MUSUBI (MegaCam Ultra-deep Survey: $u^*$-band Imaging) Data for the COSMOS and SXDS Fields

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Received 2022 February 24; revised 2022 May 12; accepted 2022 May 22; published 2022 June 30

Abstract

The Subaru Hyper Suprime-Cam (HSC) Strategic Survey is the latest-generation multiband optical imaging survey for galaxy evolution and structure formation. The “Ultra-deep” component of the HSC survey provides $grizy$ broadband images over $\sim 3.4 \text{ deg}^2$ to detection limits of $\sim 26–28$ AB, along with narrowband images, in the COSMOS and SXDS fields. These images provide an unprecedented combination of depths and area coverage, for studies of galaxies up to $z \sim 7$. However, the lack of coverage at $\lambda < 4000 \text{ Å}$ implies an incomplete sampling of the rest-frame UV at $z \lesssim 3$, which is critically needed for understanding the buildup of stellar mass in later cosmic time. We conducted a multiyear CFHT $u^*$-band imaging campaign in the two HSC Ultra-deep fields with CFHT MegaCam. By including shallower archival data, we reached $5\sigma$ depths of $u^* = 28.1$ and 28.4 (AB) at the centers of the COSMOS and SXDS fields, respectively, and $u^* = 27.7$ and 27.8 in the central 1 deg$^2$ fields. The image quality is $\gtrsim 0.9\text{arcsec}$, fairly good for the $u^*$-band. Both the photometric and astrometric quality of our data are excellent. We show that the combination of our $u^*$-band and HSC data can lead to high-quality photometric redshifts at $z = 0–3$, and robust measurements of rest-frame UV on galaxies at $0.4 < z < 0.6$ for distinguishing green-valley galaxies from star-forming and quiescent galaxies. We publicly release our reduced $u^*$-band images and reference catalogs, which can be used readily for scientific studies.

Unified Astronomy Thesaurus concepts: Ultraviolet surveys (1742); Galaxy evolution (594); Galaxy formation (595); High-redshift galaxies (734); Astronomy databases (83); Observational cosmology (1146); Green valley galaxies (683)

1. Introduction

Ever since the Sloan Digital Sky Survey (SDSS; York et al. 2000) two decades ago, optical imaging and spectroscopic surveys have revolutionized our views on galaxy evolution and structure formation. In particular, multimband imaging surveys over large areas, such as PanSTARRS (Kaiser et al. 2010), the Dark Energy Survey (Sevilla-Noarbe et al. 2021), the Hyper Suprime-Cam Subaru Strategic Program (HSC SSP; Aihara et al. 2018), and the forthcoming LSST (Ivezic et al. 2019), have become a standard and relatively inexpensive pathway in mapping the distribution of galaxies over cosmic time by utilizing the so-called photometric redshift (hereafter photo-$z$) technique.

The HSC SSP was a 7 yr program conducted during 2014–2021 on the 8.2 m Subaru Telescope, consisting of different combinations of depths and areas (Wide, Deep, and Ultra-deep). The detector was optimized to observe in the redder optical wavelengths. Five broadband ($g$, $r$, $i$, $z$, and $y$) and four narrowband (NB387, NB816, NB921, and NB101) filters were designed to make the best use of its sensitivity. Among the three HSC survey layers, the HSC Ultra-deep Survey (UDS) was the deepest component, aiming to reach $5\sigma$ AB magnitude detection limits of $g$, $r$, $i$ $\sim 28.0$, $z \sim 27.0$, $y \sim 26$, and $m_{NB} \sim 26$ over two fields widely separated on the sky (each with one HSC pointing, which covers $\sim 1.7 \text{ deg}^2$), making it the deepest survey with a few square degrees of coverage ever taken by a ground-based telescope. For comparison, these correspond to the depths of the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004) but for an area that is $40 \times$ larger, and to depths 1–2 mag greater than the Subaru Suprime-Cam data in the original Cosmic Evolution Survey (COSMOS; Capak et al. 2007; Scoville et al. 2007) with almost twice the area. The goal of the HSC UDS was to directly measure the buildup of galaxies and large-scale structures across cosmic time.

The two pointings chosen for the HSC UDS were two extremely data-rich extragalactic survey fields, the COSMOS field and the Subaru-XMM Deep Survey (SXDS; Furusawa et al. 2008) field. As we would like to measure the luminosity...
and mass functions accurately, sampling a representative volume of the universe is crucial. One HSC pointing will map 150° comoving Mpc\(^2\) at \(z \sim 3\). However, cosmic variance in one pointing will be at a level of 5%–15% depending on the redshift. By observing two independent fields, we can bring it down to 4%–10% (Driver & Robotham 2010).

While the HSC UDS was expected to discover several millions of galaxies up to \(z \sim 7\), it did not sample the wavelengths blueward of 4000 Å, which is critical to distinguishing the Balmer and Lyman breaks for precise measurements of photo-z, as well as to providing UV-based star formation rates for galaxies at intermediate redshifts. To complement the HSC UDS, we initiated a multiyear \(u^\ast\)-band imaging campaign in the two HSC UDS fields using MegaCam on the Canada–France–Hawaii Telescope (CFHT), called the “MegaCam Ultra-deep Survey: \(u^\ast\)-band Imaging” (MUSUBI). This takes advantage of the good \(u^\ast\)-band quantum efficiency of the MegaCam CCD (74% at 3800 Å; see the 36% for the HSC CDD at 3800 Å), which makes MegaCam the best instrument worldwide for this kind of UV survey. By combining MUSUBI and existing shallower \(u^\ast\)-band observations in COSMOS and SXDS, we reach a depth of \(u^\ast_{AB} \sim 27.5\), which well matches the HSC grizy and narrowband depths. The combination of the MUSUBI and HSC data sets will enable a variety of scientific studies, such as studies of Ly\(\alpha\) emitters (Hu et al. 2002; Ouchi et al. 2008; Shibuya et al. 2018) and UV luminosity functions for galaxies at \(z < 2 < 3\) (Reddy & Steidel 2009; van der Burg et al. 2010; Sawicki 2012; Moutard et al. 2020), properties of LBG/BM/BX selected populations (Adelberger et al. 2004; Ly et al. 2012), and the selection of green-valley galaxies at \(z < 1\) using the \(NUV - r\) color (Wyder et al. 2007; Salim et al. 2014; Coenda et al. 2018).

