The Spectral Energy Distribution of Galaxies
Proceedings IAU Symposium No. 284, 2011
R.J. Tuffs & C.C. Popescu, eds.

doi:10.1017/S1743921312009611

Photometric studies of PAH emission from distant infrared galaxies

Toshinobu Takagi[1], Hideo Matsuhara[1], Takehiko Wada[1], Youichi Ohyama[2] and the AKARI extragalactic team

[1]Institute of Space and Astronautical Science, JAXA, Sagamihara, Kanagawa 229-8510, Japan

[2]Academia Sinica, Institute of Astronomy and Astrophysics, Taiwan

email: takagi@ir.isas.jaxa.jp

Abstract. Using extensive mid-IR datasets from AKARI, i.e. 9 band photometry covering the wavelength range from 2 μm to 24 μm and the unbiased spectroscopic survey for sources with $S_\nu(9\mu\mathrm{m})> 0.3$ mJy, we investigated the PAHs emission features in distant starburst galaxies. PAH-selected galaxies, selected with an extremely red mid-IR colour due to PAHs, are found to have a peculiar rest-frame 11-to-8 μm flux ratio, which is systematically smaller than nearby starburst/AGN spectral templates. This may indicate a systematic difference in the physical condition of the ISM between nearby and distant starburst galaxies.

Keywords. infrared: galaxies, galaxies: starburst, ISM: evolution, dust

1. AKARI extragalactic surveys around the NEP

Along with the all-sky survey, AKARI performed 5088 pointed observations in selected areas of sky during its cold phase with liquid helium. Using 13 per cent of these pointed-observation opportunities, we conducted an extragalactic survey around the North Ecliptic Pole (NEP). A prominent characteristic of this survey is its comprehensive mid-IR wavelength coverage, using 9 photometric bands to span the wavelength range from 2 to 24 μm. Furthermore, we utilized the slitless spectroscopic capability of the IRC onboard AKARI for an unbiased spectroscopic survey at mid-IR wavelengths.

Photometric survey (NEP-Deep): The NEP survey is two-tiered, consisting of the NEP-Deep and NEP-Wide surveys with circular areas of 0.6 deg^2 and 5.8 deg^2, respectively. The field configuration of the NEP survey is shown in Figure 1. Here we mainly use the data from the NEP-Deep survey, which has follow-up observations over the whole electromagnetic spectrum from X-ray to radio. Detailed descriptions of the NEP-Deep survey and the mid-IR source catalogue are given in Wada *et al.* (2008) and Takagi *et al.* (2012, in press), respectively.

Slitless spectroscoPIC surveY of galaxies (SPICY): In the SPICY program, we obtained 5 – 15 μm spectra of a flux-limited sample of mid-IR sources with $S_\nu(9\,\mu\mathrm{m}) > 0.3$ mJy. The SPICY fields are patchily distributed around the NEP-Deep field, covering $\sim$1000 arcmin^2 in total. Most of the SPICY fields lie inside the NEP-Deep field. The spectral resolution of the IRC slitless spectroscopy is $R \simeq 50$ and therefore any narrow fine-structure lines would be smoothed out. The PAH 6.2, 7,7, and 8.6 μm peaks were simultaneously fitted along with the continuum. From these PAH features, we measured the PAH luminosity as well as the redshift for more than 50 galaxies at $z < 0.5$. The PAH

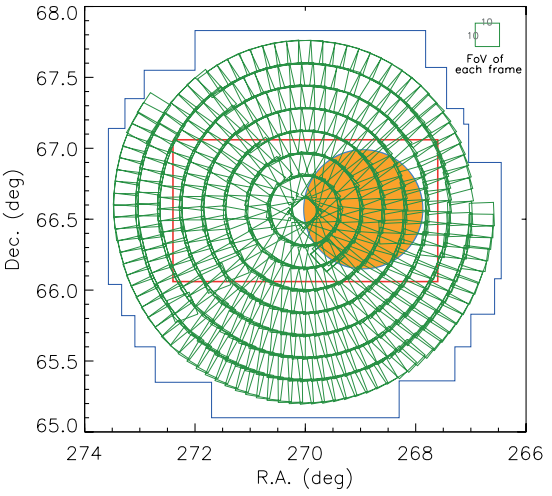

Figure 1. The field-of-view configuration of the NEP survey. The circular area depicted with boxes indicate the NEP-Wide field. The smaller shaded circular area is for the NEP-Deep coverage. The other squarish fields indicate the field of optical follow-up observations.

luminosity $[\nu L_\nu(7.7\,\mu\mathrm{m})]$ is found to be 10^9–$10^{11}\,L_\odot$. The SPICY project and spectral analyses will be presented elsewhere (Ohyama *et al.* in prep).

