Herschel 250 μm detected star-forming (SF) galaxies over the North Ecliptic Pole (NEP) Wide field of *AKARI*

Seong Jin Kim,[1,2] Woong-Seob Jeong,[1] Hyung Mok Lee,[3] Tomotsugu Goto,[2] Chris Pearson,[4,5,6] Hyunjin Shim,[7] Hideo Matsuhara,[8] and The *AKARI* NEP Team

[1]*Korea Astronomy and Space Science Institute, 776, Daedeokdae-ro, Yuseong-gu, Daejeon, Korea 34055*
[2]*National Tsing hua University, No. 101, Section 2, Kuang-Fu Road, Hsinchu, Taiwan 30013*
[3]*Department of Physics & Astronomy, FPRD, Seoul National University, Shillim-Dong, Kwanak-Gu, Seoul, Korea*
[4]*RAL Space, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK*
[5]*School of Physical Sciences, The Open University, Milton Keynes, MK7 6AA, UK*
[6]*Oxford Astrophysics, Denys Wilkinson Building, University of Oxford, Keble Rd, Oxford OX1 3RH, UK*
[7]*Department of Earth Science Education, Kyungpook National University, Deagu 702-701, Republic of Korea*
[8]*Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa 252-5210, Japan*

ABSTRACT

We study infrared properties of star-forming (SF) galaxies selected by 250 μm band detection of the *Herschel*/SPIRE survey on the entire North Ecliptic Pole (NEP) field of *AKARI*. We matched SPIRE sources with the spectroscopic survey data and combined with those in the *AKARI* NEP-Wide catalogue covering from optical to 24 μm band. We selected around 250 star-forming galaxies and carried out spectral energy distribution (SED) fit analysis to derive physical quantities. Our SED-fit is based on the continuous near- to mid-IR coverage by 9 photometric bands as well as reliable constraint on far-IR peak by *Herschel*. Our sample galaxies have prominent mid-IR PAH features and majority of them are LIRG type population in the low-z (< 0.9). Although they do not seem to form a tight concentration along the galaxy main-sequence due to a wide range of redshift ($0.0 < z < 0.9$) and various morphological types, they show the downsizing evolutionary pattern toward the present epoch.

Keywords: infrared, star-forming galaxies, galaxy evolution

1. INTRODUCTION

To understand the cosmic star-formation properties and history, it is imperative to understand the infrared (IR) luminous population of galaxies, presumably star-forming (SF) systems containing a large amount of dust, where newly forming stars are embedded. With expanding interests in dust in SF galaxies, longer wavelengths have become more important for better understanding of dusty SF galaxies (SFGs) and their evolutions. In this context, sub-mm galaxies in the North Ecliptic Pole (NEP) field observed by *Herschel* provide an important basis to sample various type of IR luminous galaxies. This NEP field observed by *Herschel*'s SPIRE is one of the most frequently visited area on the sky and a legacy field observed as a large area survey program of *AKARI* (Matsuhara et al. 2006; Murakami et al. 2007). Follow-up observations are on-going or being planned because it is a good target field for deep, unbiased, and contiguous surveys for extragalactic objects. Since the *AKARI*'s IR source catalogues have been published, various works such as source count studies (Pearson et al. 2014b), PAH-deficit SF galaxies (Murata et al. 2014), IR background analysis (Matsumoto et al. 2011), AGN feed-backs (Karouzos et al. 2014), and mid-IR (MIR) luminosity functions (LFs, Goto et al. 2010, 2015), etc., were carried out especially taking advantage of continuous near- to mid-IR wavelengths (2–25 μm) coverage of *AKARI*. Here we briefly introduce the IR properties of the low-z (< 1) SF galaxies observed over the NEP-Wide field of *AKARI*, that were detected at SPIRE 250 μm band and also have the redshift determined by the optical spectroscopic survey.