From 2014, another CFHT MegaCam \(u^\ast/\mu^\ast\)-band imaging campaign was launched by CLAUDS (CFHT Large Area \(U^\ast\)-band Deep Survey; Sawicki et al. 2019). CLAUDS imaged the four “Deep Fields” in the HSC SSP, mainly using the new \(u^\ast\) band filter on MegaCam (Figure 1), to a total area coverage of 18.6 deg\(^2\). Because of this large area coverage, CLAUDS is about 0.7 mag shallower than MUSUBI. However, CLAUDS also included our \(u^\ast\) data and \(u^\ast\) data in the CFHT archive acquired by various teams previously, and reached the same depth as MUSUBI in the COSMOS and SXDS fields (a.k.a. the CLAUDS “UltraDeep” fields). Here we provide our independent reduction and calibration of the CFHT MegaCam images, and release the images and reference catalogs to the community. The foci of this paper will be to describe the data set in detail and to compare our source catalogs with other publicly available catalogs in COSMOS and SXDS.

In Section 2, we provide an overview of the MUSUBI observations. The data reductions, calibrations, and resulting data qualities are described in Sections 3, 4, and 5, respectively. In Section 6, we provide details about the released data products. In Section 7, we showcase examples of sciences, specifically the photo-z and the evolution of green-valley galaxies, enabled from the combined MUSUBI and HSC data sets. Throughout the paper, we adopt the AB magnitude system (Oke & Gunn 1983), and the standard \(\Lambda\)CDM cosmological parameters of \(H_0 = 70\ \text{km s}^{-1}\ \text{Mpc}^{-1}\), \(\Omega_m = 0.3\), and \(\Omega_{\Lambda} = 0.7\).

2. Observations

Our MUSUBI team based in Taiwan carried out extremely deep \(u^\ast\)-band imaging of the COSMOS and SXDS fields with MegaCam on CFHT, during semesters 2012B to 2016B (PI: S. Foucaud and W.-H. Wang). All observations were conducted under the queue-observing mode, with active atmospheric extinction and seeing monitoring. The queue mode allowed us to only observe when the \(r\)-band seeing was better than 0′08, corresponding to average to good seeing on Maunakea. However, the \(u^\ast\)-band seeing was typically about 0′′14 worse than the \(r\)-band seeing, so our actual image quality was typically worse than 0′08. We requested the queue system to only observe our targets under photometric conditions. The CFHT queue service observing team also acquired standard star observations and twilight flats when the conditions were suitable.

Our primary goal is to support the two Ultra-deep fields in the HSC SSP. We therefore only imaged a 1 deg\(^2\) area of the center of each of the COSMOS and SXDS fields with one MegaCam pointing, to reach the highest sensitivity given the time constraint. Our exposures were dithered to cover the gaps between the MegaCam CCDs. From semester to semester, we slightly changed the dither pattern and the pointing center for each field, to further even out the sensitivity distribution and to slightly expand the maps. The typical exposure times adopted in our observations were 480 to 720 s, to minimize the readout and dither overheads, and to take advantage of the dark sky. Only a small fraction of the exposures were shorter, from 240 to 320 s, to accommodate observing conditions that were less ideal. Over the course of 3.5 yr, we accumulated 20.3 hr of exposures for the COSMOS field, and 41.8 hr for the SXDS field.

In addition to our own observations, in our data reduction, we also included all available archival data that covered our field centers. The exposure times of the archived data were 120 to 660 s. The seeing and extinction variations in the archived data are also larger than ours. Among all our data and the archived data, 5.2% of exposures for COSMOS were taken under thin cirrus where the extinction exceeded 0.1 mag, while

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Figure 1. Transmission profile of the CFHT MegaCam \(u^\ast\) filter used in MUSUBI. The solid blue curve is the profile of the filter, while the dashed blue curve is the profile combined with the telescope/camera transmission and CCD quantum efficiency. For readers’ reference, we also show the profiles for the new CFHT \(u\) filter (solid cyan curve), the new CFHT \(u\) filter combined with the telescope/camera transmission and CCD quantum efficiency (dashed cyan curve), the SDSS \(U\) filter (dotted magenta curve), and the SDSS \(G\) filter (dotted green curve). All profiles shown here do not contain the effect of atmospheric absorption.
the conditions for SXDS exposures all remained photometric. To minimize the impact of poorer data from the archive, our data reduction (Section 3) downweighted data taken under poorer conditions automatically. Moreover, we visually inspected all exposures to remove obviously bad ones. The inclusion of the archival data brought the total amount of data to 78.1 hr for COSMOS and 60.5 hr for SXDS. However, the archival data were taken by various teams with various imaging strategies. A substantial fraction of the past observations aimed to mosaic much wider areas, rather than use single focused pointings. Therefore, in our final reduced maps, only the map centers received more than 60 hr of exposure times for both fields.

All our own and archived imaging was conducted using the old $u^*$ broadband filter. Its filter transmission curve is presented in Figure 1. The filter itself has a central wavelength of 375 nm, and a bandwidth of 74 nm at 50% transmission. The average wavelength slightly shifts to 379 nm after taking the telescope/camera optics transmission and CCD quantum efficiency into account. Atmospheric transmission would further shift the average wavelength to longer wavelengths and this is airmass-dependent. Figure 1 also compares our filter with the two adjacent SDSS filters, denoted as $U$ and $G$. Because our $u^*$ filter is substantially different from $U$, we cannot directly use the SDSS data to calibrate our $u^*$-band photometry (Section 4.1).

3. Data Reduction

All the MegaCam data were preprocessed by the CFHT Elixir system (Magnier & Cuillandre 2004) to remove instrumental features. This included overscan and bias subtraction, flat-fielding to correct for pixel-to-pixel and CCD chip-to-chip sensitivity/illumination nonuniformity, and sky subtraction. The file headers also contained updated astrometry and photometric zero-points derived by the Elixir system. Our data reduction started from the Elixir-preprocessed files.

