The Infrared Luminosity Function of AKARI 90 µm Galaxies in the Local Universe

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ABSTRACT

Local infrared (IR) luminosity functions (LFs) are necessary benchmarks for high-redshift IR galaxy evolution studies. Any accurate IR LF evolution studies require accordingly accurate local IR LFs.

We present infrared galaxy LFs at redshifts of $z \leq 0.3$ from AKARI space telescope, which performed an all-sky survey in six IR bands (9, 18, 65, 90, 140 and 160 µm) with 10 times better sensitivity than its precursor IRAS. Availability of 160 µm filter is critically important in accurately measuring total IR luminosity of galaxies, covering across the peak of the dust emission. By combining data from Wide-field Infrared Survey Explorer (WISE), Sloan Digital Sky Survey (SDSS) Data Release 13 (DR13), 6-degree Field Galaxy Survey (6dFGS) and the 2MASS Redshift Survey (2MRS), we created a sample of 15,638 local IR galaxies with spectroscopic redshifts, factor of 7 larger compared to previously studied AKARI-SDSS sample. After carefully correcting for volume effects in both IR and optical, the obtained IR LFs agree well with previous studies, but comes with much smaller errors. Measured local IR luminosity density is $\Omega_{\text{IR}} = 1.19 \pm 0.05 \times 10^8 L_\odot$ Mpc$^{-3}$. The contributions from luminous infrared galaxies and ultra luminous infrared galaxies to $\Omega_{\text{IR}}$ are very small, 9.3 per cent and 0.9 per cent, respectively. There exists no future all sky survey in far-infrared wavelengths in the foreseeable future. The IR LFs obtained in this work will therefore remain an important benchmark for high-redshift studies for decades.

Key words: galaxies: general – galaxies: interactions – galaxies: starburst – infrared: galaxies

1 INTRODUCTION

Luminosity function (LF) represents the number density of galaxies as a function of luminosity. Luminosity functions are crucial cosmological observables to understand galaxy evolution and structure formation (e.g., Benson et al. 2003; Croton et al. 2006; Bower et al. 2010; Trayford et al. 2015; Steinhardt et al. 2016) at different redshifts. The galaxy luminosity functions have been measured at optical (e.g., Blanton et al. 2001, 2003; Madgwick et al. 2002; Bell et al. 2003; Montero-Dorta & Prada 2009; Cool et al. 2012), ultraviolet (UV) (e.g., Reddy et al. 2008; Bowler et al. 2014; Heinis et al. 2013; Finkelstein et al. 2015), near-infrared (i.e., $K$-band) (e.g., Kochanek et al. 2001; Bell et al. 2003; Eke et al. 2005; Jones et al. 2006), mid-infrared (i.e., $3.6 \leq \lambda \leq 40$ µm) (e.g., Le Floc’h et al. 2005; Pérez-González et al. 2005; Babbedge et al. 2006; Caputi et al. 2007; Dai et al. 2009; Goto et al. 2010; Fu et al. 2010; Rodighiero et al. 2010; Magnelli et al. 2011; Wu et al. 2011), far-infrared (i.e., $\lambda > 40$ µm) (e.g., Huynh et al. 2007; Sedgwick et al. 2011; Patel et al. 2013; Gruppioni et al. 2013; Marchetti et al. 2016), submillimeter (e.g., Vaccari et al. 2010; Negrello et al. 2013) wavelengths and from total infrared luminosities ($L_{\text{IR}}$, integrated over 8–1000 µm) (e.g., Le Floc’h et al. 2005; Goto et al. 2010; Rodighiero et al. 2010; Goto et al. 2011a,b; Magnelli et al. 2011; Sargent et al. 2012; Patel et al. 2013; Heinis et al. 2013; Magnelli et al. 2013; Gruppioni et al. 2013; Marchetti et al. 2016). It is evident from all of these studies that in order to constrain models of galaxy formation and evolution we need accurate galaxy LFs at different wavelengths in the local and distant Universe.

