Studies of (Ultra) Infra-Red Galaxies in the Far-Infrared Surveys: from *AKARI* to *SPICA*

K. Małek,[1] A. Pollo,[2,3] T. T. Takeuchi,[1] V. Buat,[4] D. Burgarella,[4] M. Malkan,[5] and A Kurek[2]

[1]*Department of Particle and Astrophysical Science, Nagoya University, Japan*
[2]*National Centre for Nuclear Research, Poland*
[3]*The Astronomical Observatory of the Jagiellonian University, Poland*
[4]*Laboratoire d'Astrophysique de Marseille, OAMP, Université Aix-Marseille, CNRS, France*
[5]*Department of Physics and Astronomy, UCLA, USA*

ABSTRACT

We present the results of the analysis of multiwavelength Spectral Energy Distributions (SEDs) of Far-Infrared (FIR) galaxies detected in the *AKARI* Deep Field-South (ADF-S) Survey. FIR data in connection with optical and UV measurements enable us to fit SED models and investigate physical properties of detected sources. We focus on 186 ADF-S galaxies with the best SED fits. More than 25 % of sources we identified as (Ultra) Luminous Infra-Red Galaxies. We present the average properties of ULIRGs and other galaxies found in the ADF-S. We discuss how the future *SPICA* data will help to understand the history of formation and evolution of (U)LIRGs.

1. INTRODUCTION

Nowadays the multiwavelength sky surveys play a fundamental role in astronomy. The resources of collected data are constantly expanding, providing discoveries of new types of objects or more detailed studies of previously known types of sources. Recent advances in satellite observations extended the studies of galaxies evolution by measuring their radiation at long wavelengths. Infrared (IR) observations allow for observations of dust heated by newly born stars, and therefore, measurements of warm dust component — an indicator of star formation (SF) activity. Observations in the ultraviolet (UV) and optical ranges alone cannot provide a detailed description of the SF processes in galaxies — the dust component should also be taken into account. Only combined UV, optical, and IR data can give the full information about the SF history and rate — a key observable for understanding the physical processes in galaxy formation and evolution. Additionally, the ratio between the UV and far-IR (FIR) emission sheds light on evolution of *Ultra* Luminous Infrared Galaxies (ULIRGs).

Satellite IR observations in wide fields allow us to analyze the SF history from a global, statistical point of view, and to test existing physical models of galaxy evolution. *AKARI* (Murakami et al. 2007), the Japanese satellite dedicated to IR observations, provided the second-generation, after *IRAS* (Neugebauer et al. 1984), all sky IR catalog. This catalogue, as well as two deep surveys centered at the North (NEP) and South (ADF-S) Ecliptic Poles (e.g., Wada et al. 2008; Takagi et al. 2012; Matsuura et al. 2011), vastly improved our knowledge of IR astronomical sources. Future observations provided by *SPICA* (Nakagawa et al. 2009), ranging from mid- to far-IR, will give us even a more precise insight into the basic question of how galaxies were formed and evolved.

2. DATA

The sample used in our analysis is drawn from *AKARI* ADF-S presented by Małek et al. (2010). For the catalog based on 90 μm band 545 optical counterparts were found in public catalogues (NED, SIMBAD, IRSA). The sample in total consists of the 545 ADF-S sources from the so-called 6σ catalog ($S_{90\,\mu\mathrm{m}} > 0.0301$ Jy, which corresponds to the 6σ detection level). Additional measurements, mostly from *WISE* (Wright et al. 2010) and *GALEX* (Martin et al. 2005), and further data from public databases were used in the present analysis (see also Małek et al. 2013b).

Combining data from Małek et al. (2010) and Sedgwick et al. (2011) we found spectroscopic redshifts z_{spec} for 173 galaxies from our sample in the range $0 < z_{\mathrm{spec}} < 0.25$ (the range used by Sedgwick et al. 2011). Median redshift of this sub-sample is 0.058.

