Luminosity function of high-z object candidates at the epoch of reionization (z \gtrsim 6) in cosmic evolution survey (COSMOS) field

N Thananusak\textsuperscript{1,2,*}, U Sawangwit\textsuperscript{2} and S Wannawichian\textsuperscript{2,3}

\textsuperscript{1} Master’s Degree in Astronomy, Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Mueang Chiang Mai, Chiang Mai 50200, Thailand
\textsuperscript{2} National Astronomical Research Institute of Thailand, Mae Rim, Chiang Mai 50180, Thailand
\textsuperscript{3} Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Mueang Chiang Mai, Chiang Mai 50200, Thailand

\* E-mail: n.thananusak@gmail.com

Abstract. The investigation of the luminosity functions (LF) of objects at the epoch of reionization or EoR (z \gtrsim 6) is crucial for placing stronger constraints on the contribution of different ionizing photon sources. In this study, we aim to estimate the luminosity functions of z \gtrsim 6 candidates. The data catalog obtained from Hyper Suprime-Cam Strategic Program (HSC-SSP) ultra-deep survey data released one and the ultra-deep Visible and Infrared Survey Telescope for Astronomy (UltraVISTA) data released four in optical (rizy) and near-infrared (YJHK\textsubscript{s}) photometry filters, respectively. We focus the deep survey on Cosmic Evolution Survey (COSMOS) field, centered at RA \sim 10^h 00^m 28.6^s DEC \sim +2^\circ 12' 21.0''\textsuperscript{0}. The 79 candidates are selected by the Lyman Break Galaxies (LBGs) technique with z band drop-out, and photometric redshift approximation (photo-z). We then used the candidates to calculate the z \gtrsim 6 LF. Accordingly, we compare the LF with other works that focus on the high-z objects at similar z-range.

1. Introduction
During z \gtrsim 6, the EoR is the one of the cosmic major transitions. Since, this epoch is thought to have the first-generation of stars, galaxies and super massive black holes (SMBHs) formations. Moreover, the UV photons radiation from these primordial sources have ionized hydrogen atoms in our universe \cite{1}. In recent decades, high-z objects observations are the powerful probes that lead us to better understanding about their mechanisms back from the reionization epoch to present universe. The high-z objects LF measuring is crucial for placing stronger constraints on the contribution of various primordial sources. The LF of high-z objects is defined as the number density of high-z objects per unit magnitude or per unit luminosity.

Our aim is to present the LF from z \gtrsim 6 candidates that used the photo-z technique for selection. For the deeper data over a small area (\sim 1 deg\textsuperscript{2}), we focus on the catalogs that cover over the cosmic evolution survey (COSMOS) field \cite{2}. The candidates selection used the multiband photometry data which produced by the HSC-SSP DR1 in rizy-bands \cite{3}, and UltraVISTA DR4 in YJHK\textsubscript{s}-bands \cite{4}.

Section 2 describes the high-z candidates selection from the data catalogs and approximate their redshift with photo-z technique. Section 3 presents the high-z candidates samples which use to approximate the LF. Sections 4 demonstrates the results and discussion.
Figure 1. (a) the green and violet regions are the RA/Dec plot from UltraVISTA DR4 that overlaps on the HSC-SSP DR1 on COSMOS field, respectively. The red color region is the area that exclude bad region from HSC-SSP DR1, due to their CCD. (b) the histogram of $J$-band magnitude before and after our selection of the photo-$z$ and the $z \gtrsim 6$ candidates.

