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Letter

A Wide and Deep Exploration of Radio Galaxies with Subaru HSC (WERGS). IX. The Most Overdense Region at $z \sim 5$ Inhabited by a Massive Radio Galaxy

Hisakazu UCHIYAMA[1]*, Takuji YAMASHITA[2,1], Tohru NAGAO[1], Yoshiaki ONO[3], Jun TOSHIKAWA[4], Kohei ICHIKAWA[5,6,7], Nozomu KAWAKATU[8], Masaru KAJISAWA[1], Yoshiki TOBA[2,9,10,1], Yoshiki MATSUOKA[1], Mariko KUBO[1], Masatoshi IMANISHI[2,11], Kei ITO[12], Toshihiro KAWAGUCHI[13], Chien-Hsiu LEE[14] and Tomoki SAITO[15]

[1]Research Center for Space and Cosmic Evolution, Ehime University, 2-5 Bunkyo-cho, Matsuyama, Ehime 790-8577, Japan

[2]National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan

[3]Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8582, Japan

[4]Department of Physics, University of Bath, Claverton Down, Bath, BA2 7AY, UK

[5]Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, Sendai 980-8578, Japan

[6]Astronomical Institute, Tohoku University, Aramaki, Aoba-ku, Sendai, Miyagi 980-8578, Japan

[7]Max-Planck-Institut für extraterrestrische Physik (MPE), Giessenbachstrasse 1, D-85748 Garching bei Müunchen, Germany

[8]National Institute of Technology, Kure College, 2-2-11, Agaminami, Kure, Hiroshima 737-8506, Japan

[9]Department of Astronomy, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan

[10]Academia Sinica Institute of Astronomy and Astrophysics, 11F of Astronomy-Mathematics Building, AS/NTU, No.1, Section 4, Roosevelt Road, Taipei 10617, Taiwan

[11]Department of Astronomical Science, The Graduate University for Advanced Studies, SOKENDAI, Mitaka, Tokyo 181-8588, Japan

[12]Department of Astronomy, School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, JAPAN, 113-0033

[13]Department of Economics, Management and Information Science, Onomichi City University, Hisayamada 1600-2, Onomichi, Hiroshima 722-8506, Japan

[14]NSF's National Optical-Infrared Astronomy Research Laboratory, Tucson, AZ 85742, USA

[15]Nishi-Harima Astronomical Observatory, Centre for Astronomy, University of Hyogo, 407-2

Nichigaichi, Sayo-cho, Sayo, Hyogo 679-5313, Japan

*E-mail: uchiyama@cosmos.phys.sci.ehime-u.ac.jp

Abstract

We report on the galaxy density environment around a high-z radio galaxy (HzRG) at $z = 4.72$, HSC J083913.17+011308.1 (HSC J0839+0113), probed using an r-dropout Lyman break galaxy (LBG) sample from the Hyper Suprime-Cam Subaru Strategic Program data. We find that HSC J0839+0113 resides in the outskirt of an overdense region identified by the r-dropout galaxies at a 4.7σ significance level. The projected distance between HSC J0839+0113 and the peak position of the overdense region is 0.4 physical Mpc which is shorter than the typical protocluster radius in this epoch. According to the extended Press Schechter and the light cone models, the HSC J0839+0113-hosted overdense region is expected to evolve into a halo $> 10^{14} M_\odot$ at $z = 0$ with a high probability of $> 80\,\%$. These findings suggest that HSC J0839+0113 is associated with a protocluster. The HSC J0839+0113 rich-system is the most overdense region of LBGs among the known protoclusters with LBGs in the same cosmic epoch.

1 Introduction

High-z radio galaxies (HzRGs) are useful proofs of large-scale cosmic structure, pointing towards the possible sites of the most overdense regions or rich protoclusters (Overzier et al. 2006; Venemans et al. 2007; Hatch et al. 2014; Magliocchetti et al. 2017; Uchiyama et al. 2022a). Study of the most overdense region can provide a strong constraint on the era of the onset of the environmental effects observed in the local universe (Kodama et al. 1998). However, the number of known HzRGs at $z > 4$ and consequently the number of studies on their environments have been limited. This is due to a lack of deep and wide surveys in the radio and optical wavelengths sufficient to capture rare HzRGs and the surrounding galaxies for measuring their environments. Only a few of HzRGs have been identified at $z > 4$ has been found (Miley & De Breuck 2008; Saxena et al. 2019; Yamashita et al. 2020; Endsley et al. 2022; Broderick et al. 2022). It has been confirmed that some of these HzRGs are hosted by overdense regions, such as the TN J0924–2201 field at $z = 5.2$ (Venemans et al. 2007; Overzier et al. 2009), and COS-87259 field at $z \sim 6.8$ (Endsley & Stark 2022).

