies and surrounding environments tell us about the earliest mass assembly of galaxies, which may happen in the highest-density peaks of the underlying dark matter distribution (e.g., Goto et al. 2009; Decarli et al. 2017).

For the past several years, we have been carrying out a project to search for high-z quasars, named "Subaru High-z Exploration of Low-luminosity Quasars (SHELLQs)," with the Subaru 8.2 m telescope. Matsuoka et al. (2016, 2018a, 2018b, 2019) have already reported the discovery of 65 high-z quasars, along with 24 high-z luminous galaxies, 6 [O III] emitters at $z \sim 0.8$, and 43 Galactic cool dwarfs (low-mass stars and brown dwarfs). These objects include many low-luminosity quasars with redshifts up to $z = 7.07$, objects that have been difficult to find in past shallower surveys. Combined with samples of luminous quasars from the SDSS (Jiang et al. 2016) and the Canada-France High-z Quasar Survey (Willott et al. 2010), the SHELLQs sample has allowed us to establish the quasar luminosity function (LF) at $z = 6$ over an unprecedented range of magnitude ($-22 < M_{1450} < -30$ mag; Matsuoka et al. 2018c). We found that the LF has a break at $M_{1450} \sim -25$ mag and flattens significantly toward the faint end. With this LF shape, we predict that quasars are responsible for less than 10% of the ionizing photons that are necessary to keep the IGM fully ionized at $z = 6$.

We are also carrying out multiwavelength follow-up observations of the discovered quasars. Near-infrared (IR) spectra were obtained for six quasars, which revealed that the SHELLQs quasars have a wide range of accretion properties, from sub-Eddington accretion onto a massive ($M_{\rm BH} > 10^9 M_\odot$) black hole to Eddington accretion onto a less massive ($M_{\rm BH} < 10^8 M_\odot$) black hole (Onoue et al. 2019). Atacama Large Millimeter/submillimeter Array (ALMA) observations were conducted toward seven quasars, and we found that the host galaxies are forming stars at a rate below that of luminous quasar hosts (e.g., Decarli et al. 2018), and that the low-luminosity quasars are more or less on the local relation between black hole mass and host mass (Izumi et al. 2018, 2019). We are also exploiting archival *Wide-field Infrared Survey Explorer* data to look for red quasars in the SHELLQs sample, which may represent a younger phase of evolution than normal quasars (N. Kato et al. 2019, in preparation).

This paper is the tenth in a series of SHELLQs publications, and it reports the spectroscopic identification of an additional 67 objects. The paper is structured as follows. We give brief descriptions of the data and methods used for candidate selection in Section 2. Spectroscopic follow-up observations are presented in Section 3. Results and discussion appear in Section 4. We adopt the cosmological parameters $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$. All magnitudes in the optical and near-IR bands are presented in the AB system (Oke & Gunn 1983), and are corrected for Galactic extinction (Schlegel et al. 1998). We use the point-spread function (PSF) magnitude ($m_{\rm AB}$) and the CModel magnitude ($m_{\rm CModel,AB}$), which are measured by fitting the PSF models and two-component, PSF-convolved galaxy models to the source profile, respectively (Abazajian et al. 2004). In what follows, we refer to z-band magnitudes with the AB subscript ("$z_{\rm AB}$"), while redshift z appears without a subscript.

2. Photometric Candidate Selection

The SHELLQs project is based on the multiband imaging data produced by the Hyper Suprime-Cam (HSC) Subaru Strategic Program (SSP) survey (Aihara et al. 2018). HSC is a wide-field camera on Subaru (Miyazaki et al. 2018). It has a nearly circular field of view of 1°.5 diameter, covered by 116 2K × 4K Hamamatsu fully depleted CCDs. The pixel scale is 0″.17. The HSC–SSP survey has three layers with different combinations of area and depth. The Wide layer is observing 1400 deg^2 mostly along the celestial equator, with 5σ point-source depths of ($g_{\rm AB}$, $r_{\rm AB}$, $i_{\rm AB}$, $z_{\rm AB}$, $y_{\rm AB}$) = (26.5, 26.1, 25.9, 25.1, 24.4) mag measured in 2″.0 aperture. The total exposure times range from 10 minutes in the g- and r-bands to 20 minutes in the i-, z-, and y-bands, divided into individual exposures of ∼3 minutes each. The Deep and the UltraDeep layers are observing smaller areas (27 and 3.5 deg^2) down to deeper limiting magnitudes ($r_{\rm AB} = 27.1$ and 27.7 mag, respectively). The survey data are reduced with the dedicated pipeline *hscPipe* (Bosch et al. 2018) derived from the Large Synoptic Survey Telescope software pipeline (Jurić et al. 2017).

The procedure of our quasar candidate selection has been described in the previous papers (Matsuoka et al. 2016, 2018a, 2018b), so here we repeat the essence only briefly. The selection starts from the HSC–SSP survey data in the three layers, over the area observed in the i, z, and y bands for i-dropout selection or in the z and y bands for z-dropout selection. We include data that have not yet reached the planned full depth. All sources meeting the following criteria, and that are not flagged as having suspect detection or photometry, are selected:

$$\begin{aligned} (z_{\rm AB} < 24.5 \text{ and } \sigma_z < 0.155 \text{ and } i_{\rm AB} - z_{\rm AB} > 1.5 \\ \text{and } z_{\rm AB} - z_{\rm CModel,AB} < 0.15) \end{aligned} \quad (1)$$

or

$$\begin{aligned} (y_{\rm AB} < 25.0 \text{ and } \sigma_y < 0.217 \text{ and } z_{\rm AB} - y_{\rm AB} > 0.8 \\ \text{and } y_{\rm AB} - y_{\rm CModel,AB} < 0.15). \end{aligned} \quad (2)$$

Equations (1) and (2) select i-dropout and z-dropout candidates, respectively. Here, (σ_i, σ_z, σ_y) refer to the errors of the PSF magnitudes ($i_{\rm AB}$, $z_{\rm AB}$, $y_{\rm AB}$), as measured by *hscPipe*. The y-band limiting magnitude in Equation (2) is deeper than the limit used in our previous papers ($y_{\rm AB} < 24.0$), as we are shifting our focus to establishing the quasar LF at $z \sim 7$. The difference between the PSF and CModel magnitudes ($m_{\rm AB} - m_{\rm CModel,AB}$) is used to exclude extended sources. Sources with more than 3σ detection in the g or r band (if these bands

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[25] Throughout this paper, "high-z" denotes $z > 5.7$, where quasars are observed as i-band dropouts in the Sloan Digital Sky Survey (SDSS) filter system (Fukugita et al. 1996). The term "X-band dropouts" or "X-dropouts" refers to objects which are much fainter (and often invisible) in the X and bluer bands than in the redder bands.

