The Nature and Environment of Dusty Star-Forming Galaxies Near and Far Revealed by *AKARI*

Yusei Koyama,[1] Yasuhiro Matsuki,[2] Shuhei Koyama,[2] Takao Nakagawa,[2] Hideo Matsuhara,[2] Satoshi Takita,[2] Takuji Yamashita,[3] Kana Morokuma-Matsui,[2] Tadayuki Kodama,[4] Rhythm Shimakawa,[5] Shigeru Namiki,[6] Masao Hayashi,[7] and Ken-ichi Tadaki[7]

[1]*Subaru Telescope, National Astronomical Observatory of Japan, 650 North A'ohoku Place, Hilo, HI 96720, U.S.A.*

[2]*Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa 252-5210, Japan*

[3]*Research Centre for Space and Cosmic Evolution, Ehime University, 790-8577 Ehime, Japan*

[4]*Astronomical Institute, Tohoku University, 63 Aramaki, Aoba-ku, Sendai 980-8578, Japan*

[5]*UCO/Lick Observatory, University of California, 1156 High Street, Santa Cruz, CA 95064, U.S.A.*

[6]*Graduate University for Advanced Studies (SOKENDAI), Osawa 2-21-1, Mitaka, Tokyo 181-8588, Japan*

[7]*National Astronomical Observatory of Japan, Osawa 2-21-1, Mitaka, Tokyo 181-8588, Japan*

ABSTRACT

We present our continuous efforts over the last decade — since the launch of *AKARI* — to unveil the environmental impacts on dust properties of galaxies in the local and distant universe by making full use of the *AKARI* "all-sky" and "pointed" observations. We first introduce our new result on the environmental effects on the dust temperature ($T_{\rm dust}$) of local star-forming galaxies. By performing stacking analysis of the *AKARI* FIS all-sky map (at the positions of SDSS star-forming galaxies in different environments), we find that $T_{\rm dust}$ of galaxies increases with increasing environmental density, supporting a cold dust stripping scenario in high-density environments. We also present the results from our systematic, wide-field MIR "pointed" observations of distant clusters with *AKARI*/IRC, in combination with our Subaru Hα observing campaign. Taking advantage of the wide-field coverage of *AKARI* (and Subaru), we revealed that dust-obscured galaxies are most frequently triggered at the periphery of distant clusters. The coincidence of the environment of dusty galaxies and that of galaxy color transition suggests a strong link between dusty galaxies and the process of environmental quenching during the course of cluster-scale assembly.

Keywords: Galaxy evolution

1. INTRODUCTION

The *AKARI* (Murakami et al. 2007) all-sky survey with FIS (Kawada et al. 2007) at 65, 90, 140, 160 μm provides us with a very useful tool to study dust properties in galaxies. Because it covers the peak of dust emission of typical star-forming galaxies in the local universe, we can predict their total infrared luminosities as well as dust temperature. The "all-sky" coverage also uniquely allows one to study galaxies in various environments (e.g., from rich clusters to low-density void regions), enabling us an unbiased, systematic comparison of dust properties in galaxies in different environment. It should also be noted that the *AKARI* all-sky survey is highly complementary to other large surveys in different wavelength ranges such as SDSS, *GALEX*, and so on.

On the other hand, *AKARI* also has a capability of "pointed" observations and completed a large number of deep observations of many interesting regions on sky, with which we can go much deeper than the all-sky survey data and learn more in detail about the nature of targeted objects in the infrared. The *AKARI* IRC (Onaka et al. 2007) has a unique set of filters between 2 μm and 24 μm, allowing us to track down the rest-frame 8 μm light out to $z \sim 2$ (e.g., Goto et al. 2010a).

In this contributed talk, we presented a quick overview of our achievements over the last ~10 years with *AKARI*, including our recent works on local galaxies using *AKARI* all-sky survey data, as well as our results from deep *AKARI*/IRC observations of distant clusters of galaxies, in combination of wide-field Subaru observations.