2. Data
This work used photometric data from “Hyper-Suprime Cam Subaru Strategic Program” (HSC-SSP) ultra-deep survey data release one (DR1) in $rizy$ bands; and “ultra-deep Visible and Infrared Survey Telescope and Astronomy” (ultraVISTA) data release four (DR4) in $YJHK_s$ bands. Their AB magnitude limits and effective wavelengths ($\mu$m) in each band from HSC-SSP and ultraVISTA are shown in table 1, respectively. Both of catalogs have overlapped field observations, COSMOS field. Such deep survey field covers $\approx 1.4$ deg$^2$ and has a center at RA $10^h00^m28.6^s$ DEC $+2^\circ12'21.0''$ [2]. Figure 1 (a) illustrates the plot of RA versus Dec in degree unit from UltraVISTA DR4 and HSC-SSP DR1 catalogs.

| Bands   | $r$  | $i$  | $z$  | $y$  | $Y$  | $J$  | $H$  | $K_s$ |
|---------|------|------|------|------|------|------|------|-------|
| Magnitude limits | 27.7 | 27.4 | 26.8 | 26.3 | 25.8 | 25.6 | 25.2 | 24.9  |
| Effective wavelength($\mu$m) | 0.618 | 0.771 | 0.890 | 0.976 | 1.021 | 1.254 | 1.646 | 2.149 |

2.1. $z$ drop-out candidates selection
For the objects that has $z \gtrsim 6$, the absorption lines are continuity; eventually the spectrum are “drop-out”, so called “Gunn-Petersonn trough” [5]. This drop-out in their spectrum is defined as “Lyman-Break Galaxies (LBGs).” Such LBGs’ characteristic, we use photo-$z$ to estimate the samples’ redshift by using the multi-wavelength photometry with specification of detection or non-detection in each filter. The reason for using photo-$z$ is that the high-$z$ spectroscopic observations rarely select candidates for large sky area survey, due to their faintness and long-run observations. Therefore, we use the photo-$z$ to our data set which are the $z$ band drop-out candidates. However, the candidates need to be confirmed with the spectroscopic follow-up.

In each row of HSC-SSP or UltraVISTA catalogs, there is a list that contains of the ID, location(RA/Dec), magnitudes and their errors. Summary of the methods to select $z$ band drop-out candidates are shown in table 2. Figure 1 (b) shows the histogram of our candidates.
2.2. Photometric redshift (Photo-z)

We corrected the extinction in UltraVISTA-\textit{YJHK}_s bands from the mean values of \(E(B-V)\) from Schlafly and Finkbeiner [6] before photo-z method. We used program \textit{hyperz} on the corrected z band drop-out (528) candidates [7]. The \textit{hyperz} procedure is to fit the observed magnitude from our catalogs with the Spectral Energy Distributions (SEDs) by the \(\chi^2\) minimization. We set the \textit{hyperz} parameters: the reddening law from Calzetti [8], the Hubbles parameter (\(H_0 = 69.6\), \(\Omega_m = 0.286\) and \(\Omega_\Lambda = 0.714\) which from Benett \textit{et al} [9]. From \textit{hyperz} outputs, our criteria are the probability of primary best-fit have \(z > 70\%\) and have probability of the second best-fit \(z < 50\%\). However, we included 23 candidates that have the second best-fit \(z > 50\%\) but have \(z\) in the second best-fit to \(> 6\) to increase the number of candidates. After that, we excluded the candidates that have magnitude in \(J\)-band > 25.6, which has rest frame in UV. The primary-\(z\) candidates which are used to approximate the LF are \(\approx 6.5 - 7.6\) and their numbers are presented as shown in table 2. Figure 2 (b) presents the \(J\)-band magnitude histogram of the candidates before and after being considered with our constraints.

Table 2. The selection description and the number of objects.

| Description | NO. of objects |
|-------------|----------------|
| HSC-SSP DR1 (All bands is not null.) | 1,262,680 |
| \(z\) drop-out (detected in \(Y\)-band) | 4,410 |
| UltraVISTA DR4 (All bands is not null.) | 352,119 |
| Cross-match the HSC-SSP with UltraVISTA | 942 |
| Exclude the non-uniform regions from HSC-SSP and 2MASS Point source | 528 |
| \textit{hyperz}: 1\textsuperscript{st} \(z > 70\%\), 2\textsuperscript{nd} \(z < 50\%\) (except for \(z\) in 2\textsuperscript{nd} \(z > 6\)) and \(J > 25.6\) | 79 |

Figure 2. (a) the histogram of primary redshift from \textit{hyperz} output and (blue) the selected candidates (red). (b) the absolute magnitude distribution of \(z \gtrsim 6\) candidates in \(J\)-band.