We used subroutines in the Simple Imaging and Mosaicking Pipeline (SIMPLE; Wang 2010; Wang et al. 2010) to further process and mosaic the Elixir-preprocessed CCD images. We divided the images into groups. Images taken by the same team (i.e., having similar dithering and exposure), within the same semester, and from the same CCD were grouped and processed together. We first conducted additional passes of sky background subtraction, to remove residual image background, which often shared a common pattern among the grouped exposures. In the first pass, we masked detected objects in each individual exposure, derived a median image from the group, and subtracted it from each exposure. Then on each individual exposure, we masked detected objects again, fitted the masked image with a third-degree 2D polynomial surface, and subtracted the fitted surface from the image. The object masking was done by first smoothing the image with a $3 \times 3$ square tophat kernel and then masking pixels that exceeded $3\sigma$ locally, where $\sigma$ was measured in the unsmoothed image. The above procedure almost always leads to a sufficiently flat sky in the images, such that the stacking and mosaicking do not produce sharp background offsets along the CCD boundaries. The only exception is the rare cases where extremely bright stars prevent good polynomial background models or median sky models.

The grouped and sky-subtracted images were then fed to SExtractor (Bertin & Arnouts 1996) to generate a source catalog for each of them. The photometry of compact objects that had signal-to-noise ratios ($S/N$) higher than 10 in the SExtractor catalogs was compared, so images taken under nonphotometric conditions could be identified. These images were renormalized so their photometry matched that of the others. The atmospheric absorption derived for these images was also used to weight them in the image stacking step according to the atmospheric extinction. The coordinates of objects in the SExtractor catalogs were compared among the images, to derive the exact amounts of dither offsets and optical distortion. The optical distortion could be derived because the displacement of stars among the dithered images as a function of position in the images is the first-order derivative of the distortion function (e.g., Anderson & King 2003; see more details in Wang et al. 2010). Distortion correction was then applied to each image to project it to a tangential sky. All our images in the same field shared the same projection center, position angle ($\theta$), and image scale ($\theta_*186$, the native pixel scale of MegaCam). The distortion correction and the sky projection took into account the change in area for each pixel in a way that source fluxes were conserved. This was required to achieve a uniform absolute flux calibration across the entire field (“photometric flat-fielding”). We will discuss the absolute flux calibration in Section 4.1.

Two passes of cosmic-ray removal were applied to the images. First, on each exposure, a bright pixel was masked if it exceeded $4\sigma$ in its $9 \times 9$ pixel neighborhood. This criterion was carefully chosen such that only spikes much narrower than the point-spread function (PSF) would be masked and stars would not be affected. Second, in a group of dithered, distortion-corrected, and sky-projected images, pixels that shared the same sky coordinates were compared against each other. Outliers in the pixel brightness distribution were considered spurious and masked. This was repeated for every independent pixel on the sky. Typically several tens of dithered images were in a group, meaning that tens of pixels were compared against each other. Only around the boundary of the CCD, where the number of overlapping pixels decreased, did this method become less effective.

After the above processing, the images were average-stacked to form a deep image. In the stacking, the images were weighted according to their exposure time and atmospheric extinction. Then the stacked images from all MegaCam CCDs, projects, and semesters were mosaicked and stacked to form the final wide-field, ultradepth images. In the final stacking and mosaicking, pixels that shared the same sky coordinates were again compared against each other to remove residual cosmic-ray hits that had not been previously masked, before the images were combined. In Figures 2 and 3, we present the final mosaics for the COSMOS and SXDS fields, respectively, and their associated weighted exposure time maps.

4. Calibration

In this section, we outline how we achieved the calibrations for photometry and astrometry, and present the quality of the calibrations.

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13 Since semester 2015A, a new set of broadband filters has been introduced to MegaCam. Its filter transmission curves are shown in Figure 1. In CFHT’s documentation, the old $u^*$-band filter is referred to as $u^*$ or $uS$, while the new $u$-band filter is blue. Here we simply refer to our filter as $u^*$ and readers should not confuse this with the new $u$ filter.

14 http://www.cfht.hawaii.edu/Instruments/Imaging/MegaPrime/
11.2 Photometric Calibration and Quality

4.1. COSMOS

Our general strategy was to tie our photometry to the well-calibrated CFHT Supernova Legacy Survey (SNLS; e.g., Astier et al. 2006; Guy et al. 2010). The SNLS covered the COSMOS field with MegaCam and with the same $u^*$ filter used in MUSUBI, Betoule et al. (2013) published improved photometric calibration of the SNLS, which took into account the varying passbands of the filter across the field and photometric flat-fielding (also see Regnault et al. 2009). The resultant photometric uniformity was 8 mmag at $u^*$, sufficient for studies of high-redshift galaxies. We note that the Elixir data reduction mentioned in Section 3 also adopted a photometric calibration matched to the SNLS calibration in Betoule et al. (2013), starting from 2015. However, we included a substantial amount of data taken prior to that, whose calibration was based on the SDSS calibration of Smith et al. (2002) transferred to the MegaCam system (Magnier & Cuillandre 2004). To correct for any potential offset between the old MegaCam calibration and the new one, we applied the SNLS-based photometric calibration to each data set individually before they were combined to form a deep image.

To calibrate our COSMOS $u^*$ data, we adopted the “uniform magnitude” in the SNLS photometric catalog of Betoule et al. (2013), which corrects for the varying filter passbands across the field. Then for our own data, we measured galaxy photometry using an aperture with a 5" diameter. This is reasonably large for encapsulating the total fluxes of faint galaxies, as this is the aperture that gives the fluxes closest to the SExtractor autoaperture fluxes on well-detected compact objects for our PSF (≈0.9; see Section 5). This is also similar to the aperture adopted by the SNLS (15× Gaussian $\sigma$ of the PSF). We calculated the photometric correction by comparing the two for data taken in each observing run. The differences between our measured (Elixir-calibrated) photometry and the SNLS photometry in the various observing runs were always a few percent, even for data taken after 2015. This was likely caused by the difference in seeing and in the aperture sizes adopted by Elixir. Our correction eliminated these offsets. The SNLS D2 pointing had an area of 1 deg$^2$, which only covers the central part of our 3 deg$^2$ map. For the outer region, which does not have SNLS photometry, we propagated the photometric solution that we obtained from the center using the overlapping regions between the central and outer pointings. Our calibrated images have a map unit of $\mu$Jy per pixel, which is equivalent to an AB magnitude zero-point of 23.9.