Corresponding author: Yusei Koyama
koyama@naoj.org

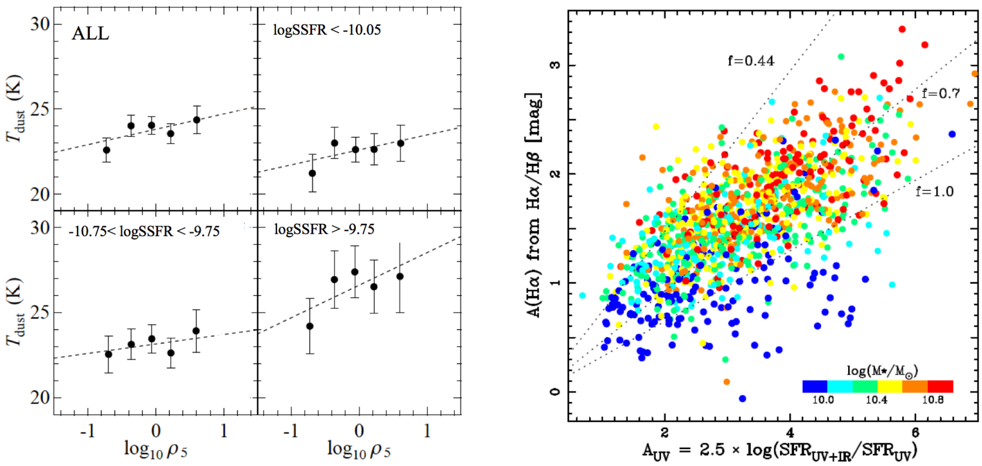

Figure 1. (Left): Average dust temperature of star-forming galaxies as a function of environment. We find that average dust temperature tends to be higher for SF galaxies in higher-density environment (Matsuki et al. 2017). (Right): Dust extinction predicted from Hα/Hβ ratio (Balmer decrement) plotted against the extinction from IR/UV ratio for the *AKARI*–SDSS–*GALEX* sample constructed by Koyama et al. (2015). The color coding indicates stellar mass of galaxies (redder symbols indicate more massive galaxies).

2. NEARBY UNIVERSE

2.1. Environmental Impacts on dust temperature of star-forming galaxies

We first present our recent study on the environmental impacts on dust temperature (T_{dust}) of local star-forming (SF) galaxies (Matsuki et al. 2017). In that work, we performed stacking analysis of *AKARI* FIS all-sky survey map (Doi et al. 2015; Takita et al. 2015) to derive average dust temperature of SF galaxies in different environments.

As a first step, we define the environment of galaxies using the SDSS (DR7) spectroscopic galaxy sample with a commonly used 5th nearest-neighbor approach. We divide the sample into five environmental bins according to their local density, and stacked all SF galaxies (carefully selected with their emission line flux ratio) in each environment to derive their average T_{dust}. Because of the limited depths of *AKARI* all-sky data, it is not possible to detect their FIR emission individually (except for extremely luminous sources), while we can improve the S/N ratio by stacking the data. As demonstrated in Matsuki et al. (2017), we confirmed that S/N ratio is improved following $\sqrt{N_{stack}}$ (as expected).

We then analytically computed T_{dust} from the photometry on the "stacked" 90 μm and 140 μm images (see details in Matsuki et al. 2017). As shown in Figure 1 (left), we find an interesting trend that T_{dust} increases with increasing galaxy local density, suggesting that SF galaxies in higher-density environment have warmer dust than field galaxies. This is the first, systematic study which addresses the environmental impacts on dust temperature of galaxies, while our result is also qualitatively consistent with a previous *Herschel* work by Rawle et al. (2012), who reported that "warm-dust galaxies" are preferentially located in cluster environment, while such galaxies are very rare in general field environment.

We also note that the result is unchanged even if we further split the sample into several sSFR bins (see Figure 1), supporting our claim that galaxies in higher-density environment tend to have warmer dust. Although the temperature difference is not large (a few degree level), follow-up studies are needed with deeper IR data (hopefully based on the measurements of T_{dust} for individual galaxies) to confirm this interesting trend.