A large survey for radio galaxies, WERGS (Yamashita et al. 2018; Toba et al. 2019; Yamashita et al. 2020; Ichikawa et al. 2021; Uchiyama et al. 2022a; Uchiyama et al. 2022b), is now being conducted. It is based on the wide ($\sim 1000\ \mathrm{deg}^2$) imaging data generated by the Subaru/Hyper Suprime-Cam (Miyazaki et al. 2012;

* Present Address is uchiyama@cosmos.phys.sci.ehime-u.ac.jp

Miyazaki et al. 2018) strategic program, HSC-SSP (Aihara et al. 2018a), and the archive catalogs of large radio surveys. In this survey, the HzRG candidates are selected by matching the sources of the faint images of the radio sky at twenty-cm (FIRST) survey (Becker et al. 1995; Helfand et al. 2015), with the HSC-SSP Lyman break galaxies (LBGs) (Yamashita et al. 2020; Uchiyama et al. 2022a). The WERGS wide survey can expand the number of HzRGs and could avoid missing rare massive HzRGs. Simultaneously, the HSC-SSP data allow us to examine the LBG density environments around the HzRGs. One of the WERGS HzRG candidates, HSC J083913.17+011308.1 (hereafter, HSC J0839+0113), has been spectroscopically confirmed at $z = 4.72$ (Yamashita et al. 2020). Through the rest-frame ultra-violet (UV)-optical multiband photometry, HSC J0839+0113 was found to have a high-stellar mass of $10^{11.4} M_\odot$, comparable to those of the most massive LBGs at $z \sim 5$ (Yamashita et al. 2020) and that of the HzRG at the same epoch, TN J0924-2201 (Seymour et al. 2007; Overzier et al. 2009). Such a massive HzRG is likely to be an ancestor of the brightest cluster galaxy (West 1994) and is expected to be hosted by the most overdense region, which can evolve into a rich cluster halo at $z = 0$.

In this letter, we report a finding that HSC J0839+0113 is associated with one of the most overdense regions of LBGs at $z \sim 5$, based on the HSC-SSP data. We assume the following cosmological parameters: $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 70\ \mathrm{km\ s^{-1}\ Mpc^{-1}} = 100\ h\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$. We use the cModel magnitude (Abazajian et al. 2004) in the AB system to measure the fluxes.

2 Samples

2.1 HSC J0839+0113

HSC J0839+0113 was selected from the r-dropout galaxies with a FIRST detection and spectroscopically confirmed using Gemini Multi-Object Spectrographs (Yamashita et al. 2020). The redshift $z = 4.723$ was estimated based on the redshifted Lyα emission line. HSC J0839+0113 is the most distant HzRG in the spectroscopically-identified WERGS sample. The stellar mass was calculated to be log $M_*/M_\odot = 11.43^{+0.22}_{-0.46}$ by fitting the spectral energy distribution (SED) with the multiwavelength data of the optical-to-mid IR bands (Edge et al. 2013; Cutri et al. 2021). The rest-frame 1.4GHz radio luminosity is $1.63^{+0.03}_{-0.03} \times 10^{27}$ W Hz^{-1}. The other spectroscopic and photometric information are available in Table 1 of Yamashita et al. (2020).

2.2 r-dropout galaxies

To measure the galaxy density around HSC J0839+0113, we use the r-dropout galaxies from the HSC-SSP Wide layer data of DR S16A (Aihara et al. 2018a; Bosch et al. 2018). The HSC-SSP is a deep-and-wide optical (g, r, i, z, and y-bands) survey using the HSC with a field-of-view of $1.^\circ5$ diameter (Aihara et al. 2018b; Furusawa et al. 2018; Kawanomoto et al. 2018; Komiyama et al. 2018). The Wide layer data of DR S16A (Aihara et al. 2018a; Bosch et al. 2018) consists of wide field area of > 200 deg^2 with a median seeing size of $0.''6 - 0.''8$. Among the spectroscopically-confirmed HzRGs at $z > 4$, only HSC J0839+0113 is included in the HSC-SSP area, even after the completion of the HSC-SSP survey.