We demonstrate the calibration quality in Figure 4, in which we compare the photometry from the SExtractor catalog derived from our final mosaic (Section 6) with that from the SNLS. Overall, the two catalogs agree with each other, and the median offset is $\Delta u^* = -0.0018$. However, there seems to be a small tilt in the sequence in Figure 4, indicated with a cyan dashed line. The median offsets are $-0.0039$ at $u^* < 21$ and 0.0040 at $u^* > 21$. There is no obvious explanation to this tilt, but the $\pm 0.4$% offset should not have practical impacts in most science cases. The largest uncertainty of calibration should come from the fact that there are typically only 20 to 30 SNLS objects available for calibrating each MegaCam CCD. Using the dispersion in Figure 4, which is 0.055 mag, we estimated that the calibration uncertainty would be approximately 0.01 mag, which is still quite good. The results here show that we have reached excellent calibration relative to the SNLS photometry in the COSMOS field.

4.1.2. SXDS

In the SXDS field, our pointing and the SNLS D1 pointing are separated by about 2°. Therefore, unlike in the COSMOS field, we could not directly use the SNLS photometric catalog of Betoule et al. (2013) to calibrate our SXDS data. Here we rely on the SDSS $U$ and $G$ photometry in our field, but convert to the SNLS $u^*$ photometric system.
First, we selected blue stars and galaxies from the SDSS DR12 catalog using their $U - G$ colors. This avoided passive galaxies and late-type stars, whose strong 4000 Å breaks can induce large color terms in the $U$ and $G$ bands, particularly for galaxies whose color terms can be redshift-dependent. We only used galaxies brighter than $U = 21$ to avoid large photometric uncertainties. By crossmatching the selected SDSS galaxies and SNLS galaxies, we derived the following conversions with least-squares fitting:

$$u^* = U - 0.187(U - G) - 0.1443. \quad (1)$$

To better understand this relation, we further picked a subsample of galaxies with SDSS spectroscopy and conducted spectral energy distribution (SED) fitting to their SDSS photometry at their redshifts. We then integrated their fitted spectra using the $u^*$ filter profile to derive their $u^*$-band magnitudes. The result is consistent with the above empirical relation, but noisier because of the uncertainties associated with the SED fitting and the smaller sample size. We therefore conclude that Equation (1) correctly describes blue stars and galaxies within the SDSS detection limit. We used this relation to derive synthetic $u^*$ photometry of SDSS galaxies in our SXDS field to calibrate our CFHT data. In Figure 5, we show a comparison between our SXDS photometry and the synthetic SDSS $u^*$ photometry on objects with SDSS $U < 21$. We used $D = 5''$ apertures from our catalog. The median at $u^* > 16.5$ is 0.012. At $u^* < 16.5$, nonlinear effects start to show up in the MegaCam data. Such bright objects were not used for calibration. They are shown here only to show the nonlinear effects.
to a calibration uncertainty of roughly 0.02 mag for each MegaCam CCD. This is about 2× worse than the case for COSMOS.

4.2. Astrometric Calibration and Quality

We tied our astrometric system to that of the Gaia (Gaia Collaboration 2016) data. During our data reduction, the individual exposures from each MegaCam CCD were corrected for distortion, tangentially reprojected onto a common sky plane for each field, and then stacked/mosaicked with other exposures. The reprojection aligned our detected objects with the coordinates in the Gaia DR2 catalog (Gaia Collaboration 2018; Lindergren et al. 2018). In this process, we only used Gaia objects that were brighter than Gaia $G = 20.5$ and had proper motions measured to be less than 30 mas yr$^{-1}$. The projection center for COSMOS is R.A. (J2000.0) = 9h59m59.59, decl. (J2000.0) = +2°12'08"18. The projection center for SXDS is R.A. (J2000.0) = 2h18m00.00, decl. (J2000.0) = −5°00'00"00. These positions were roughly determined from the common center of the various pointings of our observations and the archival data. The projected images have position angles of 0.0 on the sky and maintain the native MegaCam pixel size of 0.′186 at the projection centers.

To examine the quality of the astrometry calibration, we show comparisons of the source positions in our final catalog against their Gaia positions in Figure 6. For the COSMOS field, where 8360 sources are included in the comparison, the mean positional offsets along the R.A. and decl. are both at milliarcsecond levels, practically consistent with zero. The dispersions in the offsets are 67 mas for R.A. and 74 mas for decl., both acceptably small. For the SXDS field, where 2896 sources are included in the comparison, the mean offsets along the R.A. and decl. are 6 mas and −11 mas, respectively. Therefore, there is a slight tendency of 10 mas for our positions to offset to the southeast relative to Gaia. The dispersions in the offsets for SXDS are 52 mas for R.A. and 61 mas for decl., about 20% smaller than those in the COSMOS field. This 20% difference is likely a consequence of the smaller SXDS coverage, so the required distortion correction including reprojection is smaller. If we only use the brightest 15% of unsaturated sources ($u' = 17−19$), the dispersions are reduced by about 14% (COSMOS) and 5% (SXDS). These relatively small improvements suggest that the positional errors relative to Gaia are not S/N-driven. This could be the fundamental limit of our overall methodology and pipeline capability. We conclude that the systematic errors in our astrometric calibration are nearly negligible, while the uncertainties in the source positions measured from our images are at a small 50–70 mas level for bright sources that are not limited by S/N.

5. Data Quality

5.1. Sensitivity

To examine our imaging sensitivity, we selected sources detected at $5\sigma \pm 0.1\sigma$ with SExtractor autoapertures, and calculated their median value. The resultant median $5\sigma$ limiting magnitudes are 27.19 for COSMOS and 27.68 for SXDS.