Table 1
Journal of Discovery Spectroscopy

Object	i_{AB} (mag)	z_{AB} (mag)	y_{AB} (mag)	P_Q^B	t_{exp} (min)	Date (Inst)
			Quasars			
J235646.33+001747.3	>26.51	27.20 ± 1.07	22.94 ± 0.05	1.000	120	2018 Nov 7, 8 (O)
J160953.03+532821.0	>26.89	>26.317	24.15 ± 0.09	1.000	180	2019 Jul 4, 24 (O)
J011257.84+011042.4	>25.20	>24.27	23.04 ± 0.06	0.222	180	2018 Nov 8, 30 (O)
J161207.12+555919.2	>27.21	>26.38	24.09 ± 0.07	1.000	180	2019 Jun 25 (O)
J134400.87+012827.8	26.85 ± 0.44	>25.25	22.89 ± 0.07	1.000	30	2018 Apr 24 (F)
J000142.54+000057.5	27.21 ± 0.49	26.56 ± 0.73	22.59 ± 0.03	1.000	45	2018 Oct 13 (O)
J123137.77+005230.3	27.29 ± 0.42	25.96 ± 0.26	22.76 ± 0.05	1.000	30	2018 Apr 24 (F)
J135012.04−002705.2	26.71 ± 0.29	23.33 ± 0.03	22.89 ± 0.05	1.000	60	2018 Mar 17 (O)
J084456.62+022640.5	27.75 ± 0.98	23.83 ± 0.06	25.42 ± 0.33	1.000	30	2019 May 11 (F)
J113753.64+004509.7	26.89 ± 0.42	23.42 ± 0.03	22.30 ± 0.03	0.899	60	2018 Mar 11 (O)
J152555.79+430324.0	26.53 ± 0.20	23.34 ± 0.03	23.48 ± 0.09	1.000	60	2018 Mar 13 (O)
J151248.71+442217.5	26.15 ± 0.23	24.63 ± 0.14	24.16 ± 0.17	0.000	30	2018 Apr 24 (F)
J225520.78+050343.3	26.26 ± 0.39	22.31 ± 0.02	22.40 ± 0.04	1.000	30	2018 Aug 3 (O)
J134733.69−015750.6	25.12 ± 0.10	21.65 ± 0.01	22.12 ± 0.03	1.000	15	2019 Apr 24 (F)
J144823.33+433305.9	>24.22	22.33 ± 0.03	22.46 ± 0.04	1.000	30	2018 Aug 11 (O)
J000133.30+000605.4	26.94 ± 0.34	23.68 ± 0.05	23.57 ± 0.07	1.000	120	2019 Jul 1, 4 (O)
J151657.87+422852.9	25.85 ± 0.16	22.47 ± 0.01	22.46 ± 0.03	1.000	50	2018 Apr 25 (F)
J125437.08−001410.7	>25.45	23.89 ± 0.07	25.45 ± 0.75	1.000	30	2019May 11 (F)
J000445.81−004944.3	25.53 ± 0.12	22.54 ± 0.02	22.81 ± 0.05	1.000	30	2018 Aug 3 (O)
J093543.32−011033.3	26.79 ± 0.33	23.50 ± 0.04	24.79 ± 0.30	1.000	30	2019 May 10 (F)
J010603.68−003015.2	25.89 ± 0.43	22.83 ± 0.04	23.14 ± 0.06	1.000	45	2018 Aug 9 (O)
J142611.33−012822.8	27.38 ± 0.75	23.70 ± 0.06	23.56 ± 0.15	1.000	120	2019 Apr 9 (O)
J121049.13+013426.7	25.95 ± 0.26	23.90 ± 0.07	23.95 ± 0.24	0.900	30	2019 May 10 (F)
J093000.85+005738.4	23.51 ± 0.02	21.72 ± 0.01	21.62 ± 0.02	1.000	15	2019 Mar 8 (O)
J161819.77+552654.0	24.14 ± 0.02	22.43 ± 0.01	22.41 ± 0.02	1.000	40	2018 Apr 25 (F)
J142307.21−022519.0	24.28 ± 0.10	22.49 ± 0.05	22.85 ± 0.22	1.000	15	2018 Aug 11 (O)
J023858.09−031845.4	24.17 ± 0.08	22.64 ± 0.04	22.53 ± 0.08	1.000	30	2018 Sep 3 (O)
J113218.15+003800.1	25.90 ± 0.29	23.66 ± 0.08	23.73 ± 0.11	1.000	100	2019 Apr 24 (F)
			Galaxies			
J135348.55−001026.5	27.25 ± 0.44	23.33 ± 0.03	22.65 ± 0.03	1.000	60	2018 Mar 11 (O)
J144216.08+423632.5	26.14 ± 0.30	23.91 ± 0.07	23.63 ± 0.11	0.232	30	2019 May 10 (F)
J092117.65+030521.5	26.69 ± 0.26	24.05 ± 0.06	23.84 ± 0.14	1.000	30	2019 May 11 (F)
J115755.51−001356.2	26.53 ± 0.23	23.91 ± 0.05	23.80 ± 0.09	1.000	40	2019 Apr 26 (F)
J123841.97−011738.8	24.99 ± 0.14	23.46 ± 0.03	23.56 ± 0.08	1.000	30	2019 Apr 24 (F)
J162657.22+431133.0	26.24 ± 0.14	24.02 ± 0.07	24.30 ± 0.16	1.000	50	2019 May 10 (F)
J020649.98−020618.2	25.05 ± 0.13	23.20 ± 0.03	23.11 ± 0.06	1.000	60	2018 Sep 8 (O)
			[O III] Emitters			
J090017.67−014655.6	24.93 ± 0.09	23.30 ± 0.04	23.61 ± 0.14	1.000	60	2019 Mar 13 (O)
J015519.63−005814.7	>22.80	23.50 ± 0.07	23.56 ± 0.08	0.907	120	2018 Nov 3 (O)
J144221.95−013258.0	26.06 ± 0.20	23.98 ± 0.07	24.86 ± 0.25	1.000	10	2019 May 10 (F)
J115946.07+014023.7	22.69 ± 0.01	21.14 ± 0.01	22.94 ± 0.06	1.000	15	2019 Jun 9 (O)
J141332.93+014350.4	25.79 ± 0.17	23.65 ± 0.08	>24.39	1.000	10	2019 May 10 (F)
J094209.69−020302.1	23.57 ± 0.02	21.91 ± 0.02	23.34 ± 0.12	1.000	15	2019 Mar 8 (O)
J225124.84−010911.0	24.32 ± 0.05	22.69 ± 0.03	24.53 ± 0.19	1.000	42	2018 Sep 1 (O)
J093831.54−002523.4	25.98 ± 0.15	23.67 ± 0.05	26.12 ± 1.00	1.000	10	2019 May 10 (F)
J135049.56+013726.6	25.94 ± 0.21	23.94 ± 0.06	>24.08	1.000	10	2019 May 10 (F)
J150602.11+415317.5	23.54 ± 0.03	21.82 ± 0.01	24.11 ± 0.22	1.000	20	2018 Sep 1 (O)
			Cool Dwarfs			
J011152.80+013211.4	25.86 ± 0.43	23.54 ± 0.14	23.67 ± 0.08	0.218	120	2018 Oct 13, 15 (O)
J015548.62−061737.9	24.66 ± 0.16	23.12 ± 0.05	23.01 ± 0.10	0.242	60	2018 Sep 8 (O)
J020421.81−024421.1	23.07 ± 0.02	20.21 ± 0.01	19.19 ± 0.01	1.000	20	2018 Sep 1 (O)
J022144.40−053008.6	25.94 ± 0.15	22.93 ± 0.02	21.86 ± 0.02	0.410	60	2018 Nov 9 (O)
J085230.35+025410.0	>25.31	24.00 ± 0.07	23.86 ± 0.13	0.996	50	2019 Apr 25 (F)
J085818.99+040927.6	>25.50	23.54 ± 0.05	22.85 ± 0.08	0.929	120	2018 Nov 3 (O)
J124505.57+010550.2	⋯	22.05 ± 0.02	21.20 ± 0.01	⋯	20	2018 Apr 25 (F)
J135913.21+002740.0	26.75 ± 0.30	24.04 ± 0.06	22.16 ± 0.02	0.000	40	2019 Apr 25 (F)
J142531.82−021606.5	26.68 ± 0.62	23.50 ± 0.08	22.90 ± 0.17	0.000	120	2019 Apr 9 (O)

Table 1
(Continued)

Object	i_{AB} (mag)	z_{AB} (mag)	y_{AB} (mag)	P_Q^B	t_{exp} (min)	Date (Inst)
J145853.06+015031.8	24.05 ± 0.03	21.42 ± 0.02	20.40 ± 0.01	0.000	15	2018 Aug 10 (O)
J151812.04+440829.0	26.30 ± 0.20	23.38 ± 0.02	22.30 ± 0.02	0.062	60	2018 Mar 11 (O)
J153032.76+435615.5	25.27 ± 0.07	22.49 ± 0.01	21.55 ± 0.01	0.998	30	2018 Aug 11(O)
J154605.67+425306.1	28.07 ± 0.83	24.94 ± 0.13	22.64 ± 0.05	0.790	100	2019 Apr 24 (F)
J161042.47+554203.4	26.88 ± 0.17	24.68 ± 0.05	23.61 ± 0.05	1.000	141	2019 Jun 26 (O)
J164226.30+430749.7	25.00 ± 0.12	23.35 ± 0.05	23.48 ± 0.20	0.936	66	2019 Mar 8 (O)
J223827.66+053246.5	24.82 ± 0.13	23.13 ± 0.04	23.08 ± 0.07	1.000	60	2018 Sep 2 (O)
J224157.52+055912.6	24.52 ± 0.09	22.88 ± 0.04	23.06 ± 0.08	1.000	30	2018 Aug 3 (O)
J225132.39−011601.1	24.46 ± 0.08	22.75 ± 0.07	22.91 ± 0.06	0.994	30	2018 Aug 3 (O)
J225337.55+051440.1	>25.32	23.52 ± 0.05	22.77 ± 0.06	0.152	60	2018 Sep 5 (O)
J225513.58+044226.8	⋯	22.59 ± 0.03	21.92 ± 0.05	⋯	30	2018 Aug 3 (O)
J230811.42+023931.3	24.12 ± 0.05	22.40 ± 0.02	22.08 ± 0.06	0.998	15	2018 Aug 3 (O)
J231344.68−003931.3	24.85 ± 0.06	23.17 ± 0.03	22.94 ± 0.07	1.000	60	2018 Sep 1 (O)

Note. Coordinates are at J2000.0, and magnitude upper limits are placed at 5σ significance. We took magnitudes from the latest HSC–SSP DR, and recalculated P_Q^B for objects selected from older DRs; this is why a few objects have $P_Q^B < 0.1$. No i-band images are available at the positions of J124505.57+010550.2 and J225513.58 +044226.8 in the latest DR, due to quality issues, and thus, i_{AB} and P_Q^B are not available for these sources. The instrument (Inst) "O" and "F" denote GTC/OSIRIS and Subaru/FOCAS, respectively.

are available) are removed as likely low-z interlopers. We also remove those sources whose images appear to be moving objects, transients, or artifacts, spotted by automatic or eye inspection (see Matsuoka et al. 2016). We always keep ambiguous cases in our sample for spectroscopic follow-up, so that we do not discard any real quasars in the selection.

The candidates selected from the HSC data are matched, within 1″.0 separation, to the public near-IR catalogs from the United Kingdom Infrared Telescope Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007) data release (DR) 10 and 11, the Visible and Infrared Survey Telescope for Astronomy (VISTA) Kilo-degree Infrared Galaxy survey (VIKING) DR 4 and 5, and the VISTA Deep Extragalactic Observations Survey (Jarvis et al. 2013) DR 5. In practice, only a small fraction of the final quasar candidates have near-IR photometry, due to limited sky coverage and/or depth of the above surveys. Using all available magnitudes in the i, z, y, J, H, and K bands, we calculate the Bayesian quasar probability (P_Q^B) for each candidate. The calculation is based on models of spectral energy distributions and surface densities of high-z quasars and contaminating brown dwarfs, as a function of magnitude; galaxy models are not included in the algorithm at present (see Matsuoka et al. 2016). We keep those sources with $P_Q^B > 0.1$ in the sample of candidates, while removing sources with lower quasar probabilities.