Our main aim was to build a galaxy sample with high quality fluxes from the UV to the FIR to be used for Spectral Energy Distribution (SED) fitting and studying of physical parameters of the ADF-S sample. Consequently, we selected galaxies with the highest quality photometry and at least six measurements covering all the galaxy spectra from FIR to UV. Each galaxy from the sample used for the SED fitting has at least one measurement in FIR, 95 % of them have *WISE* MIR measurements, 85% are detected in all 2MASS bands, all of them have the APM (Maddox et al. 1990) measurement, and a half of our sample was detected by *GALEX* in the UV. For galaxies without known z_{spec} we estimated photometric redshifts z_{phot}. We used two codes: Le PHARE (Arnouts et al. 1999; Ilbert et al. 2006), widely used for z_{phot} estimation, and CIGALE (Noll et al. 2009) — SED-fitting program, originally not developed as a tool for estimation of z_{phot} but, as

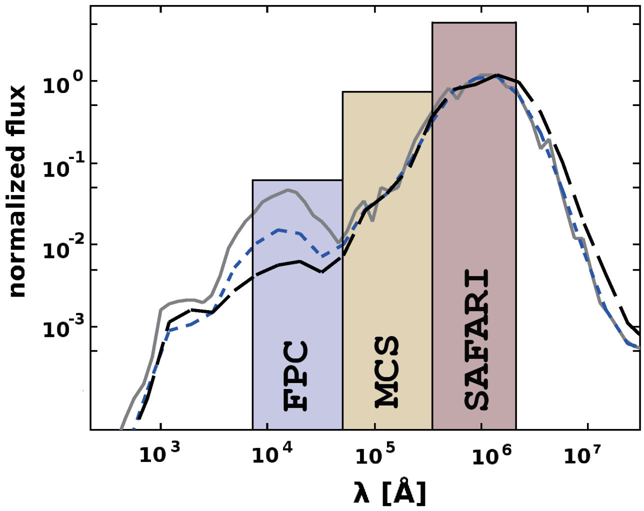

Figure 1. The average SEDs of galaxies from ADF-S field normalized at 90 μm. Average SED for ULIRGs is shown as a dashed line, for LIRGs — as a dotted line, and for the remaining galaxies as a solid line. Wavelength ranges of three *SPICA* instruments (SAFARI, MCS, and FPC) are shown as shaded areas.

we have shown, providing correct photometric redshifts especially in case of FIR-bright galaxies (Małek et al. 2013a). We performed a series of tests using both codes for a sample of ADF-S galaxies with know $z_{\rm spec}$. Both codes gave similar results, but CIGALE allowed to obtain $z_{\rm phot}$ more often, especially for galaxies with more FIR and MIR data, and lack of UV and few optical measurements.

3. SED FITTING AND AVERAGE SEDS

We used CIGALE to estimate physical properties of ADF-S galaxies. We checked the reliability of obtained parameters using mock catalogs (Małek et al. 2013b). CIGALE computes model spectra, based on a set of input parameters, and calculates fluxes in the observed filters. It determines the best-fit model for each galaxy using χ^2 minimalization. Based on the χ^2 distribution and visual inspection of obtained fitted spectra, we restrict the final sample to the SEDs with χ^2 value lower than four. As a result, our final sample consists 73 galaxies with known $z_{\rm spec}$ and 113 galaxies with estimated $z_{\rm phot}$, in total 186 sources.

As one of the main points of our analysis, we created average SEDs separately for (U)LIRGs, and for normal, star-forming galaxies in our ADF-S sample. We have normalized obtained models at 90 μm, and divided them in three groups: ULIRGs, LIRGs, and the remaining galaxies. These groups consist of 17, 31, and 138 sources, respectively. To select (U)LIRGs we applied a Sanders & Mirabel (1996) criterion on the total IR luminosity. In the next step we calculated an average SED for each of these three sub-samples. The result is shown in Figure 1. We have found that (U)LIRGs contain cooler dust than the remaining galaxies of our sample, and that their maximum of dust emission is shifted towards longer wavelengths (it is located at 1.49±0.6, 1.25±0.63, and $0.93 \pm 0.35 \times 10^6$ Å for ULIRGs, LIRGs, and the remaining ADF-S galaxies, respectively). The difference in $z_{\lambda_{\rm max}}$ is not very strong given the uncertainties of the measurement, however, according to Symeonidis et al. (2011) and other previous studies, measured dust temperature of ULIRGs is rather related to the sample selection function, than to their general physical properties. Our results confirm this claim.