Infrared (IR) emission is a practical tool to determine star formation rates of galaxies. Especially, when the star formation is embedded in dust, the star-formation activity of galaxies can only be observed in the infrared. Therefore, FIR emission is very important to reveal the star formation in the Universe that is hidden by dust (e.g., Rowan-Robinson...
The all-sky survey performed by the Infrared Astronomical Satellite (IRAS, Neugebauer et al. 1984) revealed the numbers and properties of the IR galaxies including the IR LFs in the local Universe (Soifer et al. 1987; Saunders et al. 1990; Sanders et al. 2003). The brighter IR galaxies, luminous and ultraluminous infrared galaxies are found to be rare local objects; however, they are more common at higher redshifts. Infrared satellites including the Infrared Space Observatory (ISO, Kessler et al. 1996) and Spitzer Space Telescope (Werner et al. 2004) carried out deep cosmological surveys. These observations imply a strong evolution (between $z = 0 - 2$) of the LF, particularly at the bright end (e.g., Elbaz et al. 1999; Le Floc’h et al. 2005; Pérez-González et al. 2005; Caputi et al. 2007; Magnelli et al. 2009; Rodighiero et al. 2010). Recently, Wide-field Infrared Survey Explorer (WISE, Wright et al. 2010) provided another opportunity to measure the IR luminosity function up to $z \sim 1$ (e.g., Lake et al. 2017). Our knowledge of the high-redshift IR galaxies increased with the Herschel Space Observatory (Pilbratt et al. 2010). The observed SEDs from ultraviolet to submillimetre enable to determine IR LFs of high-redshift (beyond $z = 3$) galaxies observed by Herschel (e.g., Gruppioni et al. 2010; Eales et al. 2010; Gruppioni et al. 2013; Casey et al. 2012). Observations based on galaxies at different redshifts show a dramatic redshift evolution, both in IR LF and IR luminosity density. Since all high-redshift studies need to be compared with local ones, the investigation of the redshift evolution highly depends on the local galaxies.

AKARI performed an all-sky survey with better spatial resolution, sensitivity and FIR coverage (between 50–180 μm) compared to IRAS. The advent of AKARI has provided a unique FIR data set. AKARI has four FIR filters centred at 65μm, 90 μm, 140μm and 160 μm. Therefore, it has a great advantage to constrain the peak of the FIR SED around 90μm. Goto et al. (2011b) used a larger sample of local IR galaxies than previous all-sky samples identified by IRAS (Sanders et al. 2003). They use AKARI all-sky survey photometry and SDSS DR-7 spectroscopic redshifts to measure accurate LIR. They also construct the LFs of 2357 local IR galaxies. Motivated by the results of Goto et al. (2011b), we intend to improve their investigation of local IR LF. By using AKARI all-sky survey photometry, but matching with a much larger optical survey area in northern and southern sky, we establish the local IR LF. We have an optically and 90 μm limited sample with the advantage of 90 μm detections that can accurately constrain LIR from SED fitting based on spectroscopic redshifts.

In this work, we measure the local IR luminosity function with the largest sample (15,638) of galaxies yet used for this purpose. We aim for the most accurate local IR LF which will be a reliable local benchmark for high-redshift studies especially in the era of new missions like Space Infrared Telescope for Cosmology and Astrophysics (SPICA, Nakagawa et al. 2012) and James Webb Space Telescope (JWST, Gardner et al. 2006). The structure of this paper is as follows. In section 2 we present the sample selection and data. We describe the total IR luminosity measurements and total IR LFs of the AKARI–SDSS, AKARI–6dFGS and the combined AKARI–SDSS–6dFGS–2MRS samples in §3. We summarise our conclusions in §4. We adopt a cosmology with $H_0 = 72\text{ km}\text{ s}^{-1}\text{ Mpc}^{-1}$, $\Omega_m = 0.7$ and $\Omega_{\Lambda} = 0.3$ throughout. We use the base 10 logarithm.

2 SAMPLE SELECTION AND DATA

2.1 AKARI–WISE Sample

AKARI is an infrared astronomy satellite (Murakami et al. 2007) funded by the Institute of Space and Astronautical Science (ISAS) of the Japanese Aerospace Exploration Agency (JAXA) and launched in February 2006. AKARI performed an all-sky survey in two mid-IR bands at 9 and 18 μm, and four far-IR bands centred respectively at 65, 90, 140, and 160 μm. The AKARI/FIS all-sky survey bright source catalog version 2 (Yamamura et al. 2017, in preparation) provides the positions and fluxes at 65, 90, 140 and 160μm for 918,056 sources (this is the sum of the main and the supplemental catalogue.). This catalog is the revised version of the AKARI/FIS all-sky survey bright source catalog version 1 with better position and flux accuracy, detection completeness and reliability.

The far-IR photometric measurements of AKARI are crucial to identify IR galaxies whose SEDs peak at 60–100μm. The goal of our study is to identify and study local IR galaxies. Therefore, we base our study on the AKARI/FIS all-sky survey bright source catalog version 2. In order to have the most reliable far-IR measurements we select only the sources with $F(90\mu m) = 3$ and the AKARI photometric fluxes of the 90μm (F(90μm)) greater than 0.5 Jy. Thus, our initial AKARI sample has 540,978 sources.