We used the latest HSC–SSP (internal) DR, which includes observations carried out between 2014 March and 2018 January. The data cover roughly 900 deg^2, when we limit to the fields where at least (1, 2, 2) exposures were taken in the (i, z, y) bands for i-dropout selection, or at least (1, 2) exposures were taken in the (z, y) bands for z-dropout selection. We found ∼500 final candidates over this area, and put highest priority on (i) all the z-dropouts and (ii) the i-band dropouts with $i_{AB}−z_{AB} > 2.0$, $z_{AB} < 24.0$ mag, and y-band detection. We have almost completed follow-up spectroscopy of these ∼200 high-priority candidates, as reported in the past and present papers, and continue to observe the remaining low-priority candidates.

3. Spectroscopy

We carried out follow-up spectroscopy of 67 candidates from 2018 March through 2019 July, using the Optical System for Imaging and low-intermediate-Resolution Integrated Spectroscopy (OSIRIS; Cepa et al. 2000) mounted on the Gran Telescopio Canarias (GTC), and the Faint Object Camera and Spectrograph (FOCAS; Kashikawa et al. 2002) mounted on Subaru. We prioritized observations in such a way that the targets with brighter magnitudes and higher P_Q^B were observed at earlier opportunities. Table 1 is a journal of the spectroscopic observations.

GTC is a 10.4 m telescope located at the Observatorio del Roque de los Muchachos in La Palma, Spain. We used OSIRIS with the R2500I grism and 1″.0-wide longslit, which provides spectral coverage from $\lambda_{obs} = 0.74$ to 1.03 μm with a resolution $R \sim 1500$. The observations (Program IDs: GTC3-18A, GTC8-18B, and GTC32-19A) were carried out in queue mode on dark and gray nights, under spectroscopic sky conditions and with seeing 0″.6–1″.3.

The Subaru observations were carried out as part of two Subaru Intensive Programs (Program IDs: S16B-071I and S18B-011I). We used FOCAS in the multi-object spectrograph (MOS) mode with the VPH900 grism and SO58 order-sorting filter. The widths of the slitlets were set to 1″.0. This configuration provides spectral coverage from $\lambda_{obs} = 0.75$ to 1.05 μm with a resolution $R \sim 1200$. All of the observations were carried out on gray nights, which were occasionally affected by cirrus, with seeing 0″.4–1″.0.

All of the data obtained with GTC and Subaru were reduced using the Image Reduction and Analysis Facility (IRAF). Bias correction, flat fielding with dome flats, sky subtraction, and 1D extraction were performed in the standard way. The wavelength was calibrated with reference to sky emission lines. The flux calibration was tied to white dwarfs (Feige 34, Feige 110, G191-B2B, GD 153, Ross 640) or a B-type standard star (HILT 600), observed as standard stars within a few days of the target observations. We corrected for slit losses by scaling the spectra to match the HSC magnitudes in the z and y bands for the i- and z-band dropouts, respectively.
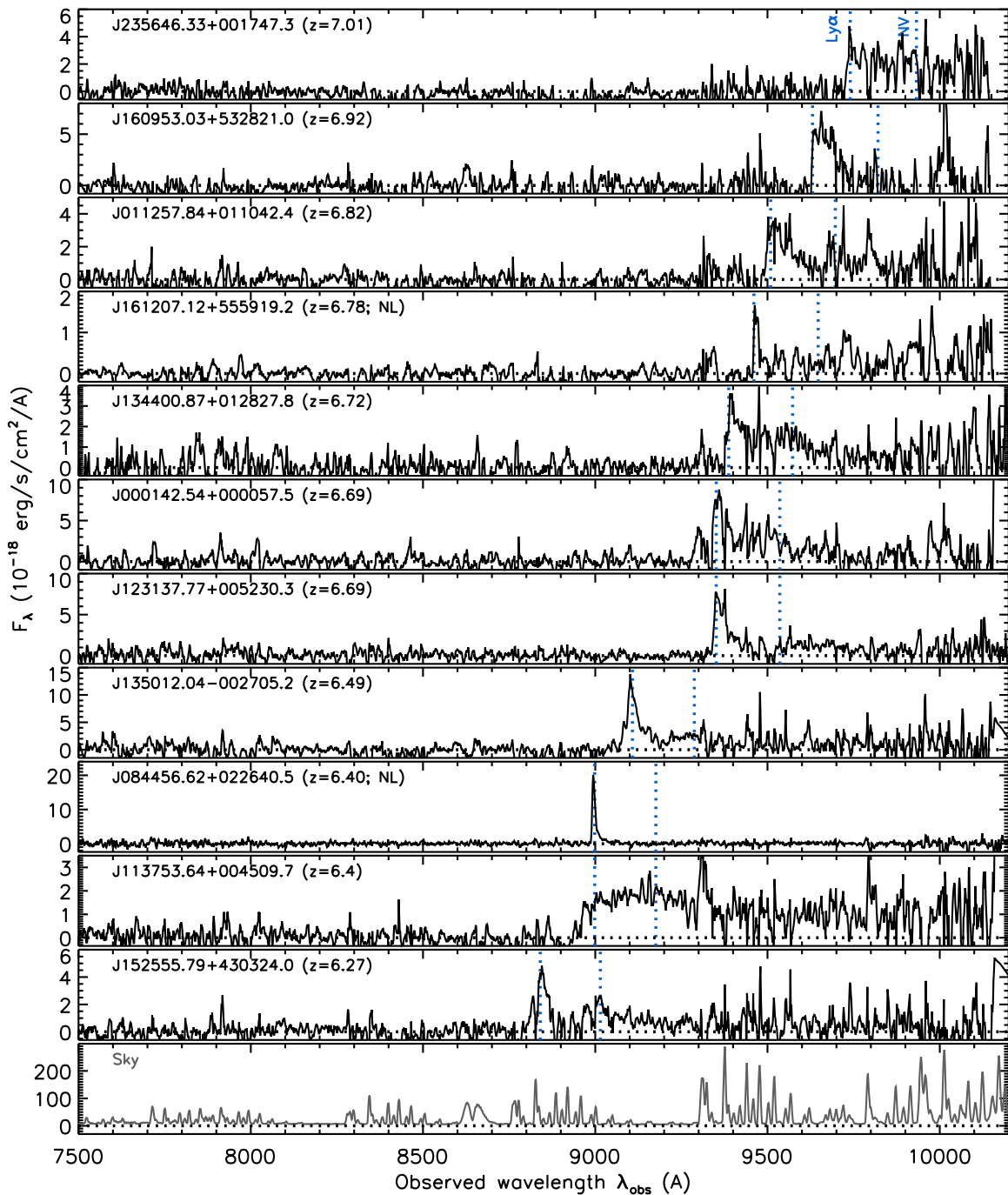
Figure 1. Discovery spectra of the first set of 11 quasars, displayed in decreasing order of redshift. The object name and the estimated redshift (and the designation "NL" for the possible quasars with narrow Lyα emission) are indicated at the top left corner of each panel. The blue dotted lines mark the expected positions of the Lyα and N V λ1240 emission lines, given the redshifts. The spectra were smoothed using inverse-variance weighted means over 1–9 pixels (depending on the signal-to-noise ratio (S/N)), for display purposes. The bottom panel displays a sky spectrum, as a guide to the expected noise.

4. Results and Discussion

We present the reduced spectra in Figures 1–7. Based on these spectra, we identified 28 high-z quasars, 7 high-z galaxies, 10 strong [O III] emitters at $z \sim 0.8$, and 22 cool dwarfs, as detailed below. The photometric properties of the observed candidates are listed in Table 1. Table 2 lists the objects detected in the near-IR bands.

Figures 1–3 present 28 new quasars we identified at $5.7 \leqslant z \leqslant 7.0$. Their spectroscopic properties are presented in the first

section of Table 3. The seven quasars at $z > 6.6$ are observed as z-dropouts on the HSC images, while the other objects are i-dropouts. The quasars have broad Lyα lines, blue rest-UV continua, and/or sharp continuum breaks just blueward of Lyα, the properties that are characteristic of high-z quasars. Following the previous papers, we classified the objects with very luminous ($L > 10^{43}$ erg s^{-1}) and narrow (full width at half maximum [FWHM] < 500 km s^{-1}) Lyα emission as possible quasars (see the discussion below). These objects tend to be
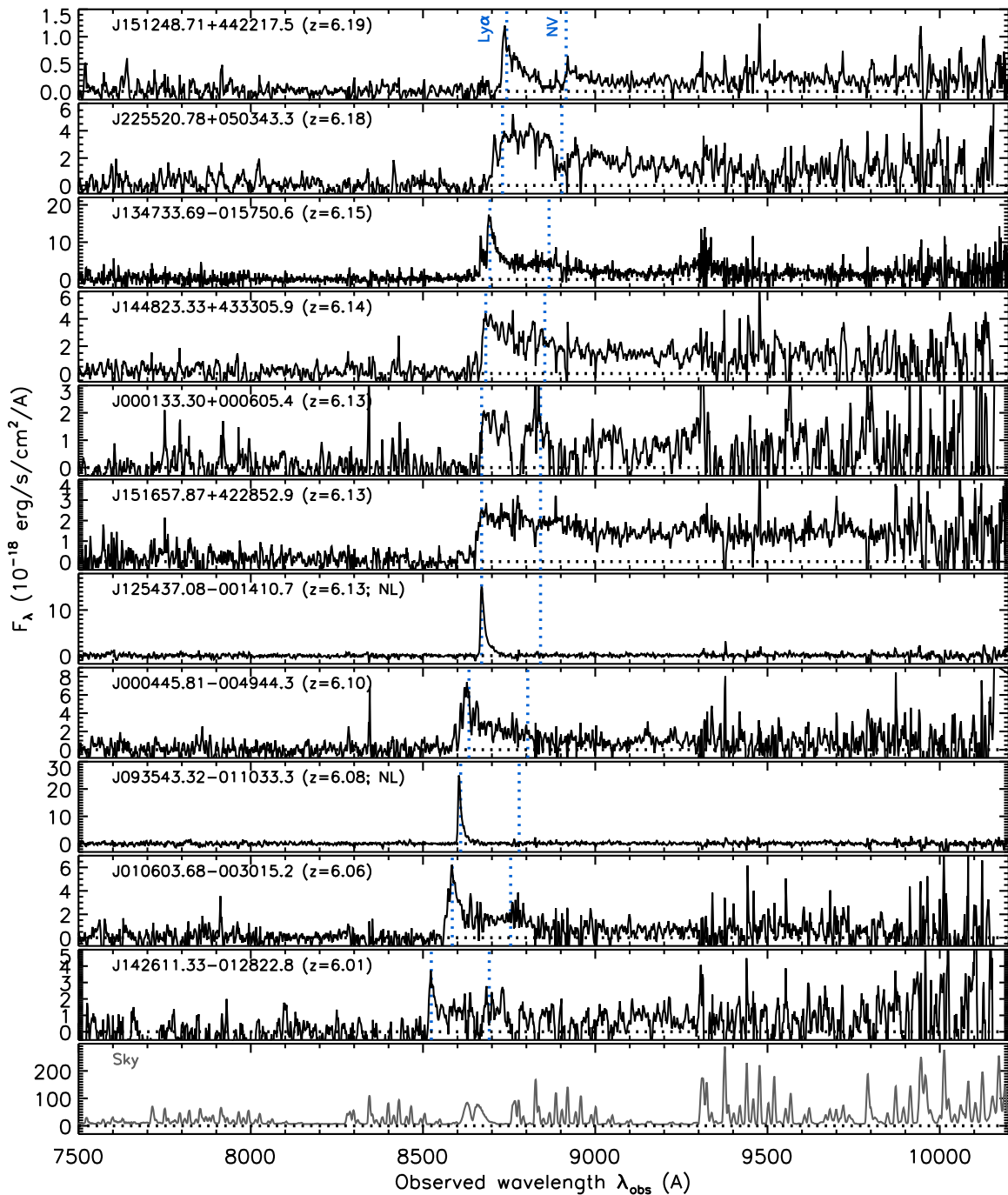
Figure 2. Same as Figure 1, but for the second set of 11 quasars.