The values quoted above are for the whole fields. However, as shown in Figures 2 and 3, our integration time distributions are highly nonuniform, because of the different imaging strategies adopted by the various teams. Therefore, the sensitivity distributions are also highly nonuniform. We measured the $5\sigma$ limiting magnitudes in small areas. The results are shown in Figure 7. In the deepest regions in COSMOS and SXDS, we reached $u' = 28.1$ and $u' = 28.4$, respectively. In the $\sim 1$ deg$^2$ relatively deep regions (yellow to red colors in Figure 7) in COSMOS and SXDS, we reached 27.7 and 27.8, respectively. These two $\sim 1$ deg$^2$ regions were referred to as “CLAUDS UltraDeep” regions by the CLAUDS team. These are by far the deepest 1 deg$^2$ fields for $u'$ and similar $U$ bands.

All the abovementioned limiting magnitudes were derived from all detected sources, among which many are extended objects. If we only selected pointlike objects whose measured sizes were $<1''/2$, the limiting magnitudes would become deeper by $\geq 0.3$. Also, if we fixed the aperture diameters to 2", which favors compact objects, the limiting magnitudes...
would become 0.24 and 0.45 mag deeper in COSMOS and SXDS, respectively. The difference between the two fields when switching to 2'' is caused by the different image quality (next subsection).

5.2. Image Quality

To evaluate the image quality, we selected SDSS photometric stars and spectroscopic quasars in the COSMOS and SXDS fields with $u^* > 17$ and measured their FWHMs with SExtractor. We only selected $u^* > 17$ objects to avoid nonlinear effects in the MegaCam data. The cutoff of SDSS detection limits is roughly $u^* = 22$. The distributions of the FWHM values are shown in Figure 8. The median values are 0''926 for COSMOS and 0''947 for SXDS, indicated by the two arrows in Figure 8.

Like the situation for sensitivity, the image quality in the two fields is not uniform. This is reflected in the asymmetric histograms in Figure 8. The histogram for FWHM becomes more symmetric and sharply peaked if we only look at small regions in both fields. We therefore measured the medians of the FWHM distributions in small areas, and show the results in Figure 9. Overall, the centers of the fields that are covered by our own deep imaging have better image quality, while the outer parts covered by various previous teams have larger image quality variation. The central 1 deg$^2$ region in the COSMOS field has an FWHM of 0''88–0''92, while the central 1 deg$^2$ region in SXDS has an FWHM of 0''92–0''95.

6. Source Catalogs

In our data release, we provide reference catalogs along with the images. These catalogs can be readily used for scientific studies. However, users may need to generate their own catalogs if there are special requirements on the photometry, completeness, or sample purity, or if there are requirements for photometry based on position priors.

6.1. Catalog Generation

We used SExtractor version 2.5.0 to generate the reference catalogs. The key SExtractor parameters are listed in Table 1. Because the two fields have very similar properties, including the ~2% difference in median image FWHMs, we used identical SExtractor parameters for both fields. For the detection and deblending parameters, we visually inspected the detected galaxies on the images, and then adjusted the parameters. Here we aim for a good balance between detecting faint and blended sources and avoiding detecting too many noise spikes, in both deep and shallow regions (Figure 10). We set the seeing FWHM to 0''93, which only affected the star classification output. Because the image quality is not uniform (Figure 9), this value is only an approximate for both fields. Therefore, star class values in our reference catalogs should have uncertainties somewhat larger than those for narrow-field
surveys with uniform image quality. The output catalogs contain both fluxes (μJy) and AB magnitudes of galaxies, measured with 1″, 1.5″, 2″, 3″, 4″, and 5″ diameter apertures, as well as SExtractor’s autoapertures, which provide estimates of the total fluxes/magnitudes. The complete sets of SExtractor input parameters are provided with the data release, so users can modify them and quickly create their own catalogs that fit their needs.

6.2. Comparison with Previous Catalogs

We briefly compare our catalogs with previously published catalogs in COSMOS and SXDS, so users can be made aware of the systematic differences in these data sets.

6.2.1. COSMOS2015

The COSMOS2015 multiband catalog (Laigle et al. 2016) has been the golden standard for photometry and photo-z for the COSMOS field. The CFHT u*-band data included in COSMOS2015 were all included in MUSUBI, but MUSUBI also included our new data. We compared the 3″ aperture magnitudes in COSMOS2015 and our reference catalog. This aperture is larger than the optimal aperture for detecting the faintest compact objects. It was chosen because it is less sensitive to the small PSF size difference between the two data sets. With this aperture size, the median 5σ limiting magnitudes for COSMOS2015 and MUSUBI are 25.63 and 27.17, respectively. The numbers of 5σ detected objects are 2.69 × 10^5 and 8.86 × 10^5, respectively. The area covered by u*-band detected objects is 2.62 and 3.25 deg^2, respectively. These differences are mostly caused by the new data obtained after the compilation of COSMOS2015. In Figure 11(a), we compare the 3″ photometry on sources whose magnitude errors are less than 0.05 in both catalogs. The calibrations of the two catalogs are highly consistent, as the median magnitude difference for objects with u* = 17–23 is 0.0005. At the bright end of u* < 17, the catalogs start to suffer from saturation effects.

6.2.2. COSMOS2020

COSMOS2020 (Weaver et al. 2022) is a new compilation of multiband data for COSMOS, including Subaru HSC data. It includes all the available u* data, like those from MUSUBI, but with its own data reduction. However, the 5σ limiting magnitude with 3″ apertures in COSMOS2020 is 27.11, slightly shallower than ours. There are 5.90 × 10^5 objects detected at 5σ, covering an area of 3.37 deg^2. The area coverage is comparable to ours, but the detected objects are about 30% fewer, likely caused by the differences in target selection criteria. In Figure 11(b), we compare the 3″ photometry on sources with magnitude errors less than 0.05. There is a −0.053 mag offset between the two catalogs. This offset should be caused by the different calibration strategies: COSMOS2020 used SDSS as the calibration reference while...
we used the SNLS. If we take this offset into account, the difference in limiting magnitudes becomes even larger, i.e., MUSUBI is 0.11 mag deeper than COSMOS2020. This should also contribute partially to the larger number of detected objects in the MUSUBI catalog.