We suggest that more detailed studies of ULIRGs, with more numerous samples and wider spectral coverage in the MIR and FIR, are needed to solve the problem of their dust temperatures and properties. *SPICA* can provide an important break in these studies.

4. SUMMARY: *AKARI* VS *SPICA*

The presented analysis of ADF-S (U)LIRG sample allows us to expect that *SPICA* mission will provide data crucial to explain the physical properties of this rare class of galaxies. The *SPICA* mission (Sturm 2009) will provide a much better coverage in the FIR part of ULIRGs spectra with a much better resolution, as well as direct spectroscopic measurements in the FIR. It will allow for excellent SED fitting, thanks to continuous observations from NIR to FIR, and for much more precise measurement of the dust temperatures and other properties of (U)LIRGs in different cosmic epochs. The *SPICA* coherent data and unprecedented sensitivity of *SPICA* instruments should allow us to minimize error bars on the fitted spectra, and to improve significantly the models used in all the fitting procedures, thanks to precise spectroscopic measurements. In the future, we plan to perform tests of SED fitting using different models of the dust spectra (e.g. Dale & Helou 2002; Siebenmorgen & Krügel 2007; Chary & Elbaz 2001; Casey 2012), and, if needed, to develop new models, better describing properties of ULIRGs. These new results will help to study properties and evolution of IR-bright galaxies of different types.

This work is based on observations with *AKARI*, a JAXA project with the participation of ESA. This research made use of the SIMBAD database, operated at CDS, Strasbourg, France, the NASA/IPAC Extragalactic Database (NED) and the NASA/IPAC Infrared Science Archive, both operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. KM and AP were financed by the research grants of the Polish National Science Center N N203 512938 and N. 2012/07/B/ST9/04425. KM has been supported from the Japan Society for the Promotion of Science (JSPS) Postdoctoral Fellowship for Foreign Researchers, P11802. MM acknowledges support from NASA grants NNX08AU59G and NNX09AM45G for analysis of *GALEX* data in the AKARI Deep Fields. TTT has been supported by the Grant-in-Aid for the Scientific Research Fund (23340046, and 24111707) and for the Global COE Program Request for Fundamental Principles in the Universe: from Particles to the Solar System and the Cosmos, Strategic Young Researches Overseas Visits Program for Accelerating Brain Circulation commissioned by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

REFERENCES

Arnouts, S., et al. 1999, MNRAS, 310, 540
Casey, C. M. 2012, MNRAS, 425, 3094
Chary, R., & Elbaz, D. 2001, ApJ, 556, 562
Dale, D. A., & Helou, G. 2002, ApJ, 576
Ilbert, O., et al. 2006, A&A, 457, 841
Maddox, S. J., et al. 1990, MNRAS, 243, 692
Małek, K., et al. 2010, A&A, 514, A11
— 2013a, Earth, Planets and Space, 65, 1001
— 2013b, A&A, accepted
Martin, D. C., Fanson, J., Schiminovich, D., et al. 2005, ApJ, 619
Matsuura, S., et al. 2011, ApJ, 737, 2
Murakami, H., et al. 2007, PASJ, 59, 369
Nakagawa, T., et al. 2009, in The Next-Generation Infrared Space Mission: SPICA, 1001
Neugebauer, G., et al. 1984, ApJ, 278, L1
Noll, S., et al. 2009, A&A, 507, 1793
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Sedgwick, C., et al. 2011, MNRAS, 416, 1862
Siebenmorgen, R., & Krügel, E. 2007, A&A, 461, 445
Sturm, E. 2009, in The Next-Generation Infrared Space Mission: SPICA, 4001
Symeonidis, M., Page, M. J., & Seymour, N. 2011, MNRAS, 411, 983
Takagi, T., et al. 2012, A&A, 537, A24
Wada, T., et al. 2008, PASJ, 60, 517
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140