Corresponding author: Seong Jin Kim
seongini@gmail.com

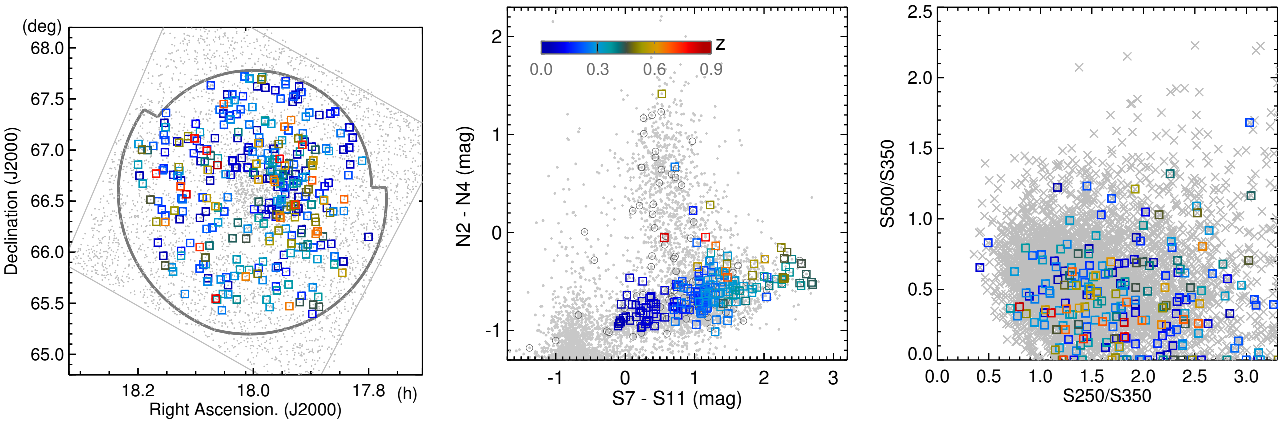

Figure 1. Leftmost panel: The North Ecliptic Pole (NEP) field surveyed by *Herschel*/SPIRE. An outermost rhombus by gray line indicates the area surveyed by the SPIRE. Many small dots inside this rhombus show the SPIRE 250 μm sources. The circular region represent the NEP-Wide (NEPW) field by *AKARI*. Mid panel: The color-color diagram based on the *AKARI* near to mid-IR bands. Various colors indicate the redshifts from 0.0 to 0.9 (see color bar). Right panel: Herschel color-color diagram.

2. OBSERVATION DATA

2.1. *Herschel* NEP Survey & *AKARI* NEP-Wide data

The *Herschel* carried out the survey towards the NEP region in 2012 as an Open time 2 programme (OT2) with the SPIRE instrument at the 250 (PSW), 350 (PMW), and 500 (PLW) μm bands. The sample used in this work was selected based on this survey towards the *AKARI*'s NEP field. This SPIRE/NEP survey area is about 9 deg^2 covering the entire NEP-Wide field (5.4 deg^2, Kim et al. 2012) of *AKARI*. OT2 observations on the NEP are relatively shallow with around 6-hours integration time achieving 9.0, 7.5, and 10.8 mJy sensitivities at each SPIRE band. The combination of all SPIRE/NEP data (including calibration observation) results in a shallow survey for large field, adequate for study of various kinds of galaxies. Adopting SUSSEXtractor algorithm (Pearson et al. 2014a), source extraction was carried out on the 250 μm map and approximately ~4800 sources were catalogued with photometry with the other SPIRE bands (Pearson et al. 2017, *in prep*). Among these sources, we selected galaxies having spectroscopic redshfit from the spectroscopic survey (Shim et al. 2013). Figure 1 presents a map showing the survey areas towards the NEP and the photometric properties of the selected galaxy sample. Here, our sample comprises about 250 galaxies in the redshift range $z < 0$ (see a color bar in the mid-panel), showing prominent mid-IR PAH features. They appear to be various type of low-z SFGs/LIRGs populations and 250 μm counterparts of *AKARI*/MIR selected SF galaxies.