The r-dropout galaxies are selected as in Ono et al. (2018). The HSC-SSP sources are first selected in the 2×2 deg^2 area centered on HSC J0839+0113 by imposing the HSC-SSP flags summarized in Ono et al. (2018). These flags can conservatively mask the regions around bright objects (Coupon et al. 2018) and bad pixels, and an area of 2.9 deg^2 with uniform depths in all the HSC $grizy$-bands can be selected. The 5σ limiting magnitudes of the $griz$- and y-bands for PSF photometry in the effective area are 26.2, 25.6, 25.9, 25.2, and 24.4, respectively. As a result, the number of r-dropout galaxies is 2043 in the effective area. Certain low-z interlopers such as red galaxies with a prominent Balmer/4000Å break can contaminate the r-dropout galaxy sample. The contamination rate is estimated to be ~ 30 % by Ono et al. (2018).
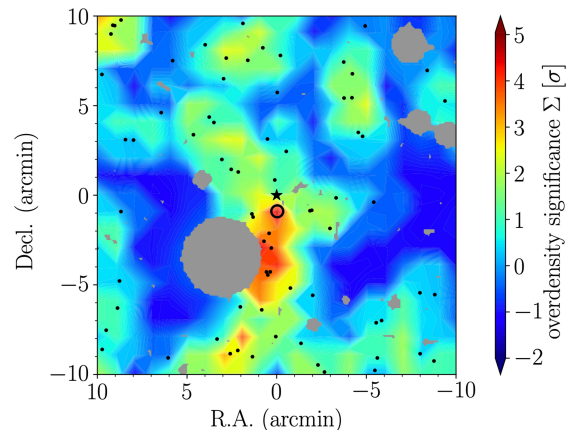
Fig. 1. Overdensity significance map around HSC J0839+0113 (black star). The color contour shows the overdensity significance. The peak position is indicated by the black open circle. The black dots denote the r-dropout galaxies. The gray shades indicate the masked regions.

3 Density Measurement and Results

We adopt the fixed aperture method to measure the surface number densities of the r-dropout galaxies, following Toshikawa et al. (2016). We first uniformly distribute the apertures in a 1 arcmin grid spacing in a sufficiently wide area of 2×2 deg^2 centered on HSC J0839+0113 to ensure adequate statistics. The aperture radius is 1.9 arcmin ($= 0.75$ physical Mpc), corresponding to the typical size of a protocluster at $z \sim 5$ with a descendant halo mass $> 10^{14}$ $M_\odot$ at $z = 0$ (Chiang et al. 2013). Next, we count the number of r-dropout galaxies within each aperture. If the apertures include parts of the masked regions, the number of r-dropout galaxies is corrected by assuming the average density in the masked regions. This operation dilutes the possible signals from the real overdense regions, leading to conservative results. We do not measure the local density if the center of the aperture overlaps with the masked regions. Finally, the overdensity significance, Σ, is defined as $(N\text{-}\bar{N})/\sigma$, where N is the number of r-dropout galaxies in each aperture, and $\bar{N}$ and σ are the mean and standard deviation of N, respectively. $\bar{N}$ and σ are estimated to be 1.8 and 1.4, respectively.

Figure 1 shows the overdensity significance map around HSC J0839+0113. Σ at the position of HSC J0839+0113 is 1.6σ. We find that HSC J0839+0113 resides in the outskirt of an overdense region with $\Sigma > 4\sigma$, south of HSC J0839+0113. The peak of Σ in this region is 4.7σ. The projected distance from HSC J0839+0113 to the peak is 0.4 physical Mpc, which is shorter than the typical radius of a $z \sim 5$ protocluster, 0.75 physical Mpc (Chiang et al. 2013). Thus, HSC J0839+0113 is implied to associate with a protocluster.

In our density estimation, the average density is used in the masked regions. However, even if no r-dropout galaxies exist in the masked regions, the Σ peak remains almost the same (4.5σ). In addition, the number density of a 4.7σ overdense region is expected to be very low at ~ 1 deg^{-2} (Toshikawa et al. 2016). $> 4\sigma$ overdense regions occupy ~ 0.3 % of the entire sky. Thus, such a high density region with a massive rare HzRG is unlikely to be explained by chance alignment or contamination from nearby sources. Besides, we check for possible contamination from low-z groups/clusters. If low-z groups/clusters happen to overlap with HSC J0839+0113 in the line-of-sight direction, then a non-negligible number of their red-sequence member galaxies which have red $r - i$ colors could satisfy the r-dropout selection, resulting in such large Σ. We find no red-sequence-like tight correlation in a color-magnitude diagram of $r - i$ and i for the r-dropout galaxies in the 4.7σ overdense region. We also confirm that there are no "CAMIRA" clusters (Oguri et al. 2018) near the 4.7σ overdense region. The CAMIRA clusters are selected by detection of red sequence, based on the HSC Wide layer data which is the same as that used in our study. Thus, it is unlikely that this large Σ is produced by low-z group/cluster interlopers.