2.2. *AKARI*-SDSS-*GALEX* band-merged catalog

The all-sky coverage of *AKARI* survey is ideally matched to other large surveys performed at different wavelengths. In Koyama et al. (2015), we cross-identified *AKARI* FIS Bright Source Catalog (ver.1; Yamamura et al. 2010) with the SDSS (DR7) and *GALEX* (GR5) data, and constructed a useful band-merged catalog which includes ~1,000 galaxies detected at UV, optical (spectroscopy), and FIR. Using this band-merged catalog, we plot in Figure 1 (right) the extinction at Hα from Hα/Hβ ratio (Balmer decrement) against UV extinction derived from IR/UV ratio (so-called "IRX"). Because both the IR/UV ratio and Hα/Hβ ratio are well-calibrated indicators of dust extinction levels of galaxies, they are well correlated with each other at the first order. However, there seems to be a trend that more massive galaxies tend to be located along the upper envelop of this correlation. An important difference between the two indicators is that the IR/UV ratio reflects the extinction of stellar light, while Hα/Hβ ratio measures the extinction of nebular lines emitted from young SF regions. Therefore, the stellar mass trend recognized in Figure 1 (right) suggests that more massive galaxies tend to have higher levels of "extra extinction" toward the nebular regions.

This study demonstrates that *AKARI* data can be useful in many ways and its value can be enhanced when combined with the multi-wavelength data. Currently, our data is mainly limited by the depths of *AKARI* Bright Source Catalog, and our next step of this particular work is to extend the investigation toward low-mass end and to establish a "recipe" to empirically predict the "extra extinction" as a function of stellar mass by using e.g., Faint Source Catalog (which will be

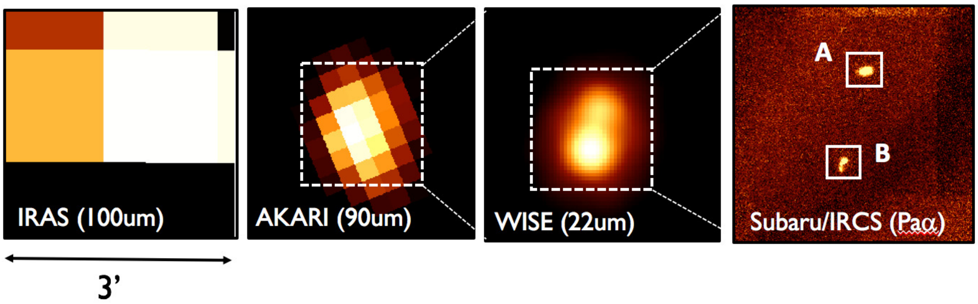

Figure 2. An example of a luminous infrared galaxy observed with *IRAS*, *AKARI*, *WISE*, and Subaru Paα. *AKARI* has much higher spatial resolution than *IRAS*, while our ground-based Paα observation provides two orders of magnitude higher spatial resolution, and allow us to spatially resolve their strong IR emission within the galaxy.

released soon), or existing deep *Herschel* data available for a small portion of sky. We also note that the band-merged catalog has also been used for a different scientific purpose (Shimakawa et al. 2017),

2.3. Follow-up observations of *AKARI*-selected sources

We are also conducting multi-wavelength follow-up observations of *AKARI*-selected galaxies with a variety of science goals. The first example is our Paα narrow-band imaging of luminous infrared galaxies with Subaru, to spatially resolve their SF regions within the galaxies and identify where in galaxies the strong IR emission are coming from. The Paα line is by far less affected by dust extinction compared with UV–optical indicators, and therefore it can provide an excellent tool to study internal structure of (dusty) galaxies. Importantly, compared to the limited spatial resolution of *AKARI* survey data (~40″), Subaru observation can easily achieve a resolution of 1″ or higher (see an example in Figure 2). This example demonstrates that the strong IR emission from this *AKARI* source is originated from two galaxies.

We also comment that *AKARI* all-sky data can provide excellent target for molecular gas studies. We recently completed observation of ~30 *AKARI*-selected LIRGs selected from various environments with Nobeyama 45 m radio telescope, and we detected CO(1–0) from all the target galaxies. By combining our sample with the COLDGASS survey data (Saintonge et al. 2011), we demonstrated that there is a universal correlation between molecular gas properties and SF activity in galaxies (Koyama et al. 2017).