3. The luminosity function and fitting results

The luminosity function is the objects' number density of unit brightness bin per unit volume, \(\phi(M)\). In this work, we estimate the LF by \(1/V_{\text{max}}\) estimator [10, 11]. From this estimator, we converted the absolute magnitude from corrected apparent magnitude in \(J\)-band on ultraVISTA DR4; used the luminosity distance (\(d_L\)) which are obtained by using their photo-z with 1\(\sigma\) error, and set cosmological parameters as used in \textit{hyperz} parameters. After that, we used the Schechter luminosity function to fit by using the \(\chi^2\) minimization and provide the best-fit parameters in table 3. The form of Schechter LF is \(n(M) = 0.4 \ln 10 \phi^* [10^{0.4(M^*-M)}]^{\alpha+1} \exp[-10^{0.4(M^*-M)}]dM\), \(L\) is the luminosity of our candidates, \(\phi^*\) is the number density, \(M^*\) is the characteristic absolute magnitude and \(\alpha\) is the faint-end slope. Figure 3 shows our \(z \approx 7\) LF (a) and the Schechter parameters joint constraints (b).
Figure 3. (a) The UV rest-frame luminosity function of our $z \approx 7$ galaxy candidates in the J-band. The best-fit Schechter function are also shown for the fitting limits at $M_J < -19.48$ (blue solid line) and $M_J < -19.73$ (red dashed line). The results from Bouwens et al [11] are also shown for comparison. The vertical dashed line marks the absolute magnitude where our candidate number begins to drop, $M_J \approx -19.73$. (b) The joint constraints on $\alpha$ and $M^*_J$ for different fitting limits are $M_J < -19.48$ (blue solid line) and $M_J < -19.73$ (red dashed line).

4. Conclusions
We have selected high-z galaxy candidates from combining deep optical and near-infrared ultra-deep surveys in COSMOS field, using $z$-dropout technique and photo-z from template fitting. Our selection has given 79 $z \approx 7$ candidates which are then used to estimate the rest-frame UV luminosity function that cover $-21 < M_{UV,AB} < -19.5$. Our strict faint-end limit, $M_J = -19.73$, may not be sufficient to determine the $\alpha$, thus resulting in steeper slope than that measured by Bouwens et al [11], $\alpha = -1.94 \pm 0.24$. However, if we extend the fitting limit to $M_J < -19.48$, i.e. 0.25-mag fainter, the slope is then consistent with Bouwens et al [11] result. We believe the true value of the slope of our sample should lies between these two limits.

Table 3. Best-fit parameter for Schechter parametrization.

| Fitting limits | $\chi^2_{\text{min}}$ | d.o.f. | $M^*_J$ | $\alpha$ | $\phi^*$ |
|----------------|----------------------|-------|---------|------------|----------|
| $M_J < -19.73$ | 2.08                 | 3     | $-20.52 \pm 0.08$ | $-2.92 \pm 0.4$ | 0.0032   |
| $M_J < -19.48$ | 2.38                 | 4     | $-19.74^{+0.2}_{-0.1}$ | $-1.76^{+0.6}_{-0.5}$ | 0.0173   |

References
[1] Fan X 2012 Res. Astron. Astrophys. 12 865
[2] Scoville N et al 2007 Astrophys. J. Suppl. S. 172 1
[3] Aihara H et al 2018 Publ. Astron. Soc. Jpn. 70 8
[4] McCracken H J et al 2012 Astron. Astrophys. 544 156
[5] Gunn J E and Peterson B A 1965 Astrophys. J. 142 1633
[6] Schlafly E F and Finkbeiner D P 2011 Astrophys. J. 737 13
[7] Bolzonella M, Miralles J and Pello R 2000, Astron. Astrophys. 363 476
[8] Calzetti D et al 2000 Astrophys. J. 533 682
[9] Bennett C L et al 2014 Astrophys. J. 794 135
[10] Schmidt M 1968 Astrophys. J. 151 393
[11] Bouwens R J et al 2011 Astrophys. J. 737 33