4 Discussion and Summary

We found that HSC J0839+0113 was spatially associated with a 4.7σ overdense region. Such overdense regions at $z \sim 5$ are expected to evolve into local rich clusters with halo masses $> 10^{14} M_\odot$, with a probability of $\gtrsim 80\%$ according to the light cone model (Toshikawa et al. 2016). Following Uchiyama et al. (2018); Uchiyama et al. (2020), this high probability is also supported by the halo mass of the HzRG as described below. Uchiyama et al. (2022a) performed clustering analysis to estimate the halo masses of the WERGS HzRGs at $z = 3.3 - 4.5$, and found that the typical HzRG halo mass is log $M_h/h^{-1}M_\odot = 13.02^{+0.13}_{-0.14}$. Assuming that HSC J0839+0113 at $z = 4.72$ is hosted in a halo with a similar mass, we can evaluate the expected descendant halo mass at $z = 0$ using the extended Press Schechter model (Press & Schechter 1974; Bower 1991; Bond et al. 1991; Lacey & Cole 1993). As a result, the $z = 0$ descendant halo mass of the HzRG is estimated to be $4.0^{+1.1}_{-0.9} \times 10^{14} h^{-1} M_\odot$ on an average. This indicates that the HzRG halo is expected to evolve into a cluster halo at $z = 0$ almost certainly with a probability of $99.8^{+0.2}_{-1.9}$ %. HSC J0839+0113 is expected to be associated with a protocluster.

It is worth comparing the HSC J0839+0113 system with the spectroscopically-confirmed protoclusters traced by LBGs in the same epoch. At $z \sim 5$, two protoclusters have been identified with LBGs (Overzier et al. 2009; Toshikawa et al. 2020). Overzier et al. (2009) found that LBGs with $z \lesssim 27.0$ mag are strongly clustered around HzRG TN J0924-2201 at $z = 5.2$. In the 3.2×3.2 arcmin^2 area including TN J0924-2201, the galaxy density is approximately twice that of the fields. For comparison with the HSC J0839+0113 system, we limit the LBG sample of Overzier et al. (2009) to one with $z < 25.2$ corresponding to to our 5σ limiting magnitude. We find that the density of the HSC J0839+0113 system is approximately twice that of the TN J0924-2201 field. Toshikawa et al. (2020) discovered a $z = 4.9$ rich protocluster ("D1RD01") without any HzRGs, by conducting follow-up spectroscopy on a $\Sigma = 4.4\sigma$ overdense region of r-dropout galaxies, which was found by use of the Canada-France-Hawaii Telescope Legacy Survey data (Toshikawa et al. 2016). The D1RD01 region is included in the HSC-SSP Wide layer data of DR S16A. The 5σ limiting magnitude of the HSC-SSP z-band in the D1RD01 region is 24.9, which is 0.3 mag shallower than that in our study. We select r-dropout galaxies in the D1RD01 region based on the same selection criteria used in our study. By evaluating the density of the r-dropout galaxies with $z < 24.9$ within an area of a circle with 1.9 arcmin radius, we find that the density of our HzRG system is 1.2 times higher than that of the D1RD01 region. Therefore, the system with which HSC J0839+0113 is associated has a LBG overdensity comparable to or higher than that of the spectroscopically-confirmed protoclusters traced by LBGs in the same epoch.