3. ANALYSIS RESULTS

3.1. Physical Modelling by SED-Fit

To derive the physical quantities of the sample, we used all available data from the CFHT u^* to SPIRE 500 μm bands and carried out the SED fit using `MAGPHYS` (da Cunha et al. 2008), which assumes an energy balace between absorbed stellar light and IR emission by dust. Original code doesn't take AGN component into the IR emission, therefore it is so useful for our SED-fit because all our sample is classified as SF galaxies and this code provides flexibility in the SED-fit throughout our photometric data points. Based on the physical modelling with `MAGPHYS`, we derive various physical quantities such as star-formation rate (SFR), stellar mass (M_*), total infrared luminosity (L_{IR}), and so on. In addition to these significant parameters, one of the interesting parameter f_μ represents the fraction of the contribution to L_{IR} by old ($> 10^7$ yr) stars residing outside SF clouds. If the contribution by old stars predominate, f_μ approaches to 1, suggesting the details of the galaxy energy distribution depend on the condition in each galaxy.

3.2. Derived Physical Quantities

In the L_{IR} vs SFR plane, most of our sample form a sequence near the relation converting L_{IR} to SFR (Kennicutt 1988) with some scatter toward lower SFRs because the IR emission traces the dust-obscured part of the radiation by newly-forming stars. The downward scatter on the L_{IR} − SFR relation seems to be caused by the cold and old stellar component according to the modelling. Also, our sample galaxies display a wide scatter around the main sequence in the SFR vs stellar mass (M_*) plane. This scatter is thought to be originated from a wide ranges of redshifts and a variety of galaxy types. We show this in figure 2 (the left panel). The variation of parameter f_μ seems closely related to the spreading direction, here, perpendicular to the main sequence. The gray lines indicate the width from (Elbaz et al. 2011), determined by 16 th and 84 th percentiles of the distribution of median. As previous studies (Wuyts et al. 2011; Lutz 2014) showed that the spread on this direction is strongly associated with the morphology (e.g., sersic index), it is likely that f_μ also seems to be an indicator for this kind of properties. And, our sample seems to be composed of various types of galaxies in a wide range across the galaxy main sequence. In the right panel of figure 2, we show the specific SFR (sSFR)