3. DISTANT UNIVERSE

3.1. Dusty starbursts triggered in the outskirts of a distant cluster at $z = 0.8$

We present the results from our wide-field MIR (pointed) observations of a distant cluster, RXJ1716+6708, at $z = 0.81$ (Koyama et al. 2008, 2010). For this redshift range, the 15 μm band (L15) of *AKARI*/IRC captures the rest-frame 8 μm emission from star-forming galaxies (see also Goto et al. 2010b; Murata et al. 2015). Our 15 μm survey covers ~200-arcmin^2 area in and around the cluster, and we find that the fraction of 15 μm-detected galaxies is highest in the intermediate-density environment (including cluster outskirts, groups, or filaments). It is also reported (by optical studies) that there is a sharp transition in galaxy colors in the same environment (Koyama et al. 2008). This suggests a potential link between dusty starbursts and the process of environmental quenching. Our Hα survey of the same cluster with MOIRCS/Subaru has also demonstrated that many of the 15 μm-detected galaxies in group-scale environment have extremely high levels of dust extinction ($A_{\mathrm{H}\alpha} \gtrsim$ 3-mag; Koyama et al. 2010), suggesting that quenching process includes some violent process to rapidly consume their gas to explain the enhanced passive galaxy fraction in the cluster core.

3.2. *AKARI* observations of a newly discovered cluster at $z = 1.5$

We also presented the *AKARI*/IRC data of a newly discovered cluster, 4C65.22, at $z = 1.52$ located near the NEP region (Koyama et al. 2014; Namiki et al. in prep.). This (proto-)cluster was discovered by Subaru Suprime-Cam/MOIRCS survey (Koyama et al. 2014), and the structure has recently been spectroscopically confirmed (Namiki et al. in prep.). Our idea is to extend the MIR study performed at $z \sim 0.8$ with L15 imaging (Section 3.1) to $z \sim 1.5$ with 18 μm imaging (L18W). We show in Figure 3 the large-scale structure associated with the central radio galaxy. Although individual MIR detection becomes much harder at this redshift, we find examples of 18 μm detection from some of the Hα-selected cluster member galaxies. We find that some of the 18 μm sources are detected from the dense groups of Hα emitters, including a "triple merger" candidate (see Figure 3). In these ways, the wide-field approach with *AKARI* and Subaru can provide a powerful tool to unveil the dust-obscured star formation activity of galaxies along the large-scale structures in the very distant universe. More details on this *AKARI*–Subaru joint work will be published elsewhere.

4. SUMMARY

We demonstrated that *AKARI* data can be a very powerful tool to study galaxy evolution and its environmental effects. We also showed that stacking analysis works reasonably well for *AKARI* FIS all-sky map, and we revealed a hint of

