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The average FIR SED of proto-clusters at $z = 4$

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Abstract. One of the key questions of the observational cosmology is how the environmental dependence of galaxies today formed. Proto-clusters, galaxy overdense regions at high redshift are important laboratory to study the formation history of clusters of galaxies. We perform the first statistic study of far-infrared spectral energy distribution(SED)s of proto-clusters at $z \sim 4$ by the stacking analysis of *Planck*/*AKARI*/*IRAS* images of proto-clusters at $z \sim 4$ selected from the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP) survey. By stacking ~ 200 proto-clusters, we successfully constrain their average total SEDs in $60 - 850$ μm. Our results imply the excess of dusty starburst galaxies with star formation rate several 1000 $M_{\odot} yr^{-1}$ in total and obscured AGNs in proto-clusters at $z \sim 4$.

Keywords. galaxies: formation, large-scale structure of universe

1. Introduction

One of the key question of observational cosmology is when and how the environmental dependence of galaxies today formed. Proto-clusters, galaxy overdense regions at high redshift are thought to be progenitors of clusters of galaxies today. They are important targets to discuss how the environmental dependence of galaxies today evolved.

Proto-clusters have been studied a lot, however, there are several problems with observational method. One is the statistics. The number of the known proto-clusters is not so large. Since the number density of proto-clusters at a given epoch is not so large (~ 1 per 1 deg^2 at a given epoch according to the cosmological numerical simulations), they are generally searched around radio galaxies/QSOs at high redshift, which are thought to evolve into the brightest cluster galaxies today (e.g., Venemans *et al.* 2007), and sometimes found by chance (e.g., Steidel *et al.* 1998). In addition, the selection bias on them is not clear. According to the past few studies, there is a large variation in proto-clusters. Large statistical studies of proto-clusters are needed to show their typical properties and variation.

Another observational issue is their properties obscured by dust. The large fraction of the UV radiation from newly formed stars in starburst galaxies is absorbed by dust and re-emitted as thermal emission from dust at infrared (IR) wavelength (Casey *et al.* 2014). Dusty starburst galaxies at high redshift found at sub-mm referred as sub-mm galaxies (SMGs) are the most intense (SFR> several 100 $M_{\odot}/yr$) starburst galaxies. They comprise the greater part of the observed cosmic star formation history (Madau & Dickinson 2014). Such SMGs are of particular importance in proto-clusters. Indeed, significant density excess of SMGs in proto-clusters have been reported by the deep mm/sub-mm imaging and spectroscopic observations (e.g., Tamura *et al.* 2009; Wang *et al.* 2016; Umehata *et al.* 2018; Miller *et al.* 2018). However the capability of current telescopes is not enough to perform a statistical study of IR properties of galaxies in proto-clusters.

In this study, we perform the statistical study of the IR SEDs of proto-clusters by the stacking analysis of the archival IR images *Planck/IRAS/AKARI* of a large proto-cluster catalog from the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP) survey.

2. Data/Method

We use the catalog of protoclusters at $z \sim 3.8$ selected systematically based on the HSC-SSP survey (Aihara *et al.* 2018) by Toshikawa *et al.* (2018). HSC is the prime focus camera on Subaru Telescope. It has a large field-of-view (FoV) of 1.8 deg^2 and high sensitivity (Miyazaki *et al.* 2012). The HSC-SSP survey is an on-going multi-color ($griz$ + narrow band) survey in optical consisting of three layers, UltraDeep (UD; 3.5 deg^2, $i \sim 28$ mag), Deep (26 deg^2, $i \sim 27$ mag) and Wide (1400 deg^2, $i \sim 26$ mag) layers. In Toshikawa *et al.* (2018), they construct the catalog of Lyman break galaxies using gri-band images (here after g-drop galaxies) from an area of 121 deg^2 of the current HSC-SSP wide layer. This color cut is sensitive for galaxies at $3.3 \leqslant z \leqslant 4.2$. They measure the surface number density of g-drop galaxies with $i < 25.0$ mag within an aperture of $1'.8$ (0.75 Mpc in physical), and select the regions with overdensity significance larger than 4σ as proto-cluster candidates. This radius is the typical extent of the region which will collapse into a single massive halo of $> 10^{14}$ $M_{\odot}$ by $z = 0$, according to the cosmological numerical simulations (e.g., Chiang *et al.* 2013). In total, they identified 179 unique proto-cluster candidates.

We cut out the archival IR all sky maps at the positions of the proto-clusters; the 353, 545 and 857 GHz images taken with *Planck* High Frequency Instrument (HFI); 60 and 100 μm taken with *IRAS*, and *N60*, *WIDE-S*, *WIDE-L* and *N160* band images taken with *AKARI* Far Infrared Surveyor (FIS; Kawada *et al.* 2007). The major contaminant from foreground sources on these IR images is diffuse emission from Galactic cirrus. In case of *Planck*, we use the 353, 545 and 857 GHz cosmic infrared background (CIB) products (Planck Collaboration *et al.* 2016 XLVIII) from the *Planck* legacy archive† which are subtracted of the Galactic cirrus component. *IRAS*/*AKARI* images are stacked after evaluating and subtracting the sky values and smoothed to have the FWHM PSF sizes similar to *Planck* images (≈ 5 arcmin). We measure the fluxes and errors by the bootstrap resampling.

Before the stacking analysis, we checked whether the HSC-SSP proto-clusters are detected individually on the *Planck* images. We found that none of them are detected above 5 σ significance. On the other hand, the overall flux distribution of them is slightly brighter than random points. We make a sub-sample, "brightest half", based on this tentative detections on *Planck*.