The emergence of the environmental effect, i.e., the dependence of the stellar population or the amount of dust in the galaxy on the ambient density, is already observed in the galaxy overdense regions at $z \sim 4$ (Toshikawa et al. 2016; Ito et al. 2019). Beyond $z \sim 4$, the existence of the environmental effect remains unclear. The HSC J0839+0113 system, which is the most overdense region of LBGs in this epoch, can offer insights on the era of the onset of environmental effects. The left panel in Figure 2 shows the distribution of the absolute UV magnitudes $M_{\rm UV}$ of eight r-dropout galaxies in the HSC J0839+0113 overdense region, i.e., within 0.75 physical Mpc from the position of the 4.7σ peak overdensity, compared to that in the field excluding the HSC J0839+0113 overdense region. $M_{\rm UV}$ is estimated as in Ono et al. (2018). We find no significant difference in $M_{\rm UV}$ between the overdense region and the field. The P-value in the Kolmogorov-Smirnov test is estimated to be 0.51 for the two distributions. The right panel in Figure 2 shows the distributions of the $i - z$ colors of the r-dropout galaxies in the HSC J0839+0113 overdense region and the field. There are no r-dropout galaxies with blue color of
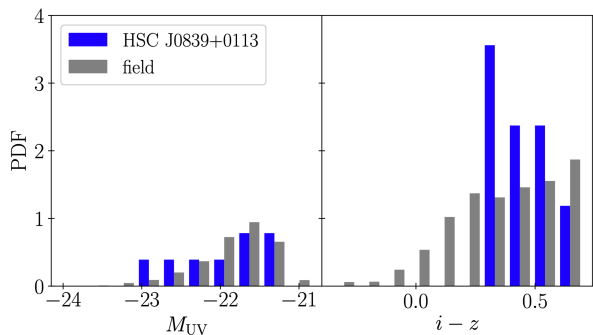
Fig. 2. Probability density function of $M_{\rm UV}$ (left panel) and $i-z$ (right panel) of the r-dropout galaxies in the HSC J0839+0113 overdense region (blue bars) and field (gray bars).
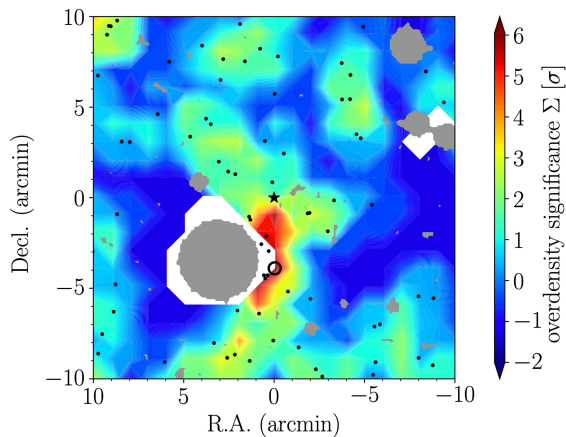
Fig. 3. Overdensity significance map around HSC J0839+0113 (black star) with a different mask correction. The densities of the r-dropout galaxies in the masked and unmasked portions of the aperture are equal. The white shades indicate the regions where the > 50 % of the area is masked in each aperture.

$i-z \lesssim 0.3$ in the HSC J0839+0113 overdense region. These two distributions differ from each other, with a D-value of 0.45 and P-value of 0.05 in the Kolmogorov-Smirnov test. This trend does not change even in the Anderson-Darling test, with an A^2-value of 2.6 and a P-value of 0.05. This result implies that the HSC J0839+0113 overdense region predominantly includes galaxies with an old stellar population and/or large amounts of dust. These situations are consistent with the fact that HSC J0839+0113 is hosted by a massive and dusty galaxy (Yamashita et al. 2020). The galaxies in the HSC J0839+0113 overdense region may have experienced enhanced star formation in an earlier epoch. The absence of blue r-dropout galaxies suggests the existence of the environmental effect in the HSC J0839+0113 overdense region.

It is worthwhile to examine the rigidity of the results using a different mask correction method. We assume that the densities of the r-dropout galaxies in the masked

and unmasked portions of an aperture are equal. When > 50 % of the area is masked in the aperture, we do not measure the local density in the aperture to avoid a considerable uncertainty. We find that even in this case, the HSC J0839+0113 overdense region maintains a high-overdensity significance of $\Sigma = 6.0\sigma$ (Figure 3). Hence, HSC J0839+0113 is associated with a protocluster candidate even with this mask correction. A large overdense region is clearly visible to the south of the HSC J0839+0113 overdense region. The peak significance of the southern overdense region is $\Sigma = 6.3\sigma$. From the current data, it is not clear whether the HSC J0839+0113 overdense region is separated from the southern overdense region or it is a substructure of a large structure. In either case, the HSC J0839+0113 overdense region remains one of the most overdense regions of LBGs at $z \sim 5$.

In summary, we examined the galaxy density environment around HSC J0839+0113 with a massive stellar-mass at $z = 4.72$. We found that HSC J0839+0113 exists in the outskirt of a 4.7σ overdense region. According to the extended Press Schechter and light cone models, the HSC J0839+0113 overdense region is expected to evolve into a halo $> 10^{14} M_\odot$ at $z = 0$, with a high-probability of > 80 %. The HSC J0839+0113 rich-system is one of the most overdense regions of LBGs compared to the overdensities of the LBGs of two protoclusters in the same epoch. The absence of r-dropout galaxies with blue colors in the high-density region suggests the existence of the environmental effect in the rich-system. So far, the surrounding galaxies are based only on photometric information. A wide-area spectroscopic follow-up observation will allow us to scrutinize the overdense region and the underlying Baryon physics.

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