2. PAH-selected galaxies

The excellent mid-IR wavelength coverage of the NEP survey enables us to photometrically identify galaxies whose mid-IR emission is clearly dominated by PAHs. Takagi *et al.* (2007) demonstrated that the AKARI/IRC all-band photometry is capable of identifying the approximate spectral shape of the PAH emission, specifically the steep rise in flux at the blue side of the PAH 6.2 μm feature. Based on this fact, we selected PAH-dominated galaxies at $z \sim 0.5$ using a single colour, i.e. the 11-to-7 μm flux ratio (see Takagi *et al.* 2010). This flux ratio corresponds to the PAH-to-stellar luminosity ratio for galaxies at $z \sim 0.5$. We call galaxies with this flux ratio greater than 8 "PAH-selected galaxies". These galaxies are expected to have high specific star formation rates (SFR).

For local galaxies, such a large PAH-to-stellar luminosity ratio is found only in intensive star-forming regions (Ohyama *et al.* in prep). For the PAH-selected galaxies, we found a greater PAH-to-stellar luminosity ratio in global measurements, indicating that intensive star formation spreads across the whole body of the galaxies.

3. SED fitting

We analysed the SED of PAH-selected galaxies using an evolutionary SED model of starburst galaxies (Takagi *et al.* 2003 – SBURT), and also with spectral templates of local galaxies. The SBURT model is a radiative transfer model of the spherical starburst region, which has centrally concentrated stars and uniformly distributed dust clouds. Fitting parameters are the starburst age, total mass of the system, the compactness of the starburst region (controlling the optical depth), and the type of the extinction curve (MW, LMC, or SMC). In Fig. 2, we show the example of the resulting best-fitting SED models for optical-NIR and AKARI/IRC all-band photometries. PAH-selected galaxies

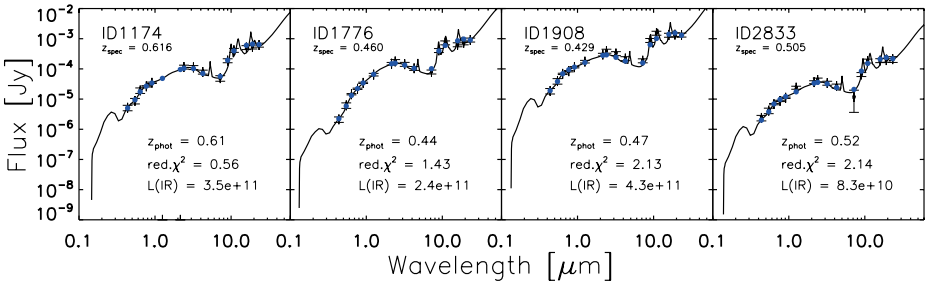

Figure 2. Example of the SED fitting with the SBURT model. Filled circles and data with error bars indicate the model (with filter convolution) and observed fluxes, respectively.

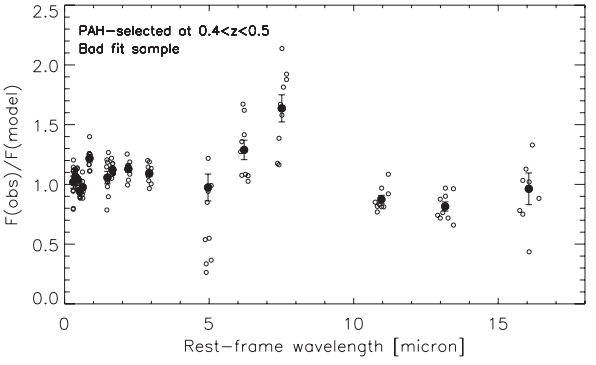

Figure 3. The ratio of the observed to model fluxes of the PAH-selected galaxies at $0.4 < z < 0.5$ versus rest-frame wavelength. The circles with error bars indicate the average flux ratios.

are all fitted with the dust model of the MW, which has the highest PAH fraction in dust, i.e. 5 per cent.