found at the faintest magnitudes of our selection (Matsuoka et al. 2018a), and have been missed in past shallower surveys.

Redshifts of the discovered quasars were determined from the Lyα lines, assuming that the observed line peaks correspond to the intrinsic Lyα wavelength (1216 Å in the rest frame). This assumption is not always correct, due to the strong H I absorption by the neutral IGM. More accurate redshifts require observations of other emission lines, such as Mg II λ2800 observed in the near-IR or [C II] 158 μm accessible with ALMA. When there were no clear Lyα lines, we obtained rough estimates of redshift from the wavelengths of the onset of the Gunn & Peterson (1965) trough. Therefore,

the redshifts presented here are only approximate, with the uncertainties up to $\Delta z \sim 0.1$.

Absolute magnitudes (M_{1450}) and Lyα line properties of the quasars were measured as follows. For every object, we defined a continuum window at wavelengths relatively free from strong sky emission lines, and extrapolated the measured continuum flux to estimate M_{1450}. A power-law continuum model with a slope $\alpha = -1.5$ ($F_\lambda \propto \lambda^\alpha$; e.g., Vanden Berk et al. 2001) was assumed. Since the continuum windows fall in the range of $\lambda_{rest} = 1220$–1350 Å, which is close to $\lambda_{rest} = 1450$ Å, these measurements are not sensitive to the exact value of α. The Lyα properties (luminosity, FWHM, and rest-frame equivalent
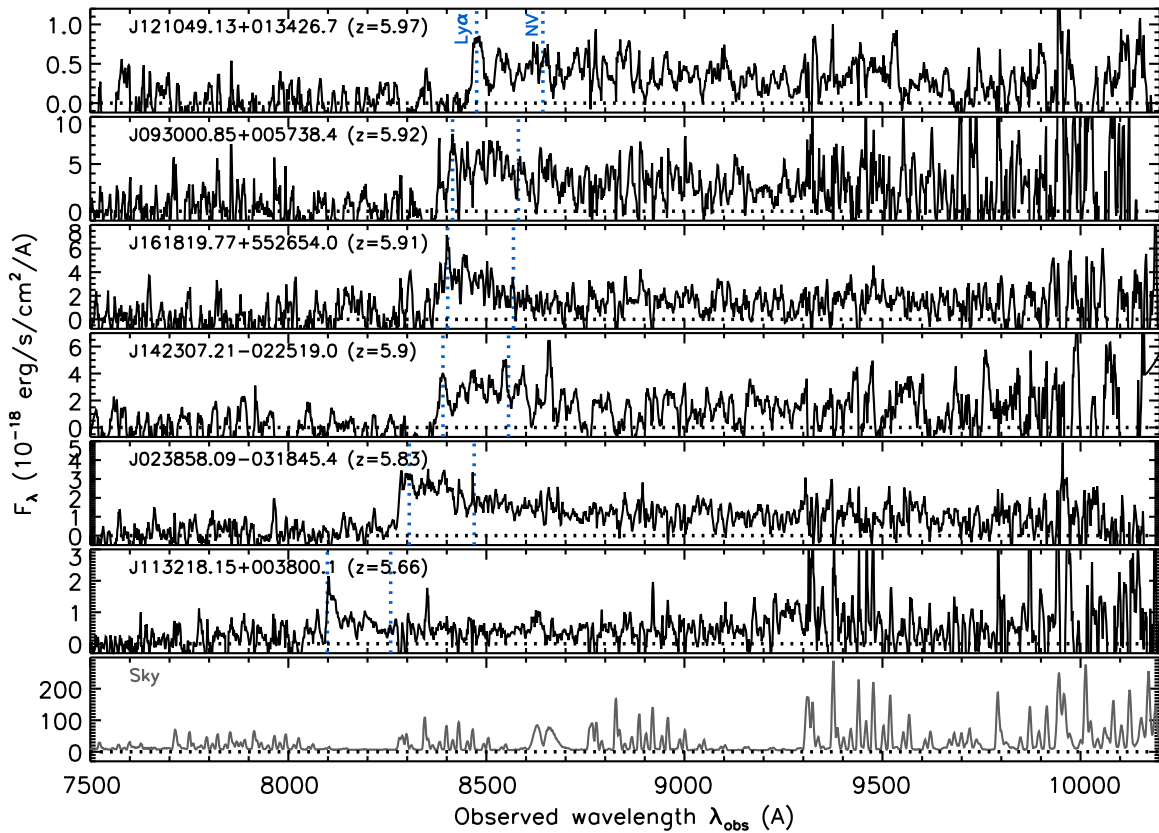
Figure 3. Same as Figure 1, but for the last set of six quasars.

width [EW]) of a quasar with relatively weak continuum emission, such as J084456.62+022640.5, was measured with a local continuum defined on the red side of Lyα. For the remaining objects with strong continuum, we measured the properties of the broad Lyα + N V λ1240 complex, with a local continuum defined by the above power-law model. The resultant line properties are summarized in Table 3.

J235646.33+001747.3 has a Lyα line peak at 9740 Å, which corresponds to a redshift $z = 7.01$. But this redshift may be an overestimate, as the intrinsic Lyα peak may be at a shorter wavelength and absorbed by the IGM. The flux spike at $\sim$9800 Å in the J011257.84+011042.4 spectrum is likely due to residual of a strong sky emission line. J151248.71+442217.5 has a relatively red continuum, and indeed the HSC magnitudes from the latest DR ($i - z = 1.5$ and $z - y = 0.5$) indicates a Bayesian quasar probability of $P_Q^B = 0.000$ (see Table 1); this object was selected from an older DR, which happened to give a higher P_Q^B.

Only three quasars are detected in the near-IR bands (see Table 2) and, interestingly, two of them (J113753.64+004509.7 and J142307.21−022519.0) apparently lack strong Lyα in emission. We re-examined all 75 broad-line quasars we discovered so far and found that out of the eight quasars with near-IR detection, five are such weak-line quasars. This is significantly higher than the average fraction of weak-line quasars among all 75 quasars ($\sim$20%; Y. Matsuoka et al. 2019, in preparation), or among more luminous quasars in the literature ($\sim$10%; Diamond-Stanic et al. 2009; Bañados et al. 2016). This may suggest a link between observed Lyα

weakness and the continuum shape at longer wavelength. We defer further analysis of this topic to a future paper.

Figure 4 presents seven high-z objects with no or weak Lyα emission line, which are most likely galaxies at $z \sim 6$. Redshifts of these galaxies were estimated from the observed wavelengths of Lyα, the interstellar absorption lines of Si II λ1260, Si II λ1304, C II λ1335, and/or the onset of the Gunn & Peterson (1965) trough. Due to the limited signal-to-noise ratio (S/N) of the spectra, the estimated redshifts should be regarded as only approximate ($\Delta z \lesssim 0.1$). The absolute magnitudes and Lyα properties were measured in the same way as for quasars, except that we assumed a continuum slope of $\beta = -2.0$ ($F_\lambda \propto \lambda^\beta$; Stanway et al. 2005).

Our quasar survey explores the luminosities where quasars and galaxies have comparable number densities (Matsuoka et al. 2018c), and hence contamination of galaxies is inevitable. Given the limited wavelength coverage of our spectra ($\lambda_{\rm rest} \sim 1200$–1500 Å), high-$z$ objects without broad Lyα emission are difficult to classify unambiguously into quasars or galaxies. Therefore, the above quasar/galaxy classification is not perfect, and it may change in the future, with new data providing additional S/N or wavelength coverage.