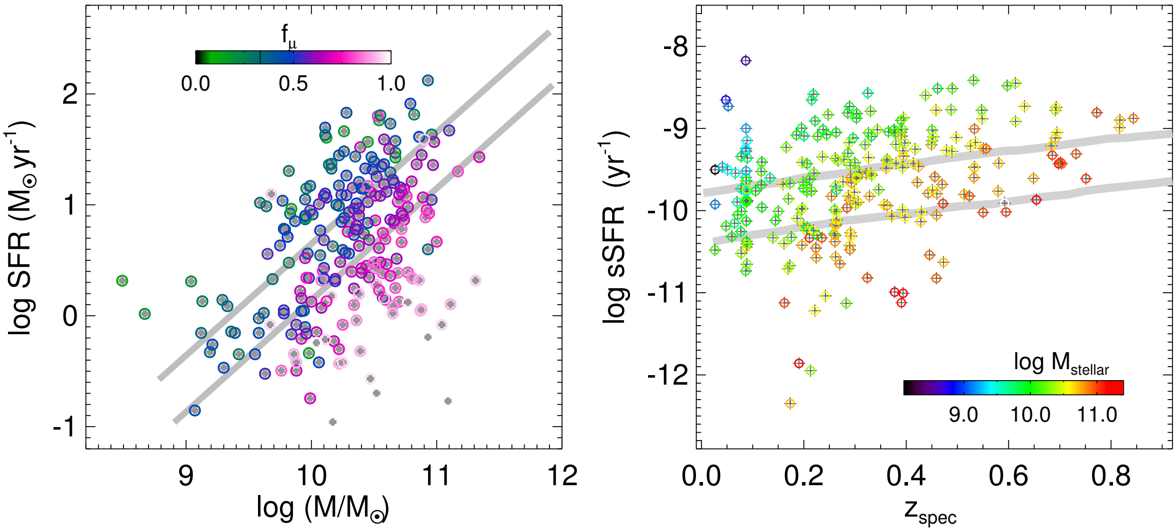

Figure 2. Left panel: Distribution of star-formation rate (SFR) against stellar mass derived using MAGPHYS (da Cunha et al. 2008). Gray thick lines indicate the width (standard deviation) of the galaxy main sequence (Elbaz et al. 2011). The color bar shows the parameter f_μ, indicating the contribution to $L_{\rm IR}$ by old ($> 10^7$ yr) stars. Right panel: Specific star-formation rate (sSFR) as a function of the redshift. Gray thick lines indicate the area of the galaxy main sequence defined by Elbaz et al. (2011).

as a function of redshift. The overplotted gray lines show the redshift evolution of the median sSFR of SF galaxies (16 and 84 th percentiles) from Elbaz et al. (2011). As shown in term of the stellar mass indicated by a color bar, the most massive galaxies have the lowest sSFR at a certain redshift range. It shows more massive galaxies have formed stars more rapidly compared to the less massive galaxies in the same redshift bin, consistently from $z \sim 0.9$ to $z \sim 0$. This mass dependent time evolution suggests the sub-mm detected (i.e., containing a large amount of dust) PAH galaxies follow the downsizing evolutionary pattern toward the present epoch, at least from $z \sim 0.9$.

4. SUMMARY

We sample various SF galaxies in the low-z ($z < 1$) Universe over the *AKARI*'s NEP-Wide field by 250 μm detection of *Herschel*/SPIRE. In order to see the physical quantities, we carried out SED-Fit based on all the available photometric data points from optical (u^*) to SPIRE 500 μm band. This analysis is based on the continuous near- to mid-IR wavelength coverage and accurate redshifts determined by optical spectroscopy. Also, SPIRE photometric bands reliably constrain FIR peak of dust. Comparisons between derived physical parameters such as SFR, M_*, $L_{\rm IR}$) etc. suggest that local SF galaxies with prominent PAH features follow down sizing evolution and seem to have various morphological types.

REFERENCES

da Cunha, E., Charlot, S., & Elbaz, D. 2008, MNRAS, 388, 1595
Elbaz, D., Dickinson, M., Hwang, H. S., et al. 2011, A&A, 533, A119
Goto, T., Takagi, T., Matsuhara, H., et al. 2010, A&A, 514, A6
Goto, T., Oi, N., Ohyama, Y., et al. 2015, MNRAS, 452, 1684
Karouzos, M., Im, M., Trichas, M., et al. 2014, ApJ, 784, 137
Kennicutt, R. C., Jr. 1988, ApJ, 334, 144
Kim, S. J., Lee, H. M., Matsuhara, H., et al. 2012, A&A, 548, A29
Lutz, D. 2014, ARA&A, 52, 373
Matsuhara, H., Wada, T., Matsuura, S., et al. 2006, PASJ, 58, 673
Matsumoto, T., Seo, H. J., Jeong, W.-S., et al. 2011, ApJ, 742, 124
Murakami, H., Baba, H., Barthel, P., et al. 2007, PASJ, 59, 369
Murata, K., Matsuhara, H., Inami, H., et al. 2014, A&A, 566, A136
Pearson, C., Lim, T., North, C., et al. 2014a, Experimental Astronomy, 37, 175
Pearson, C. P., Serjeant, S., Oyabu, S., et al. 2014b, MNRAS, 444, 846
Shim, H., Im, M., Ko, J., et al. 2013, ApJS, 207, 37
Wuyts, S., Förster Schreiber, N. M., van der Wel, A., et al. 2011, ApJ, 742, 96