Formation and Evolution of Galaxy Outskirts
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Large scale profiles of galaxies at z=0-2 studied by stacking the HSC SSP survey data

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Abstract. We are carrying out the study of the evolution of radial surface brightness profiles of galaxies from $z = 0$ to 2 by stacking analysis using data corrected by the Hyper Suprime-Cam (HSC) Subaru Strategic Program (SSP). This will allow us to constrain the large scale average profiles of various galaxy populations at high redshift. From the stacking analysis of galaxies selected based on their photometric redshifts, we successfully detected the outer components of galaxies at $z > 1$ extending to at least ~ 80 kpc, which imply an early formation for the galaxy outskirts.

Keywords. galaxies: evolution, galaxies: halos, galaxies: high-redshift

1. Introduction

The formation scenario of galaxy outskirts is still an open question. E.g., radial migrations of stars to outside by secular processes (e.g., Roškar *et al.* 2008) and minor mergers (e.g., Peñarrubia *et al.* 2006) are proposed to form various outer disk profiles. It is predicted that the radial profiles of stellar halos depend on the merger histories of galaxies although there can be the contributions of stars formed *in situ* (Cooper *et al.* 2015). The abundance and distribution of satellite galaxies is one of the biggest problems of the galaxy formation models in the ΛCDM Universe. Thus, the galaxy outskirts are key to test the cosmological galaxy formation models. To study the formation histories of galaxy outskirts, we need to look back at galaxy outskirts at high redshift. Since the surface brightness of a galaxy dims by $\propto (1 + z)^{-4}$, very deep data is required to constrain large scale radial profiles of galaxies at high redshift. For galaxies at up to $z \sim 1$, the radial profiles within ~ 40 kpc can be studied by using the *Hubble Space Telescope (HST)* (Trujillo & Bakos 2013) but at a high cost and it is still hard to constrain far outskirts of individual galaxies.

2. Stacking analysis with the HSC SSP survey

We are now running the deep stacking analysis project using the very large sample of galaxies found from the wide and deep galaxy survey of the Hyper Suprime-Cam Subaru Strategic Program (HSC SSP PI: S. Miyazaki). The HSC is the newly developed high sensitivity camera with very wide field of view (1.5 deg^2) equipped on Subaru Telescope. The HSC SSP survey consists of wide (*griz*-band imaging with the 5σ limiting magnitudes 25-27 mag in AB for $\sim$1500 deg^2), deep (*griz*-band imaging as deep as 26-28 mag and narrow-band survey for LAEs at $z = 2-6.5$ for 28 deg^2) and ultra deep surveys

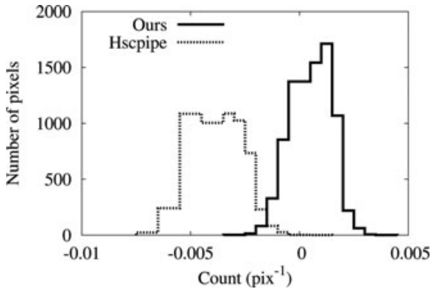

Figure 1. The distributions of count per pixel at blank fields in the stacked images (= remnant sky values after sky subtractions) reduced with our own method (solid line) and the hscPipe (dotted line).

($griz$-band imaging as deep as 27-29 mag and narrow-band survey for LAEs at $z = 2 - 7$ for 3.5 deg^2) and provides us with the widest and deepest galaxy catalog ever built.

The catalog of galaxies selected based on photometric redshifts in the wide layer are available. At $z \sim 1$, we can stack 10,000 to 100,000 objects per sample and constrain the average radial profiles of galaxies down to 33 mag arcsec^{-2} at a 5σ detection limit. However there are several problems for such a deep stacking analysis using data obtained with ground based telescopes. First, the natural seeing is too large to constrain the morphologies of galaxies at high redshift. We applied the color-magnitude relations obtained with the *HST* (Shibuya *et al.* 2015) to divide the sample into early-type and late-type galaxies. Second, the dip-like features around the objects prevent us to constrain the large scale profiles (reported in Momose *et al.* 2014). This feature is mostly originated in the over sky subtraction problem. Since the sky subtraction in the data reduction pipeline for the HSC (hscPipe) is much improved, we can perform the stacking analysis as deep as ~ 33 mag arcsec^{-2} but more improvements are required to go deeper and with a better accuracy. We tried to improve the sky subtraction by applying better object masks. The remnant sky values in our own reduction successfully get closer to zero (Fig. 1).