In addition to the above high-z objects, we found 10 [O III] emitters at $z \sim 0.8$, as displayed in Figure 5. Their strong [O III] lines contribute significantly to the HSC z-band magnitude, and thus mimic colors of $z \sim 6$ quasars. We measured the properties of the Hγ, Hβ, [O III] λ4959, and λ5007 emission lines, as listed in Table 3. Since these galaxies have very weak continuum, we estimated the continuum levels by summing up all available pixels after masking the above
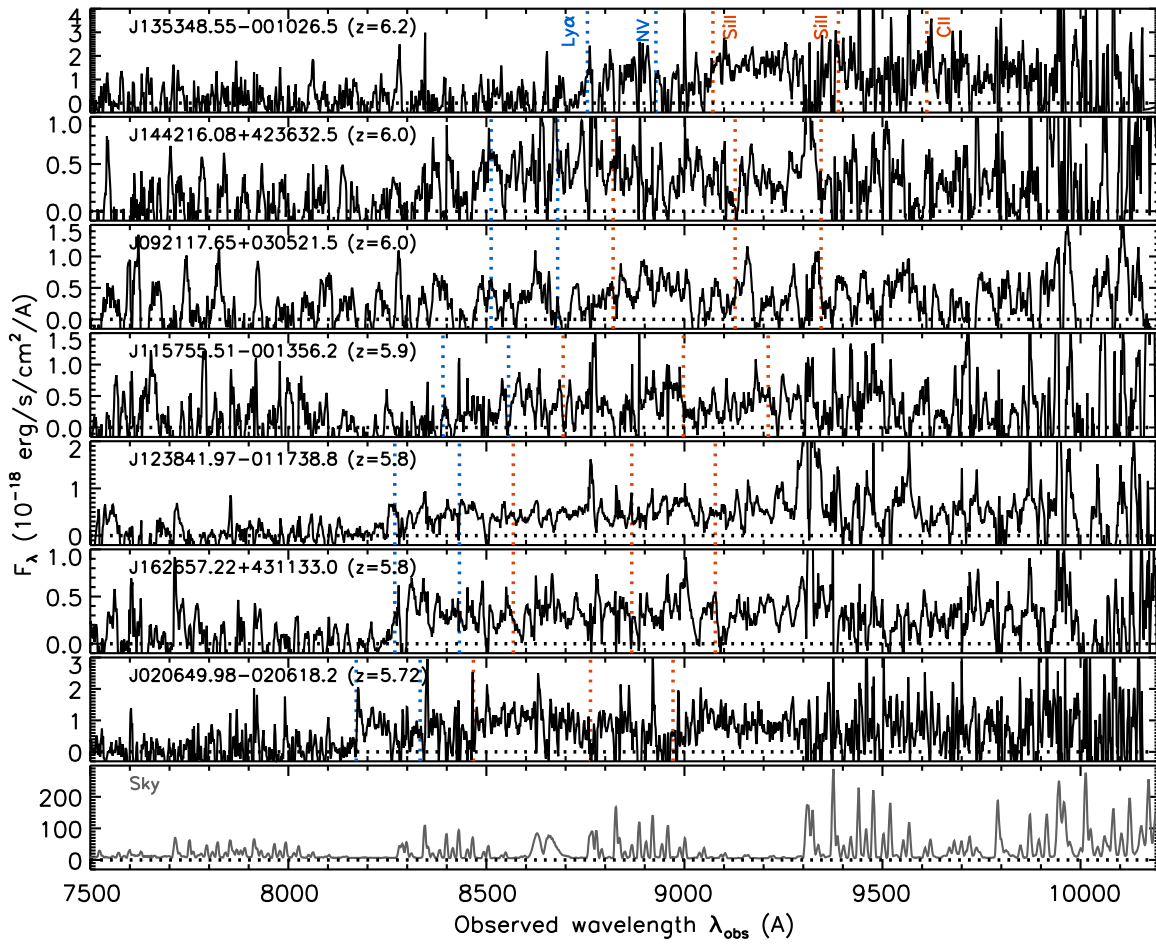
Figure 4. Same as Figure 1, but for the seven high-z galaxies. The expected positions of the interstellar absorption lines of Si II $\lambda1260$, Si II $\lambda1304$, and C II $\lambda1335$ are marked by the red dotted lines.
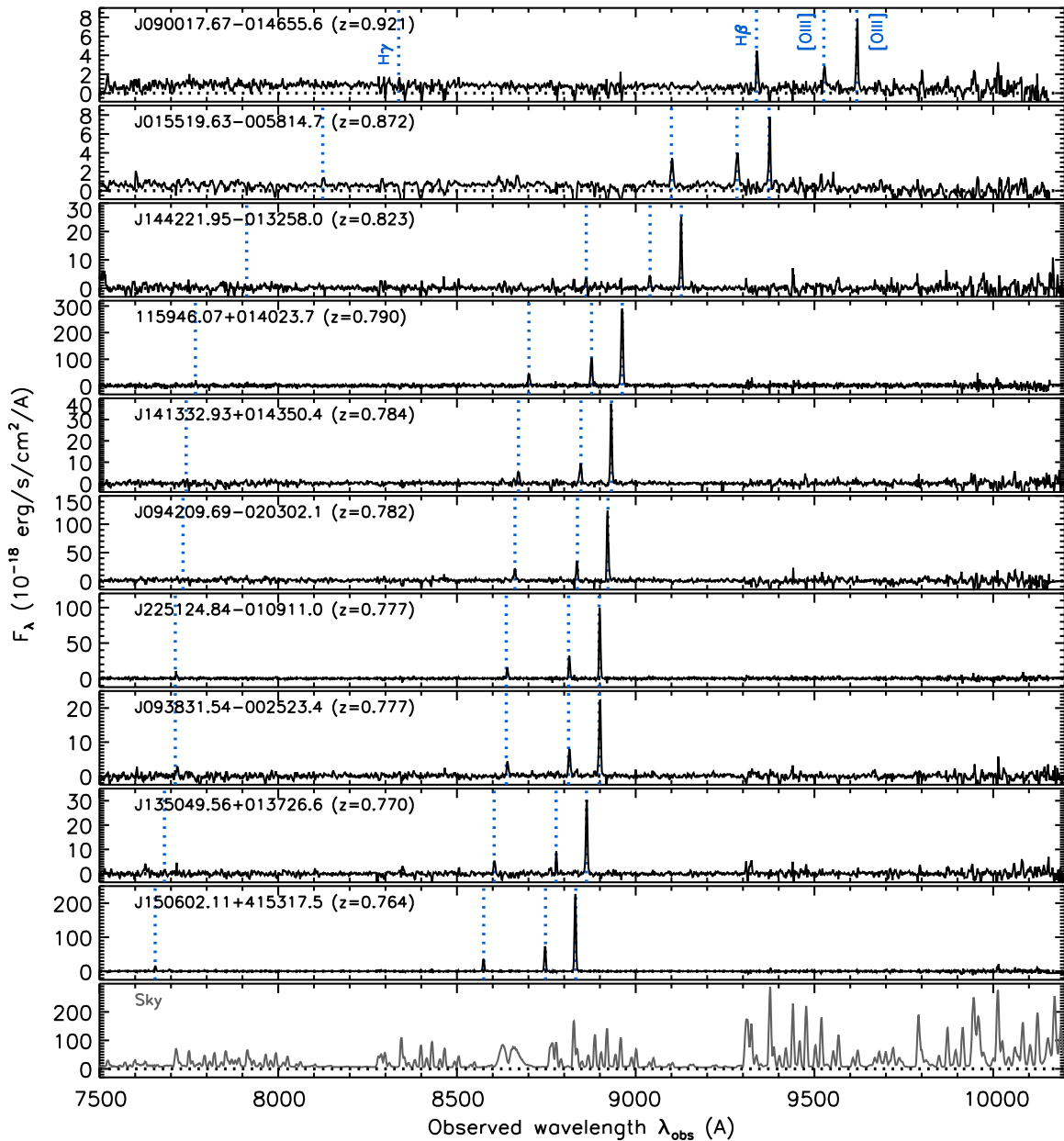
Table 2
Objects Detected in the Near-IR Bands

Name	J_{AB} (mag)	H_{AB} (mag)	K_{AB} (mag)	Survey
		Quasars		
J113753.64+004509.7	21.51 ± 0.20	21.67 ± 0.36	⋯	VIKING
J161819.77+552654.0	22.45 ± 0.10	⋯	21.82 ± 0.09	UKIDSS (Deep Extragalactic Survey)
J142307.21−022519.0	22.17 ± 0.27	⋯	⋯	VIKING
		Galaxies		
J135348.55−001026.5	22.15 ± 0.26	⋯	20.78 ± 0.16	VIKING
		Cool Dwarfs		
J142531.82−021606.5	21.54 ± 0.15	20.84 ± 0.16	20.46 ± 0.12	VIKING
J161042.47+554203.4	23.14 ± 0.19	⋯	23.25 ± 0.32	UKIDSS (Deep Extragalactic Survey)
J230811.42+023931.3	⋯	20.74 ± 0.26	⋯	UKIDSS (Large Area Survey)

emission lines. As we discussed in Matsuoka et al. (2018b), their extremely high [O III] $\lambda5007/\mathrm{H}\beta$ ratios may indicate that these are galaxies with sub-solar metallicity and a high ionization state of the interstellar medium (e.g., Kewley et al. 2016), and/or a contribution from an active galactic nucleus (AGN).