6.3. SPLASH-SXDF

SPLASH (Spitzer Large Area Survey with Hyper-Suprime-Cam; Steinhardt et al. 2014) is a warm Spitzer imaging program for both COSMOS and SXDS (a.k.a. SXDF). The multiband catalog for SPLASH-SXDF was published by Mehta et al. (2018), including CFHT $u'$-band photometry from MUSUBI. Their $u'$-band photometry was derived from an earlier version of our reduced image. The differences between that early version and the present version are the photometric and astrometric references. So the two catalogs should be highly consistent, in principle. However, the SPLASH-SXDF photometry was derived from images with PSF homogenization across the
optical, near-IR, and Spitzer IRAC bands. As a result, there is no meaningful direct comparison between the photometry in the catalogs of SPLASH-SXDF and MUSUBI. In Figure 11(c), we show a comparison between the 3″ photometry on sources with magnitude errors less than 0.05 in both catalogs. There is a 0.177 mag offset between the two. If we switch to SExtractor automagnitudes, the difference between the two catalogs reduces by ~50% but is still quite significant. Such differences are likely
caused by the PSF homogenization process. On the other hand, it can be seen that the scatter of the differences is much narrower and flatter, compared to the cases in Figures 11(a) and (b). This reflects the fact that the SPLASH-SXDF and MUSUBI catalogs were derived from images based on identical data sets and very similar reductions conducted by us.

7. Application Examples

7.1. Photo-z

To demonstrate the value of our MUSUBI $u^\text{t}$-band data, we compared photo-z derived with and without the $u^\text{t}$ data. We used the empirical machine-learning code Direct Empirical Photometric Code (DEmP; Hsieh & Yee 2014) to derive the photo-z. We combined the SExtractor $u^\text{t}$-band AUTO photometry in the MUSUBI catalog and the HSC second public data release grizy afterburner photometry (Aihara et al. 2019) to compile a $u^\text{t}$ grizy multiband photometric catalog. For the COSMOS field, the training sets were generated by matching the MUSUBI/HSC $u^\text{t}$ grizy multiband photometric catalog to the redshifts in the COSMOS2020 catalog (Weaver et al. 2022). The COSMOS2020 catalog has two versions, CLASSIC and FARMER, which were derived using different photometric techniques. We used $ip_{\text{ZBEST}}$ derived using the LePHARE photo-z code (Arnouts et al. 2002; Ilbert et al. 2006) in the FARMER catalog as the training reference for photo-z. For the SXDS field, we repeated the same procedure to generate the training sets by matching the MUSUBI/HSC multiband catalog to the redshifts in the SPLASH-SXDF catalog (Mehta et al. 2018). We used $Z_{\text{BEST}}$ in the SPLASH-SXDF catalog as the training reference for photo-z, which was also derived using LePHARE. We emphasize that the $u^\text{t}$-band photometry was derived using a different technique from that used to derive the HSC grizy photometry. Therefore any analyses that need accurate $u^\text{t} - [g, r, i, z, y]$ colors can be seriously affected, such as template SED fitting for photo-z. However, because the same photometry/color offsets exist in both the training set and the target set, the conversion between the photometry and the derived quantity (e.g., photo-z) should be identical for the training set and the target set. Therefore the effect typically does not impact the results from an empirical machine-learning code like DEmP.

Because the training set completely overlaps with the target set, we ran the DEmP code in the “leave-one-out” mode to prevent overfitting. DEmP always generates a dedicated subset of the training set for each target object. In the leave-one-out mode, DEmP excludes the training object with an ID identical to the target object’s in the dedicated subset of the training set. With the leave-one-out technique, we were able to compute accurate statistics of the derived quantities (e.g., photo-z, or stellar mass; see Section 7.2) for the whole sample.

The results are shown in Table 2 and Figure 12. The left panels of Figure 12 are for the COSMOS field, while the right panels are for the SXDS field. All the statistics were calculated for objects with $u^\text{t} < 27.0$. For the COSMOS field, the scatter, bias, and outlier ([$\Delta z > 0.15$]) fraction for the results using the HSC filters alone are 0.045%, 0.0008%, and 19.7%, respectively. Those with the MUSUBI $u^\text{t}$-band are 0.043%, 0.0001%, and 16.8%. Adding the $u^\text{t}$-band improves the scatter, bias, and outlier fraction. For the SXDS field, the scatter, bias, and outlier fraction for the results using the HSC filters alone are 0.061%, 0.0037%, and 24.6%, respectively. With the $u^\text{t}$-band, these values are 0.067%, 0.0016%, and 24.6%. The scatter, bias, and outlier fraction are all improved by adding the $u^\text{t}$-band data. These are similar to what we find in the COSMOS field.

At $z > 2$, the photo-z performance improvement extends to the outlier fractions. The photo-z performance mainly relies on strong features of the galaxy spectrum such as the Lyman break and the 4000 Å break. The HSC filter with the longest effective wavelength is $y$, which is not able to sample the 4000 Å break for galaxies at $z > 1.44$. Therefore the photo-z scatter increases dramatically at $z > 1.5$. However, adding the MUSUBI $u^\text{t}$-band data can help in sampling the Lyman break ($\lambda_{\text{rest}} = 1216$ Å) for galaxies at $z > 2.0$ and the Lyman limit ($\lambda_{\text{rest}} = 912$ Å) for galaxies at $z > 3.1$. Therefore, the photo-z performance at $z > 2.0$ can be significantly improved. For galaxies at $z > 2.0$ in the COSMOS field, the photo-z scatter, bias, and outlier fraction are 0.110%, −0.059%, and 30.1%, respectively when using only the HSC filters. These values are improved to 0.088%, −0.050%, and 24.0% after addition of the $u^\text{t}$-band data. For the SXDS field, the scatter, bias, and outlier fraction for galaxies at $z > 2.0$ are 0.234%, −0.132%, and 49.2%, respectively, with the HSC filters alone. They are 0.153%, −0.081%, and 40.5% after addition of the $u^\text{t}$-band data. The improvements in the scatter, bias, and outlier fraction are quite substantial. We conclude that adding $u^\text{t}$-band data to grizy can significantly improve the photo-z in the HSC UDS fields.

We note that this test is just to demonstrate the improvement of photo-z quality produced by adding the MUSUBI $u^\text{t}$-band data; the result does not represent the optimal absolute photo-z performance that can be derived using the MUSUBI/HSC catalog.