The AKARI/IRC all-sky survey point source catalog version 1 provides mid-IR photometry at 9 and 18 μm for 870,973 sources. In order to include these mid-IR measurements in our data set we cross-match the initial AKARI sample with all-WISE Source Catalog version 1 using a search radius of 20″. We find mid-IR measurements for 28,578 sources.

Most of the sources (512,400) in our initial AKARI sample do not have mid-IR measurements from AKARI, therefore we include WISE data to have more sources with mid-IR photometry. The WISE completed an all-sky survey in four mid-IR bands, W1, W2, W3, W4, centred at 3.4, 4.6, 12, and 23 μm, respectively. The AllWISE Source Catalog provides positions, photometric measurements, quality information for over 747 million sources (Cutri et al. 2013). We match our initial AKARI sample with AllWISE Source Catalog using a 20″search radius. We only include WISE sources with zero $cc\_flags$ values ($cc\_flags = ^{00000}$) to avoid objects with contaminated measurements (i.e., by

1 http://www.ir.isas.jaxa.jp/AKARI/Archive/Catalogues/FISBSCv2/
2 http://www.ir.isas.jaxa.jp/AKARI/Observation/PSC/Public/RN/AKARI-FIS_BSC_V1_RN.pdf
3 http://www.ir.isas.jaxa.jp/AKARI/Observation/PSC/Public/RN/AKARI-IRC_PSC_V1_RN.pdf
4 http://wise2.ipac.caltech.edu/docs/release/allwise/
diffraction spikes, bright sources, optical ghost images). We also require that sources have S/N greater than 2 in any of the 4 bands to eliminate upper limit values. We choose such a low S/N ratio mainly to avoid upper limits and to keep as many WISE sources as possible in our sample, and also note that we already have source detection at 90 µm (in our final samples, sections 2.2.1, 2.2.2 and 2.2.3 the S/N in all 4 WISE bands are between 2.0 and 141.3 with a median value of 46.5). Additionally we require standard aperture measurement quality flag (w1,2,3,4/fg) to be smaller than 32 in any of the 4 bands to exclude sources with upper limits. We eliminated the magnitude in any band with null uncertainties (i.e., if 'wnsignpro' photometric measurement uncertainty is null it indicates an upper limit or no measurement, where n refers to the band number); with high saturated pixel fraction (i.e., if the fraction of saturated pixels in any band is greater than 0.05); with high scattered moonlight contamination (i.e., 'moon_lev' ≥ 5); with measurement quality flag greater than 1 (i.e., 'wmsgflg' and 'wmsgflg' indicate pixel saturation, confusion with other objects, unusable pixels or upper limits, where n refers to the band number). We also check the extended source flag (extended sources have evx-flg > 0) and use the elliptical aperture magnitudes for these sources ('wmsgmag', n refers to the band number). Our AKARI−WISE sample consists of 208,459 sources. In the initial AKARI sample the number of sources without WISE measurements is 332,519; 62% of AKARI sources do not have a WISE detection.

2.2 Cross-Correlation with Optical Spectroscopic Redshift Catalogs

In order to include most of the northern and southern sky, we search SDSS Data Release 13 (DR 13; Albareti et al. 2016), the Six-degree Field Galaxy Survey (Jones et al. 2004, 2005, 2009) and the Two Micron All Sky Survey (Huchra et al. 2005, 2012) public spectroscopic catalogs to find redshifts of the IR sources with optical counterparts. Since position accuracy of WISE is more accurate than AKARI for the cross-match between infrared and optical sources we use WISE coordinates with a cross-match radius of 5′′, where available. For AKARI sources without WISE positions we use AKARI FIS coordinates and use a matching radius of 20′′.

2.2.1 The AKARI−SDSS DR13 sample

The Sloan Digital Sky Survey (SDSS) is a ground-based imaging and spectroscopy survey started in 2000 (York et al. 2000; Abazajian et al. 2009; Eisenstein et al. 2011). The data release DR 13 of SDSS fourth phase (SDSS-IV, Blanton et al. 2017) covers 14,555 square degrees, more than one-third of the whole sky (Albareti et al. 2016). The specObj5 catalog lists positions (PLUG_RA,PLUG_DEC), best spectroscopic redshift (z) and spectral class (as "GALAXY", "QSO" or "STAR"). Since our main goal is to study galaxies, we exclude sources with "STAR" classification and left with 3,400,232 sources in the specObj catalog.