The remaining 22 objects presented in Figures 6–7 were found to be Galactic cool dwarfs (low-mass stars and brown dwarfs). Their rough spectral classes were estimated by fitting the spectral standard templates of M4- to T8-type dwarfs, taken from the SpeX Prism Spectral Library (Burgasser 2014; Skrzypek et al. 2015), to the observed spectra at $\lambda = 7500$–10200 Å. The results

Figure 5. Same as Figure 1, but for the 10 [O III] emitters at $z \sim 0.8$. The expected positions of Hγ, Hβ, and two [O III] lines ($\lambda4959$ and $\lambda5007$) are marked by the dotted lines.

are summarized in Table 4 and plotted in the figures. Due to the low S/N and limited wavelength coverage of the spectra, the classifications presented here are rather uncertain and should be regarded as only approximate.

Figure 8 presents shape indicators of the HSC objects with spectroscopic identification from our survey. The horizontal axis uses second-order adaptive moments in two image directions (μ_{11} and μ_{22}; Hirata & Seljak 2003), which should be equal to those of PSF ($\mu_{11}^{\rm PSF}$ and $\mu_{22}^{\rm PSF}$) for ideal point sources. The figure shows that quasars with narrow Lyα lines are slightly more extended than the other quasars, which indicates contribution of stellar emission (see the discussion further below). We could eliminate some of the galaxy contamination by a stricter cut of point-source selection (e.g., $m_{\rm PSF} - m_{\rm CModel} < 0.10$) than currently used, but that would also

reject those potentially important population of narrow-line objects. On the other hand, the figure suggests that the adoptive moments (μ_{11} and μ_{22}) may be less affected by catastrophic measurement errors, and hence may be a better shape indicator, than the magnitude difference ($m_{\rm PSF} - m_{\rm CModel}$); this option will be considered in future candidate selection.

Figure 9 presents the composite spectra of all 75 broad-line quasars, 18 narrow-line quasars, and 31 galaxies discovered by our survey. These spectra were generated by converting the individual spectra to the rest frame and normalizing to $M_{1450} = -23$ mag, and then median-stacking. Thus, the individual objects have equal weights in the stacking, regardless of the brightness or spectral S/N. The overall shape of the quasar spectrum is similar to that of the local quasar composite (Vanden Berk et al. 2001), except for the narrower
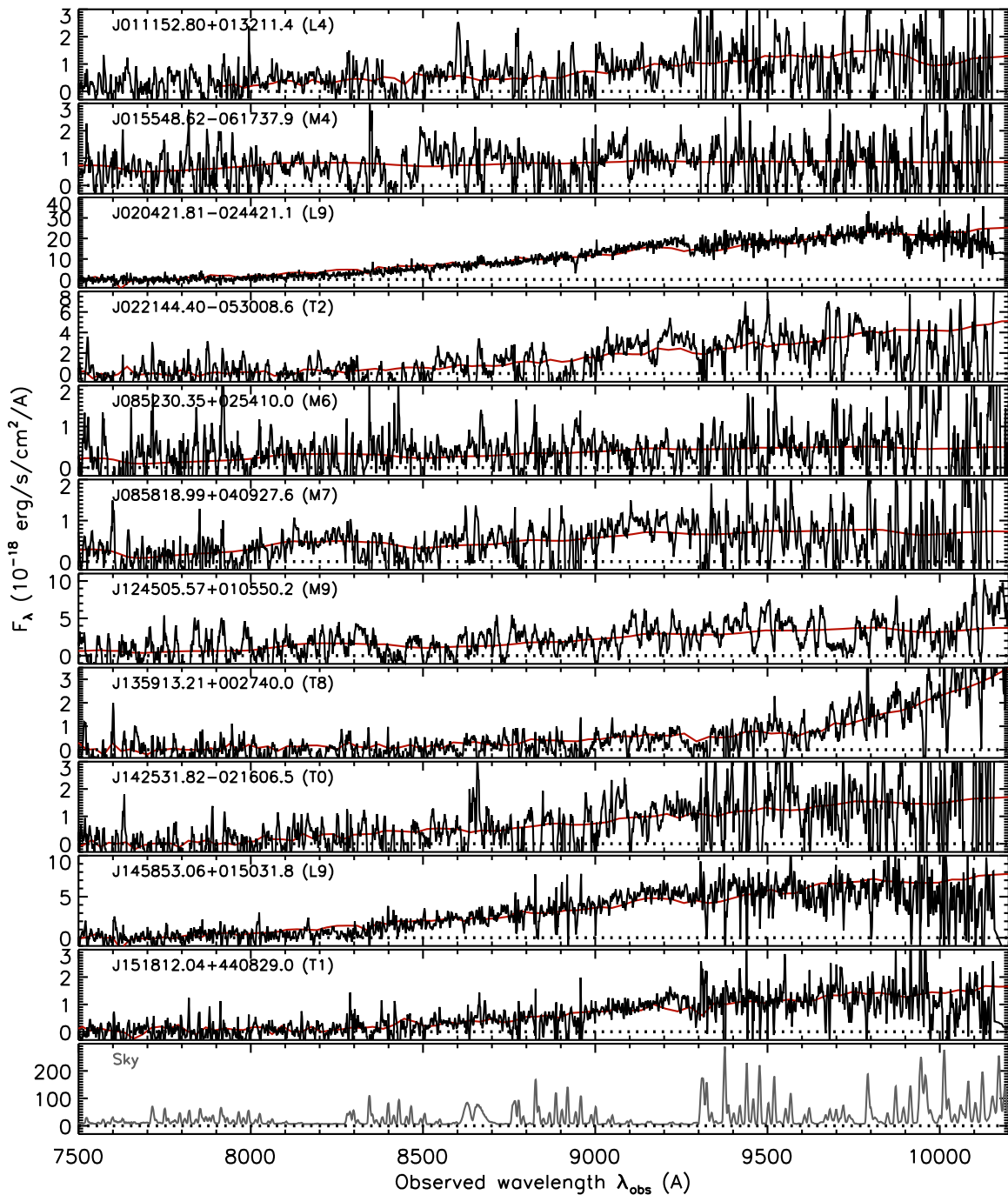
Figure 6. Same as Figure 1, but for the first set of 11 cool dwarfs. The red lines represent the best-fit templates, whose spectral types are indicated at the top left corner of each panel. The small-scale (<100 Å) features seen in the spectra are due to noise in most cases, given the limited S/N.

Lyα line and the IGM absorption. Our composite spectrum is also similar in shape to a composite spectrum of high-z luminous quasars from the Panoramic Survey Telescope & Rapid Response System 1 (Pan-STARRS1; Chambers et al. 2016) survey (Bañados et al. 2016), again except for the narrower Lyα line, which may reflect the Baldwin (1977) effect. While a clear sign of the quasar near-zone effect is visible just blueward of Lyα, it should be noted that the redshifts of most of our quasars have been determined with Lyα, and are thus not very accurate. A detailed analysis of emission and absorption profiles around Lyα, including the effect of IGM damping-wing absorption, must wait for

accurate measurements of systemic redshifts via other emission lines.

The composite spectrum of the narrow-line quasars is characterized by the strong and asymmetric Lyα line. The rest-frame EW of this line is 29 ± 2 Å in the composite, while it ranges up to ∼500 Å in the individual spectra. The spectrum shows a P Cygni-like profile around 1240 Å, which is likely due to N V λ1240 emission line and an associated mini broad absorption line system. This spectral feature, along with the very luminous Lyα line usually associated with AGN ($L_{Lyα} > 10^{43}$ erg s^{-1}; Konno et al. 2016) and the absence of interstellar absorption in the continuum, strongly suggest that
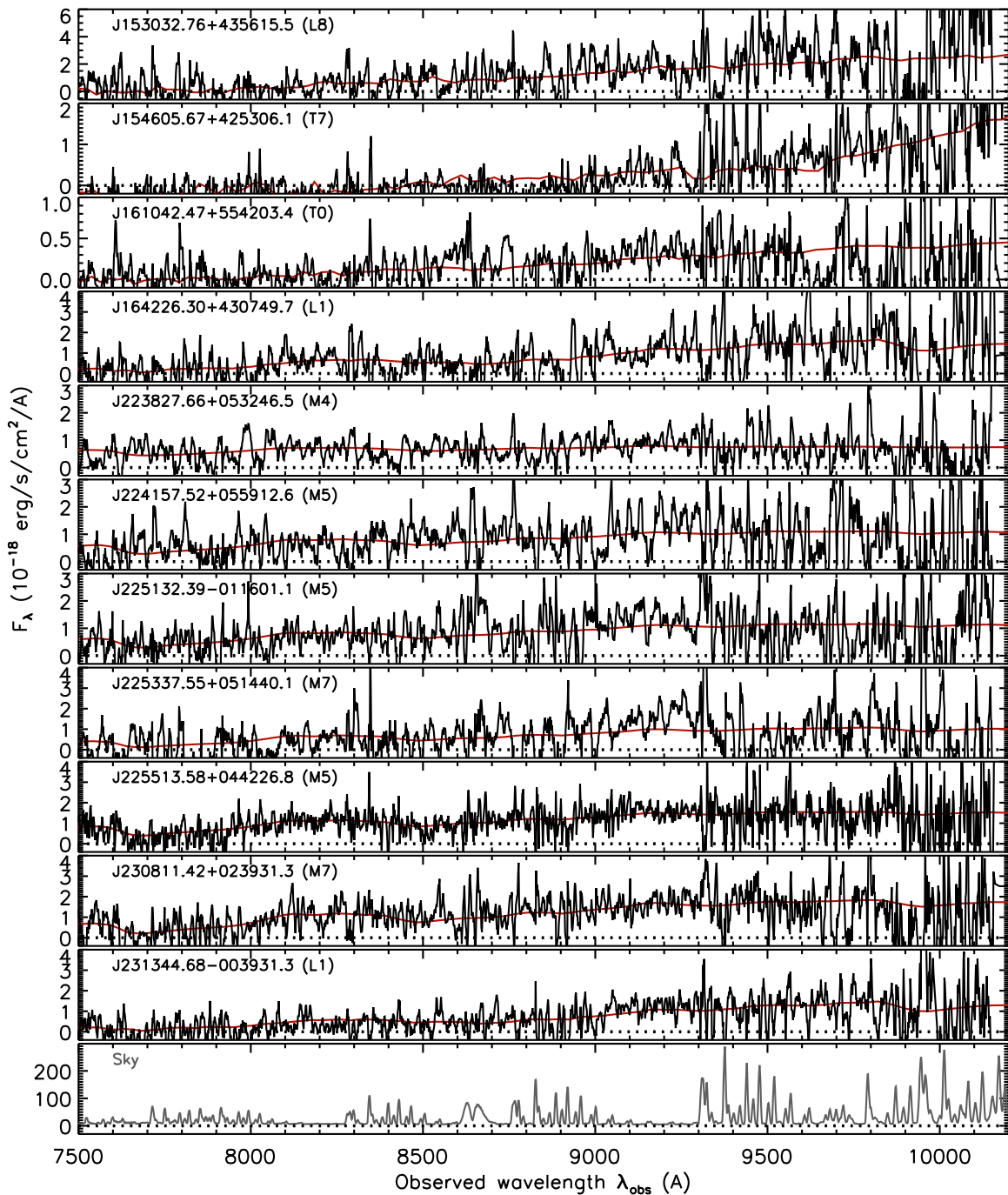
Figure 7. Same as Figure 6, but for the second set of 11 cool dwarfs.