3. Results & Discussion

Here we present the early results of the stacking analysis by using the data reduced with the hscPipe since our own data reduction has not yet been completed. Fig. 2 shows the $griz$-band stacked images and the z-band radial profile of the late-type galaxies with the stellar mass comparable to Milky Way at $z_{\rm phot} = 1.15 - 1.5$. The dotted line shows the radial profile of a late-type galaxy with the Sérsic (Sersic 1968) index $n = 1$ and the effective radius $r_e = 2$ kpc convolved with the PSF of the HSC. The PSF profile of the HSC images are obtained by stacking the stars in the current survey fields. We note that the PSFs have long tails extended over 10 arcsec and slightly differ from filter to filter.. There is a clear deviation from the single Sérsic model at radius > 2 arcsec (~ 20 kpc) while the outer component is fitted with an exponential profile.

Our preliminary results imply an early formation of stellar halos although there can be the contributions of not only the stellar halo components but also satellite galaxies under the detection limits of the individual images. The evolution of radial color gradients and central to stellar halo mass ratios will give constraints on the evolution scenario of galaxy outskirts. The comparison of outer profiles with the dark matter mass profiles predicted in the cosmological numerical simulations will be helpful to test cosmological galaxy formation models. Our results will be a good reference for planning the detailed sciences of outskirts of individual galaxies at high redshift with the next generation telescopes.

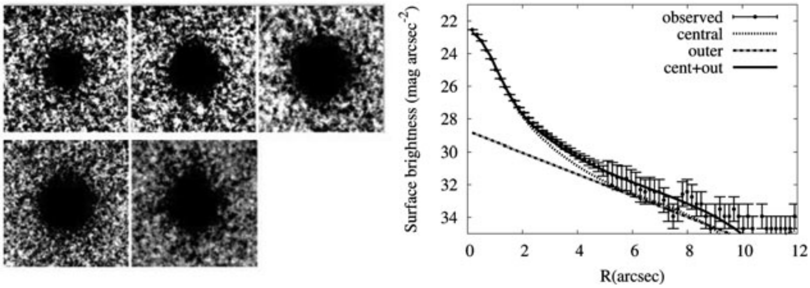

Figure 2. *Left:* The *grizy*-band stacked images of the late-type galaxies with the stellar mass $10^{10.25-10.75}$ $M_\odot$ and $z_{\rm phot} = 1.15 - 1.5$ from left top to right bottom ($25''.0 \times 25''.0$). *Right:* Its z-band radial profile. The filled circles are the observed points. The dotted, dashed dotted and solid curves are the model fit of the central component with the Sérsic profile, the model fit of outer component with an exponential profile and the sum of these two models, respectively.

4. Acknowledgements

This paper makes use of software developed for the Large Synoptic Survey Telescope (LSST Ivezic *et al.* 2008 ; Axelrod *et al.* 2010). We thank the LSST Project for making their code available as free software at http://dm.lsstcorp.org. The LSST code is licensed under the terms of the GNU General Public License, Version 3, granting the freedom to run, copy, distribute, study, change and improve the software as you see fit. For further details, see the official LSST requirement is posted https://confluence.lsstcorp.org/display/LSWUG/Getting+Started+with+the+LSST+Software+Stack. The Pan-STARRS1 Surveys (PS1 Magnier *et al.* 2013; Schlafly *et al.* 2012; Tonry *et al.* 2012) have been made possible through contributions of the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max-Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg and the Max Planck Institute for Extraterrestrial Physics, Garching, The Johns Hopkins University, Durham University, the University of Edinburgh, Queen's University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, the National Aeronautics and Space Administration under Grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation under Grant No. AST-1238877, the University of Maryland, and Eotvos Lorand University (ELTE).

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