We found that the SBURT model can provide acceptable models for the half of the PAH-selected galaxies based on the χ^2 values. For the remaining half of the sample, we show the ratio of the observed-to-model fluxes as a function of the rest-frame wavelength in Fig. 3. These flux ratios indicate that the fit is rather good, except for the 5–7 μm wavelength range where the most prominent PAH features are found. A similar trend can be seen for the good fit sample as well.

4. PAH interband flux ratio

The SED fitting analysis indicate a systematic variation of the PAH features, compared to the local template of the PAH features. Fig. 3 shows that the model reproduces the rest-frame 11–15 μm emission well, but indicates a large anomaly in the rest-frame 11/8 μm flux ratio, i.e. the flux ratio of C-H to C-C mode emission of PAHs. A possible origin of this deviation is the ionization state of PAHs, which affect the absorption cross section of PAHs specifically around 8 μm (e.g. Li & Draine 2001).

From the SPICY dataset, we measured the inter-band flux ratio of PAH 6.2-to-7.7 μm and found that this inter-band ratio is similar to the values of nearby starburst galaxies. Unfortunately, the wavelength coverage of the SPICY is not large enough to cover the PAH 11.3 μm. However, the excellent wavelength coverage of photometric data allows us to estimate the PAH luminosity without a significant k-correction. With the SPICY data,

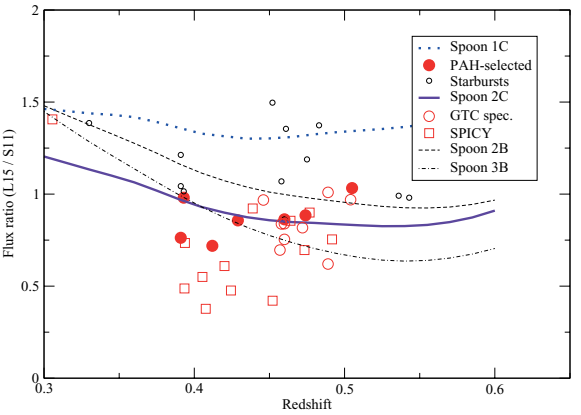

Figure 4. The 15-to-11 μm flux ratio of PAH-selected galaxies at $z_{\rm spec} \sim 0.4$. This flux ratio corresponds to the 11-to-8 μm flux ratio at $z = 0.4$. Different lines indicate the flux ratios expected from nearby starburst galaxies/AGNs taken from Spoon *et al.* (2007).

we confirmed that photometrically measured PAH 7.7 μm luminosities linearly correlate with the spectroscopic measurements.

We investigated the rest-frame 11/8 μm flux ratio of the PAH-selected galaxies at $z \sim 0.4$, for which a spectroscopic redshift is available. At this redshift, the rest-frame 11/8 μm flux ratio can be measured from the AKARI 15-to-11 μm flux ratio. In Fig. 4 we compare these flux ratios with those expected from a spectral template of Spoon *et al.* (2007) which has spectra with a wide variety of the PAH equivalent widths and silicate absorption. We found that the observed flux ratios of the PAH-selected galaxies are too small to be reproduced with the nearby spectral template. This trend is consistent with the scenario that PAHs are mostly ionized in the PAH-selected galaxies.

In a resolved image of M82 (see Arimatsu *et al.*; these proceedings), similar anomalies of the inter-band flux ratio can be found only in small spots around the centre. In PAH-selected galaxies, the anomaly is found for the global measurements, indicating a systematic difference in the physical condition of the ISM between nearby and distant starburst galaxies.

References

Li, A. & Draine, B. T. 2001, *ApJ*, 554, 778
Spoon, H. W. W., Marshall, J. A., Houck, J. R., *et al.* 2007, *ApJ*, 654, L49
Takagi, T., Matsuhara, H., Wada, T., *et al.* 2007, *PASJ*, 59, 557
Takagi, T., Arimoto, N., & Hanami, H. 2003, *MNRAS*, 340, 813
Takagi, T., Ohyama, Y., Goto, T., *et al.* 2010, *A&A*, 514, A5+
Wada, T., Matsuhara, H., Oyabu, S., *et al.* 2008, *PASJ*, 60, 517

Discussion

CLEMENTS: How large is the sample of objects where you see this change in PAH SEDs?

TAKAGI: There are approximately 100 sources with S > 0.3 mJy at 9 μm for which we obtained MIR spectra. We detected PAH emission for half of them.