these objects are narrow-line quasars (see also the discussion in Matsuoka et al. 2018b). Compared with narrow-line quasar candidates in SDSS (Alexandroff et al. 2013), these high-z objects have apparently narrower Lyα, indeed many are spectrally unresolved (most of the narrow-line quasars were observed with Subaru/FOCAS, which has a resolving power of $\sim$250 km s^{-1} with our observing mode). This may suggest a significant contribution from the host galaxies; thus, these objects may be composites of quasars (or AGNs) and star-forming galaxies.

We note that a color selection of high-z quasars (including a more sophisticated Bayesian selection we used) is generally more sensitive to objects with stronger Lyα lines. Thus, the composite spectra may not represent the whole populations of broad- and narrow-line quasars that reside in the high-z universe. On the other hand, we confirmed in a previous work (LF paper; Matsuoka et al. 2018c) that our quasar selection is fairly complete, as long as high-z quasars have a similar distribution of intrinsic spectral shapes to low-z SDSS quasars.

Finally, the galaxy spectrum in Figure 9 shows strong absorption lines, with rest-frame EWs of 1.7 ± 0.8 Å, 1.8 ± 0.7 Å, and 2.2 ± 1.6 Å for Si II λ1260, Si II λ1304, and C II λ1335, respectively. These are broadly consistent with the values measured in a composite spectrum of $z \sim 3$ Lyman break

Table 3
Spectroscopic Properties

Name	Redshift	M_{1450} (mag)	Line	EW_{rest} (Å)	FWHM (km s^{-1})	log L_{line} (L_{line} in erg s^{-1})
Quasars						
J235646.33+001747.3	7.01	-25.31 ± 0.04	$\cdots$	$\cdots$	$\cdots$	$\cdots$
J160953.03+532821.0	6.92	-22.75 ± 1.67	Lyα	210 ± 320	3600 ± 1300	44.31 ± 0.07
J011257.84+011042.4	6.82	-24.07 ± 0.35	Lyα	15 ± 7	1500 ± 400	43.71 ± 0.14
J161207.12+555919.2*	6.78	-23.02 ± 0.32	Lyα	12 ± 8	560 ± 270	43.15 ± 0.14
J134400.87+012827.8	6.72	-23.46 ± 0.15	Lyα	73 ± 12	9000 ± 1100	44.13 ± 0.04
J000142.54+000057.5	6.69	-24.49 ± 0.59	Lyα	11 ± 15	1600 ± 1000	43.72 ± 0.59
J123137.77+005230.3	6.69	-24.39 ± 0.09	Lyα	27 ± 3	2400 ± 900	44.09 ± 0.03
J135012.04−002705.2	6.49	-24.38 ± 0.19	Lyα	56 ± 11	620 ± 200	44.39 ± 0.04
J084456.62+022640.5*	6.40	-21.57 ± 0.47	Lyα	280 ± 160	<230	44.05 ± 0.01
J113753.64+004509.7	6.4	-24.20 ± 0.13	Lyα	22 ± 6	11000 ± 3000	43.91 ± 0.11
J152555.79+430324.0	6.27	-23.61 ± 0.06	Lyα	35 ± 4	340 ± 740	43.88 ± 0.04
			NV	18 ± 2	2900 ± 1600	43.60 ± 0.04
J151248.71+442217.5	6.19	-22.07 ± 0.04	Lyα	28 ± 2	3700 ± 200	43.18 ± 0.03
			NV	11 ± 2	2800 ± 300	42.77 ± 0.07
J225520.78+050343.3	6.18	-24.43 ± 0.02	Lyα	30 ± 1	6200 ± 700	44.14 ± 0.02
J134733.69−015750.6	6.15	-24.73 ± 0.02	Lyα	65 ± 2	1480 ± 10	44.59 ± 0.01
J144823.33+433305.9	6.14	-24.36 ± 0.04	Lyα	26 ± 2	7200 ± 1900	44.05 ± 0.03
J000133.30+000605.4	6.13	-23.72 ± 0.06	Lyα	11 ± 1	2500 ± 1100	43.44 ± 0.04
J151657.87+422852.9	6.13	-24.35 ± 0.01	Lyα	17 ± 1	9500 ± 2100	43.85 ± 0.03
J125437.08−001410.7*	6.13	-20.91 ± 0.32	Lyα	470 ± 160	310 ± 20	44.03 ± 0.01
J000445.81−004944.3	6.10	-23.90 ± 0.06	Lyα	53 ± 4	2400 ± 900	44.18 ± 0.02
J093543.32−011033.3*	6.08	-21.97 ± 0.18	Lyα	410 ± 170	<230	44.12 ± 0.01
J010603.68−003015.2	6.06	-23.53 ± 0.05	Lyα	46 ± 3	3300 ± 600	43.97 ± 0.02
J142611.33−012822.8	6.01	-23.75 ± 0.10	Lyα	11 ± 4	4100 ± 300	43.45 ± 0.13
J121049.13+013426.7	5.97	-22.60 ± 0.07	$\cdots$	$\cdots$	$\cdots$	$\cdots$
J093000.85+005738.4	5.92	-24.91 ± 0.05	Lyα	24 ± 4	13900 ± 400	44.22 ± 0.07
J161819.77+552654.0	5.91	-24.26 ± 0.09	Lyα	32 ± 5	8100 ± 3300	44.10 ± 0.06
J142307.21−022519.0	5.9	-24.26 ± 0.13	Lyα	26 ± 7	7400 ± 3300	44.01 ± 0.10
J023858.09−031845.4	5.83	-23.94 ± 0.03	Lyα	45 ± 3	14700 ± 100	44.11 ± 0.02
J113218.15+003800.1	5.66	-23.18 ± 0.05	Lyα	24 ± 4	650 ± 130	43.34 ± 0.05
Galaxies						
J135348.55−001026.5	6.2	-24.76 ± 0.02	$\cdots$	$\cdots$	$\cdots$	$\cdots$
J144216.08+423632.5	6.0	-22.93 ± 0.07	$\cdots$	$\cdots$	$\cdots$	$\cdots$
J092117.65+030521.5	6.0	-22.76 ± 0.16	$\cdots$	$\cdots$	$\cdots$	$\cdots$
J115755.51−001356.2	5.9	-22.98 ± 0.08	$\cdots$	$\cdots$	$\cdots$	$\cdots$
J123841.97−011738.8	5.8	-23.37 ± 0.04	$\cdots$	$\cdots$	$\cdots$	$\cdots$
J162657.22+431133.0	5.8	-22.78 ± 0.04	$\cdots$	$\cdots$	$\cdots$	$\cdots$
J020649.98−020618.2	5.72	-23.83 ± 0.03	Lyα	1.1 ± 0.2	250 ± 170	42.39 ± 0.08
[O III] Emitters						
J090017.67−014655.6	0.921	$\cdots$	Hβ	16 ± 1	<190	40.99 ± 0.03
		$\cdots$	[O III] λ4959	8.7 ± 0.6	<190	40.71 ± 0.03
		$\cdots$	[O III] λ5007	31 ± 1	<190	41.26 ± 0.02
J015519.63−005814.7	0.872	$\cdots$	Hγ	6.5 ± 0.6	<190	40.37 ± 0.04
		$\cdots$	Hβ	28 ± 1	180 ± 20	41.00 ± 0.02
		$\cdots$	[O III] λ4959	33 ± 1	150 ± 40	41.07 ± 0.01
		$\cdots$	[O III] λ5007	71 ± 6	<190	41.41 ± 0.03
J144221.95−013258.0	0.823	$\cdots$	Hβ	200 ± 80	<230	40.81 ± 0.06
		$\cdots$	[O III] λ4959	290 ± 110	<230	40.97 ± 0.05
		$\cdots$	[O III] λ5007	1600 ± 600	<230	41.70 ± 0.01
J115946.07+014023.7	0.790	$\cdots$	Hγ	33 ± 7	<190	41.24 ± 0.07
		$\cdots$	Hβ	150 ± 20	<190	41.89 ± 0.02
		$\cdots$	[O III] λ4959	350 ± 40	<190	42.26 ± 0.01
		$\cdots$	[O III] λ5007	1000 ± 100	<190	42.73 ± 0.01
J141332.93+014350.4	0.784	$\cdots$	Hβ	> 1500	<230	40.99 ± 0.05
		$\cdots$	[O III] λ4959	> 2800	<230	41.28 ± 0.02
		$\cdots$	[O III] λ5007	> 9700	<230	41.82 ± 0.01
J094209.69−020302.1	0.782	$\cdots$	Hβ	71 ± 5	<190	41.61 ± 0.02
		$\cdots$	[O III] λ4959	110 ± 7	<190	41.79 ± 0.02
		$\cdots$	[O III] λ5007	380 ± 20	<190	42.34 ± 0.01