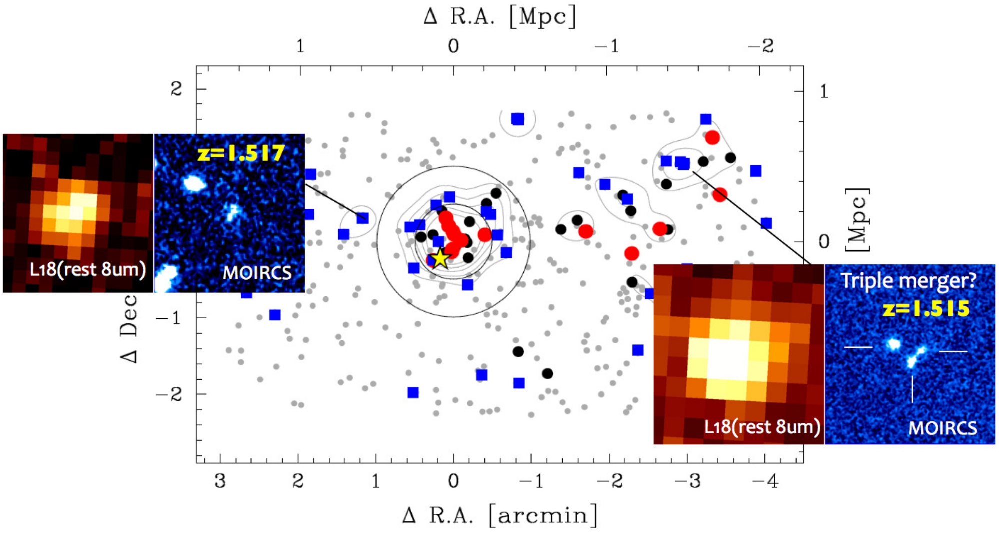

Figure 3. The spatial distribution around the newly-discovered, spectroscopically confirmed proto-cluster at z = 1.52 (Koyama et al. 2014). The red circle show red-sequence galaxies, while blue squares show Hα emitters. We highlight two examples of 18 μm-detected sources discovered in the periphery of the cluster.

environmental dependence of $T_{\rm dust}$ of galaxies (Matsuki et al. 2017). The *AKARI* FIS Bright Source Catalog is also a very powerful tool to study IR properties of galaxies in a statistical manner. We emphasize that the *AKARI* all-sky coverage is uniquely matched to other large surveys performed at different wavelengths, and we constructed an *AKARI*–SDSS–*GALEX* band-merged catalog to study dust extinction properties for a statistical sample of galaxies (Koyama et al. 2015). We also mention that *AKARI* can be an excellent target feeder for multi-wavelength follow-up observations. For examples, we presented our on-going follow-up studies with Subaru (to spatially resolve their IR emission), as well as our recent observations with Nobeyama 45 m radio telescope (to study the molecular gas content in galaxies; Koyama et al. 2017). It is also important to note that *AKARI* completed a large number of deep, "pointed" observations for many interesting regions on sky, which played, for example, an important role in identifying dusty starburst galaxies in/around distant cluster environment at $z \gtrsim 1$ (Koyama et al. 2008, 2010). The importance of *AKARI* data and its legacy value is thus recognized more and more widely by the astronomical community in the world.

ACKNOWLEDGMENTS

Many of the results presented in this contributed talk are based on observations with *AKARI*, a JAXA project with the participation of ESA. I deeply thank the *AKARI* team members for their successful operation of *AKARI*, and thank all the people who supported the *AKARI* mission over the long period of time.

REFERENCES

Doi, Y., Takita, S., Ootsubo, T., et al. 2015, PASJ, 67, 50
Goto, T., Takagi, T., Matsuhara, H., et al. 2010a, A&A, 514, A6
Goto, T., Koyama, Y., Wada, T., et al. 2010b, A&A, 514, A7
Kawada, M., Baba, H., Barthel, P.D., et al. 2007, PASJ, 59, S389
Koyama, Y., Kodama, T., Hayashi, M., et al. 2015, MNRAS, 453, 879
Koyama, Y., Kodama, T., Shimasaku, K., et al. 2008, MNRAS, 391, 1758
Koyama, Y., Kodama, T., Shimasaku, K., et al. 2010, MNRAS, 403, 1611
Koyama, Y., Kodama, T., Tadaki, K.-i., et al. 2014, ApJ, 789, 18
Koyama, S., Koyama, Y., Yamashita, T., et al. 2017, ApJ, 847, 137
Matsuki, Y., Koyama, Y., Nakagawa, T., & Takita, S. 2017, MNRAS, 466, 2517
Murakami, H., Baba, H., Barthel, P., et al. 2007, PASJ, 59, S369
Murata, K., Koyama, Y., Tanaka, M., Matsuhara, H., & Kodama, T. 2015, A&A, 581, A114
Onaka, T., Matsuhara, H., Wada, T., et al. 2007, PASJ, 59, S401
Rawle, T. D., Rex, M., Egami, E., et al. 2012, ApJ, 756, 106
Saintonge, A., Kauffmann, G., Kramer, C., et al. 2011, MNRAS, 415, 32
Shimakawa, R., Koyama, Y., Prochaska, J. X., et al. 2017, arXiv:1705.01127
Takita, S., Doi, Y., Ootsubo, T., et al. 2015, PASJ, 67, 51
Yamamura, I., Makiuti, S., Ikeda, N., et al. 2010, VizieR Online Data Catalog, 2298,