### Table 2

Photo-z Performance for $u^\text{t} < 27.0$

| Samples         | Scatter × | Bias  | $f_{\text{out}}$ |
|-----------------|-----------|-------|-----------------|
| COSMOS grizy    | 0.045     | −0.0008 | 19.7%           |
| COSMOS $u^\text{t}$ grizy | 0.043   | 0.0001  | 16.8%           |
| SXDS grizy      | 0.067     | −0.0037 | 28.2%           |
| SXDS $u^\text{t}$ grizy | 0.061   | −0.0016 | 24.6%           |

| Samples         | Scatter × | Bias  | $f_{\text{out}}$ |
|-----------------|-----------|-------|-----------------|
| $z > 2.0$       | 0.110     | −0.059 | 30.1%           |
| COSMOS grizy    | 0.088     | −0.050 | 24.0%           |
| SXDS grizy      | 0.234     | −0.132 | 49.2%           |
| SXDS $u^\text{t}$ grizy | 0.153  | −0.081 | 40.5%           |

**Notes.**

a) $1.48 \times$ median absolute deviation of $\Delta z$, where $\Delta z = \frac{\text{photo-z} - \text{reference z}}{1 + \text{reference z}}$.

b) Median of $\Delta z$.

c) Outlier fraction: fraction of objects with $|\Delta z| > 0.15$. 

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7.2. Green-valley Galaxies at 0.4 < z < 0.6

We further demonstrate the power of the combination of our $u^*$-band data and the HSC UDS grizy data with a mini study of galaxies in the "green valley" at $z = 0.4-0.6$ down to $10^{9.1} M_\odot$ for a $u^* \leq 25$ sample. The green valley is a sparse region between the blue cloud and the red sequence, and is often thought of as the transition zone in which galaxies are in the process of migrating from an active star-forming phase to a quiescent phase (Martin et al. 2007; Wyder et al. 2007; Salim et al. 2014). The presence of low galaxy density in the green valley, if firmly established, can have profound implications in galaxy evolution. For example, the inferred timescale of galaxy transition cannot be very long; otherwise one would expect to see a continuous distribution extended from the green valley to the red color space (e.g., Salim et al. 2014). Some studies, however, have suggested that the quenching timescales of green-valley galaxies vary with morphology and environment (Salim et al. 2012; Schawinski et al. 2014; Smethurst et al. 2015; Jian et al. 2020). Therefore, quantifying the fraction of green-valley galaxies and studying their properties will provide crucial insights into the quenching mechanisms.

Among various color combinations, the rest-frame $NUV - R$ color has been suggested to be efficient in selecting galaxies with intermediate specific star formation rates between the star-forming and quiescent populations (Wyder et al. 2007; Salim et al. 2014; Coenda et al. 2018). We focused on the redshift of $z \sim 0.5$, where the MUSUBI $u^*$ band directly samples the rest-frame $NUV$ wavelength, which is sensitive to ongoing star formation. When this wavelength was combined with the HSC UDS grizy photometry, we were able to accurately characterize galaxies in the $NUV - R$ versus stellar mass space and quantify the frequency of galaxies in different populations. Hsieh & Yee (2014)

Figure 12. Photo-z performance on adding MUSUBI $u^*$-band data to HSC grizy data for objects with $u^* \leq 27.0$. The left panels are for the COSMOS field and the right panels are for the SXDS field. The upper panels are the results derived using the HSC filters alone, while the lower panels are the results derived using the HSC filters and the MUSUBI $u^*$ band. Adding the MUSUBI $u^*$ band improves the photo-z quality in terms of scatter, bias, and outlier fraction.
For the SXDS absolute magnitude, and stellar mass and rest-frame COSMOS2020 FARMER catalog for the stellar mass, band luminosity, respectively. LUM galaxies.

For the COSMOS green-valley analysis, we repeated the procedure described in Section 7.1. For the COSMOS2020 FARMER catalog for the stellar mass, NUV absolute magnitude, and R-band absolute magnitude, respectively. For the SXDS field, MASS BEST, LUM NUV BEST, and LUM R BEST in the SPLASH-SXDF catalog were used to generate the training sets for stellar mass, NUV luminosity, and R-band luminosity, respectively.

We selected galaxies with $u^* \leq 25$. The limiting magnitudes (3σ aperture; 5σ) in the HSC grizy bands are significantly deeper (27.5, 27.2, 27.0, 26.6, and 25.9 in g, r, i, z, and y, respectively) than 25.0. Since the observed $u^* = [g, r, i, z, y]$ colors are nearly all greater than −1 in the redshift range used in this analysis, the $u^* \leq 25$ selection ensures that the majority of galaxies are also detected in the HSC bands, with nondetection rates in the HSC bands between 0.01% and 0.05%.

Figure 13 displays the distribution of galaxies in our HSC UDS sample in the redshift range of 0.4 < $z$ < 0.6. While there are various definitions of green-valley zones in the literature, it may not be straightforward to apply those selections in our data set directly due to possible systematics in the measurements of color and stellar mass. Therefore, we chose to separate galaxies into three populations, i.e., star-forming, quiescent, and green-valley galaxies, by following an iterative procedure similar to the one described in Jian et al. (2020). Briefly, we first adopted a constant NUV − $R = 3.5$ on the NUV − $R$ versus $M_*$ plane to divide the galaxies into two broad groups, blue and red populations, and find the median values of the NUV − $R$ color of the two groups at a given stellar mass bin, separately. We proceeded to fit the median NUV − $R$ versus log $M_*$ distributions with a linear relation for the two sequences, where the log mass ranges used for the fitting are between 8.7 and 9.5 and between 9.7 and 11.1 for the blue and red populations, respectively. Next, we defined the middle points of the two sequences as the green-valley line and the green-valley zone was then defined as the region with a ±0.5 color value from the green-valley line. The star-forming and quiescent galaxies were referred to as those located above and below the upper and lower boundaries of the green valley, respectively. Once the star-forming and quiescent populations were defined, we fit again the linear relations for the two populations, defined the green-valley zone, and iterated this process until the green valley converged. The final mass-dependent color criterion for the green valley is as follows:

$$NUV − R = 0.446 \times \log_{10}(M_*/\text{M}_\odot) − 1.348 \pm 0.5.$$  

In Figure 14, we show the fractions of star-forming (blue), quiescent (red), and green-valley (green) galaxies as functions of $M_*$, where the sum of the three fractions is unity. The errors were estimated using bootstrap resampling from 2000 runs. The stellar mass completeness limit was estimated using a method similar to that described in Ilbert et al. (2010). In the redshift range of 0.4 < $z$ < 0.6, we compared the stellar mass distributions in $u^* \leq 25$ and $u^* \geq 27$ samples, assuming that the $u^* \leq 27$ sample was complete for the stellar mass range of our interest. We computed the fraction of galaxies with $u^* \leq 25$ in the complete sample ($u^* \geq 27$) as a function of stellar mass. We then defined the lower limit of the stellar mass as the mass at which 30% of the galaxies are fainter than $u^* = 25$. Because of the exceptional depth of the HSC and MUSUBI data sets used in this study, the stellar mass completeness limit in our sample reaches down to $10^{9.1} \text{M}_\odot$ for quiescent galaxies and to $10^{9.7} \text{M}_\odot$ for star-forming galaxies, almost one order of magnitude lower than that in Coenda et al. (2018). We then chose the mass limit of quiescent galaxies to represent the mass limit for the whole sample to ensure that at this mass limit, star-forming and green-valley galaxies are also complete. It can be seen from Figure 14 that the fraction of star-forming (quiescent) galaxies is a strong function of stellar mass, decreasing (increasing) rapidly with increasing mass. In contrast, the fraction of green-valley galaxies is roughly constant (∼25%) in the stellar mass range between $10^{9.8}$ and $10^{10.8} \text{M}_\odot$, but gradually declines to ∼0.12 as the stellar mass decreases to $10^{9.1} \text{M}_\odot$. The static green-valley fraction at the high-mass end is in broad

Figure 13. Rest-frame NUV − $R$ color vs. stellar mass for HSC UDS + MUSUBI galaxies at 0.4 < $z$ < 0.6. The encoded color scale is in a log scale. The region between the two dark green lines is the green-valley zone. Black vertical lines denote the mass completeness limits for star-forming (left) and quiescent (right) galaxies.
agreement with the results obtained by Coenda et al. (2018). On the other hand, the small green-valley fraction for low-mass galaxies revealed in this study suggests that quenching is inefficient in low-mass \((M_\star < 10^{10} \, M_\odot)\) galaxies. This result supports the finding by Lin et al. (2014), who addressed stellar mass dependent quenching with a different approach and showed that the quenching efficiency strongly increases with stellar mass. Lin et al. (2014) found that stellar mass quenching becomes dominant over environmental quenching only for galaxies more massive than \(10^{10} \, M_\odot\). We therefore speculate that the low green-valley fraction at the low-mass end seen in this work might be due to the lack of stellar mass quenching below \(10^{10} \, M_\odot\).

8. Summary

We conducted extremely deep \(u'\)-band imaging with CFHT MegaCam in the COSMOS and SXDS fields, named “MUSUBI,” to sample the rest-frame UV galaxies at \(z \lesssim 3\) to complement the Subaru HSC UDS grizy imaging in these two fields. Our deep imaging covers \(\gtrsim 1 \, \text{deg}^2\) in each field. By combining our data with shallower \(u'\) data in the CFHT archive, we reached 5\(\sigma\) limiting magnitudes of \(u' = 28.1\) and 28.4 on faint galaxies in the deepest areas of our COSMOS and SXDS maps, respectively. In the central 1\(\text{deg}^2\) regions, which are more representative for the survey, the limiting magnitudes are 27.7 and 27.8 for COSMOS and SXDS, respectively. The image quality is quite uniform, with FWHMs of 0\(''\)88–0\(''\)95 measured on stars, in the 1\(\text{deg}^2\) regions in the two fields. Our photometry was calibrated to the highly accurate CFHT SNLS \(u'\) photometry. We estimated that the uncertainties of the calibration are 0.01 mag for COSMOS and 0.02 mag for SXDS. We tied our astrometry to Gaia DR2. The astrometric uncertainties of our data are 70 mas for COSMOS and 60 mas for SXDS. Using a machine-learning photo-\(z\) code, DEMp, we showed that adding our \(u'\)-band data to the HSC grizy data can significantly improve the photo-\(z\) in terms of scatter and bias at \(z = 0\) to \(z \sim 3\), and also can mildly improve the photo-\(z\) outlier fractions at \(z > 2\). We also demonstrated that combining the \(u'\) and grizy data enables the identification of green-valley galaxies at \(z = 0.4–0.6\) down to \(10^{9.1} \, M_\odot\). This allows us to study their evolution as a function of stellar mass and their fraction relative to star-forming and quiescent galaxies. We publicly release our reduced and calibrated \(u'\) images for COSMOS and SXDS, as well as reference SExtractor catalogs that are science-ready.

We thank the referee for comments that greatly improved the article. We thank the CFHT staff for observational support, and in particular for making the legacy \(u'\) filter available to us when MegaCam was migrating to the new filter system. MegaCam is a joint project of the CFHT and CEA/DAPNIA, at the CFHT, which is operated by the National Research Council of Canada, Institut National des Science de l’Univers of Centre National de la Recherche Scientifique of France, and the University of Hawaii. The observations at the CFHT were performed with care and respect from the summit of Maunakea, which is a significant cultural and historic site. We are most fortunate to have the opportunity to conduct observations from this mountain. We gratefully acknowledge support from the Ministry of Science and Technology of Taiwan through grants 110-2112-M-001-006 (W.-H.W.), 108-2628-M-001-001-MY3 (L.L. and H.-Y.J.), and 110-2112-M-001-004 and 109-2112-M-001-005 (Y.-T.L.), and from Academia Sinica through Career Development Awards CDA-107-M03 (L.L. and H.-Y.J.) and CDA-106-M01 (Y.-T.L.). This work was conducted partially when W.-H.W. was visiting the CFHT as a resident astronomer. W.-H.W. is grateful for the hospitality of the CFHT ohana.

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