Table 3
(Continued)

Name	Redshift	M_{1450} (mag)	Line	EW_{rest} (Å)	FWHM (km s^{-1})	$\log L_{line}$ (L_{line} in erg s^{-1})
J225124.84−010911.0	0.777	⋯	Hγ	95 ± 11	<190	41.00 ± 0.04
		⋯	Hβ	210 ± 20	<190	41.34 ± 0.02
		⋯	[O III] $\lambda4959$	420 ± 40	<190	41.65 ± 0.01
		⋯	[O III] $\lambda5007$	1300 ± 100	<190	42.13 ± 0.01
J093831.54−002523.4	0.777	⋯	Hγ	390 ± 270	<230	40.64 ± 0.07
		⋯	Hβ	600 ± 410	<230	40.83 ± 0.04
		⋯	[O III] $\lambda4959$	1300 ± 900	<230	41.18 ± 0.02
		⋯	[O III] $\lambda5007$	3800 ± 2600	<230	41.63 ± 0.01
J135049.56+013726.6	0.770	⋯	Hγ	> 110	<230	40.43 ± 0.06
		⋯	Hβ	> 350	<230	40.93 ± 0.02
		⋯	[O III] $\lambda4959$	> 470	<230	41.06 ± 0.05
		⋯	[O III] $\lambda5007$	> 2100	<230	41.70 ± 0.01
J150602.11+415317.5	0.764	⋯	Hγ	103 ± 4	<190	41.30 ± 0.01
		⋯	Hβ	249 ± 8	<190	41.68 ± 0.01
		⋯	[O III] $\lambda4959$	540 ± 20	<190	42.02 ± 0.01
		⋯	[O III] $\lambda5007$	1600 ± 100	<190	42.50 ± 0.01

Note. The asterisks after the object names indicate the possible quasars with narrow Lyα emission. Upper limits of line EWs are placed at 3σ significance, for the objects without continuum detection.

Table 4
Spectral Classes of the Cool Dwarfs

Name	Class
J011152.80+013211.4	L4
J015548.62−061737.9	M4
J020421.81−024421.1	L9
J022144.40−053008.6	T2
J085230.35+025410.0	M6
J085818.99+040927.6	M7
J124505.57+010550.2	M9
J135913.21+002740.0	T8
J142531.82−021606.5	T0
J145853.06+015031.8	L9
J151812.04+440829.0	T1
J153032.76+435615.5	L8
J154605.67+425306.1	T7
J161042.47+554203.4	T0
J164226.30+430749.7	L1
J223827.66+053246.5	M4
J224157.52+055912.6	M5
J225132.39−011601.1	M5
J225337.55+051440.1	M7
J225513.58+044226.8	M5
J230811.42+023931.3	M7
J231344.68−003931.3	L1

Note. These classification should be regarded as only approximate; see the text.

Figure 8. Shape indicators of the quasars (blue dots, including previously known quasars in the HSC survey footprint), narrow-line quasars (blue dots with larger circles), high-z galaxies (green dots), [O III] emitters (green open circles), and Galactic cool dwarfs (red open circles). For each object, we calculated these quantities in either of the z or y band with higher S/N. Ideal point sources meet $m_{PSF} = m_{CModel}$ and $\mu_{11}/\mu_{11}^{PSF} = \mu_{22}/\mu_{22}^{PSF} = 1$, which are represented by the two dotted lines. The solid line represents our criterion of point-source selection ($m_{PSF} − m_{CModel} < 0.15$).

galaxies (Shapley et al. 2003). The galaxies discovered by our survey are very luminous, with $M_{1450} \simeq −22$ to $−25$ mag, well above the break magnitude of the galaxy LF at $z = 6$ ($M_{1450} \simeq −21$ mag; Ono et al. 2018).

We also present a composite spectrum of the 16 [O III] emitters at $z \sim 0.8$ in Figure 10. This spectrum was created by converting the individual spectra to the rest frame and normalizing to the continuum flux of 10^{18} erg s^{-1} cm^{-2} Å^{-1}, and then median-stacking. In addition to Hγ, Hβ, [O III] $\lambda4959$

and $\lambda5007$, we detected [O III] $\lambda4363$ and He I $\lambda4473$ emission; these two lines are weak and undetected in the individual spectra. The rest-frame EWs of the six emission lines are 53 ± 3 Å (Hγ), 35 ± 3 Å ([O III] $\lambda4363$), 21 ± 3 Å (He I $\lambda4473$), 165 ± 7 Å (Hβ), 264 ± 10 Å ([O III] $\lambda4959$), and 1030 ± 40 Å ([O III] $\lambda5007$). All lines are spectrally unresolved.
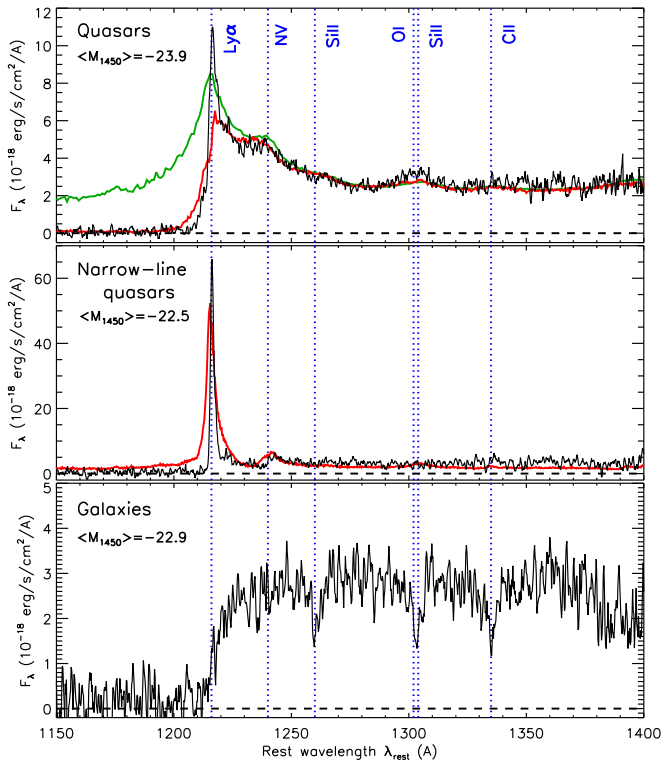
Figure 9. Rest-frame composite spectra of all 75 broad-line quasars (top), 18 narrow-line quasars (middle), and 31 galaxies (bottom) discovered by our survey. The median absolute magnitude $\langle M_{1450}\rangle$ of each sample is reported at the top left corner of each panel. The red and green lines in the top panel represent the arbitrarily scaled composite spectrum of luminous high-z quasars from Pan-STARRS1 (Bañados et al. 2016) and that of SDSS low-z quasars (Vanden Berk et al. 2001), respectively, while the red line in the middle panel represent that of narrow-line quasar candidates in the SDSS (Alexandroff et al. 2013). The blue dotted lines mark the wavelengths of Lyα, N V $\lambda1240$, Si II $\lambda1260$, O I $\lambda1302$, Si II $\lambda1304$, and C II $\lambda1335$.
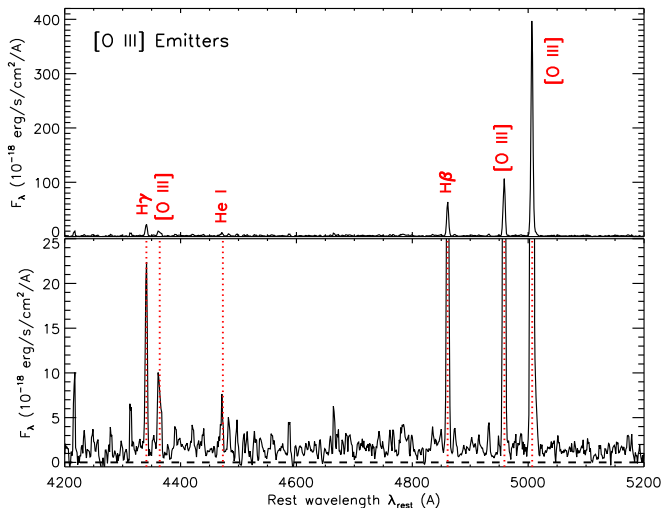
Figure 10. Rest-frame composite spectrum of all 16 [O III] emitters at $z \sim 0.8$ over the full (top) and lower (bottom) flux scales. The red dotted lines mark the wavelengths of Hγ, [O III] $\lambda4364$, He I $\lambda4473$, Hβ, [O III] $\lambda4959$, and $\lambda5007$.

The HSC–SSP survey has completed observations on more than 80% of the planned 300 nights, and we are making steady progress on our high-z quasar survey. We plan to continue our

follow-up spectroscopy in the next few years, and will report new discoveries, along with measurements of the properties of individual objects with multiwavelength observations. The quasar sample thus established will provide a more accurate quasar LF at $z \geqslant 6$ than is currently available (e.g., Matsuoka et al. 2018c; Wang et al. 2018). In a few years, we also aim to start a large SSP survey with the Prime Focus Spectrograph, a new wide-field multi-object spectrograph for the Subaru Telescope under development (Takada et al. 2014). This will enable us to take spectra of a significant number of HSC objects, including quasar candidates at all redshifts.

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