3. Result and Discussion

Figure 1 shows the stacked images of the brightest half sample of proto-clusters. There are clear detections with $3 - 10\sigma$ significance except for *AKARI/N60*-band. The red circles in Fig. 2 show the observed values. It is the first time to constrain the average total FIR SED of proto-clusters at $z \sim 4$.

The IR emission at rest-frame $> 70\mu$m is likely from the cold dust emission originated in starburst. This implies significant star formation activities hidden by dust. If the whole

† https://wiki.cosmos.esa.int/planckpla2015/index.php/CMB_and_astrophysical_component_maps

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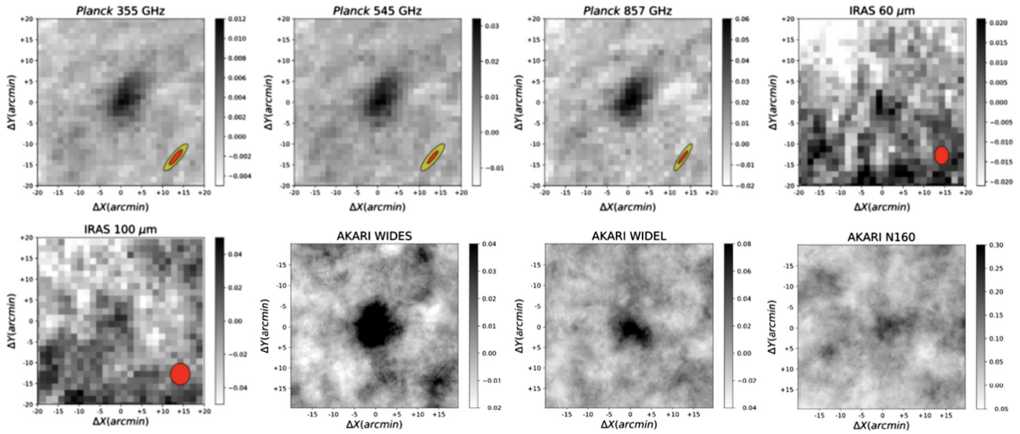

Figure 1. The stacked images of *Planck* 353, 545 and 857 GHz, *IRAS* 60 and 100 μm, and *AKARI WIDES*, *WIDEL* and *N160*-band images of “brightest half” g-drop proto-clusters from *top left* to *bottom right*. The size of each image is 40 arcmin by side. The ellipses on the *Planck* stacked images show the simulated beam profiles. 50 and 90% of flux is contained within red and yellow filled ellipses, respectively. The red ellipse at the bottom right of the *IRAS* image show FWHM of the beam.

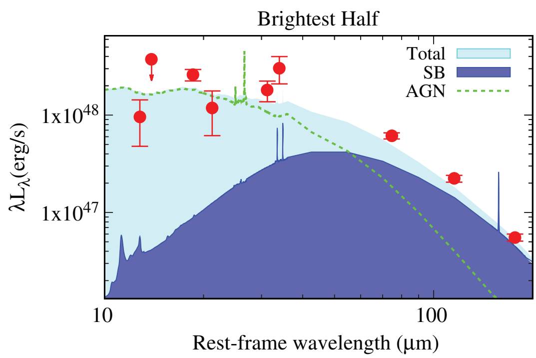

Figure 2. The best fit IR SED for the brightest half sample. Red filled circles show the observed points. The SED model is consisting of a starburst and an AGN components. The total SED is shown with the light blue filled region. The starburst component among the total SED is shown with the thick blue region. The SED of the AGN component is shown with the green dashed line.

IR emission is dominated by cold dust emission from starburst galaxies, the SED should have the shape characterized as a gray body with dust temperature $20 \sim 40K$, however, the observed SED shows significant excess from this at shorter wavelength. The excess at shorter wavelength is likely originated in a warm dust heated by AGNs.

We perform the SED fitting with the models composed from the starburst and AGN components using the templates in Dale *et al.* (2014). The light blue filled region in Fig. 2 shows the best fit SED. The best-fit models of the starburst and AGN components are shown with the thick blue region and the green dashed line, respectively. We found that, in case of the all proto-cluster sample, the total SFR is $\sim 1300\ M_{\odot}/yr$ while it comprises $\sim 8\%$ of the total IR emission from $8 - 1000\mu$ m. In case of the brightest half sample, the total SFR is $\sim 6700\ M_{\odot}/yr$ while it comprises $\sim 20\%$ of the total IR emission. This implies the wide variation in IR properties of proto-clusters while their properties in optical do not correlate significantly with IR properties. We note that the calibration

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errors between the stacked images should be considered. The constraints at $< 10\ \mu$m is also needed to evaluate the contribution of AGNs robustly. To reduce these uncertainties, we need to compare our results with the stacking of the better calibrated IR data like WISE and *Herschel*.

We successfully detect the IR emission of proto-clusters at $z \sim 4$ as their average sum. We show that the greater part of the starburst and AGN activities of proto-clusters are likely to be hidden in optical but luminous in IR. We note that the excess IR emission from AGNs in the SSA22 proto-cluster was reported by Kubo *et al.* (2013) and Umehata *et al.* (2017). This supports our results. On the other hand, based on the same catalog used in this study, Uchiyama *et al.* (2018) report that proto-clusters at $z \sim 4$ are likely to anti-correlate with QSOs selected in optical. Our results imply the presence of obscured QSOs/AGNs which are missed by the QSO catalog in optical. Further follow up observations of individual galaxies in proto-clusters at mm/NIR/X-ray are desired to characterize the obscured starburst/AGNs in proto-clusters and study their roles in galaxy evolution.

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