We cross-match our initial AKARI sample with SDSS-DR13 specObj catalog. The AKARI−SDSS sample has 6,181 sources, among these 5,786 are WISE sources. We check the redshift quality flag, ZWARNING, given by SDSS. 6,019 sources have reliable secure measurements (ZWARNING = 0) and 162 sources have uncertain redshift values ZWARNING > 0. The spectra of these 162 sources are visually inspected. Among this subset, 61 sources are excluded because of their unreliable spectra. We further restricted the AKARI−SDSS sample to those galaxies with extinction corrected $I_{petro}$ ≤ 17.7 within the 0.02 ≤ z ≤ 0.3 redshift range. We adopt the spectroscopic redshift completeness estimate given by (Montero-Dorta & Prada 2009) and use a lower redshift limit of 0.02. As a result, the AKARI−SDSS sample consist of 4,705 local IR galaxies with reliable spectral redshift and photometric measurements.

2.2.2 The AKARI−6dFGS sample

The Six-degree Field Galaxy Survey (6dFGS Jones et al. 2004, 2005, 2009) covers almost the entire southern sky 10° above the Galactic plane. The 6dF Galaxy Survey Redshift Catalogue Data Release 3 (final) catalogue6 lists redshifts of 124,647 sources. Among those we only keep 108,030 sources classified as a galaxy. We cross-match the initial AKARI sample with the extracted 6dF catalog and obtain 7,547 sources; 6,654 are WISE sources. For 8 sources the redshift comparison flag indicate there is a disagreement between SDSS and 6dFGS redshift values or between different 6dFGS measurements. Since these are not sole measurements we exclude these 8 sources from the 6dFGS sample and left with 7,539 sources. AKARI−6dFGS sample includes 4,717 IR galaxies with extinction corrected $b_J$ ≤ 16.75 within the 0.01 ≤ z ≤ 0.3 redshift range. We do not include galaxies at z < 0.01 since they would have unreliable spectroscopic redshift estimates due to their relatively large peculiar velocities.

We note that we identify duplicates between the SDSS and 6dFGS samples. When a duplicate is identified, if the redshift difference is below 0.002, it is kept in the SDSS sample. If the redshift difference is greater than 0.002, the spectra are checked by eye and kept in the SDSS sample if the spectra were reliable.

2.2.3 The AKARI−2MRS sample

The Two Micron All Sky Survey (2MASS Skrutskie et al. 2006) completed an all-sky survey in J, H, and Ks bands. The 2MASS Redshift Survey (2MRS Huchra et al. 2005, 2012) completed a magnitude-limited ($K_s = 11.75$ mag) spectroscopic survey of 2MASS galaxies over ~91% of the sky. The 2MRS catalog (Huchra et al. 2012) presents redshifts for 43,533 galaxies. The initial AKARI sample is cross-matched with the 2MRS catalog. We identified 11,282 IR galaxies in the initial AKARI−2MRS sample. When the duplicates in the AKARI−SDSS and AKARI−6dFGS samples eliminated, the final AKARI−2MRS sample includes 6,216 galaxies within the z ≤ 0.3 redshift range.

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5 https://data.sdss.org/sas/dr13/sdss/spectro/redux/

6 http://www-wfau.roe.ac.uk/6dFGS/download.html
3 RESULTS AND DISCUSSION

3.1 The Total Infrared Luminosity Measurements

We measure the total infrared luminosity of 15,638 galaxies in the AKARI–SDSS, AKARI–6dFGS and AKARI–2MRS samples by performing SED fitting using the lephare\(^7\) (Photometric Analysis for Redshift Estimations, Arnouts et al. 1999; Ilbert et al. 2006). The lephare code finds the best-fitting galaxy template from a given SED library by a $\chi^2$ minimisation according to the input photometric magnitudes and redshift. For our sample we use the SED library of Dale & Helou (2002) which represents the far-IR SEDs of IR galaxies. We use the six AKARI bands, the four WISE bands (when available) with the associated optical photometry ($u$, $g$, $r$, $i$, $z$, $b$, $K_s$) and fix the redshift of each galaxy to the spectroscopic one in the fitting procedure. The $k$ corrections are obtained by integrating the filter response functions in the best-fitting SED. We obtain $L_{IR}$ integrated over 8–1000 $\mu$m with the upper and lower uncertainties of $L_{IR}$ based on the photometric flux uncertainties. The $L_{IR}$ measurements are listed in Table 1. Table 1 presents AKARI ID’s, coordinates, IR and optical photometry, redshift, and IR luminosities of the AKARI–SDSS–6dFGS–2MRS sample.

\(^7\) http://www.cfht.hawaii.edu/arnouts/lephare.html
Table 1. *AKARI*–SDSS–6dFGS–2MRS sample. The full table in available in the electronic version of the article. NaN value is represented by -99. for photometric values. Columns: (1) *AKARI* ID from the *AKARI*/FIS all-sky survey bright source catalog version 2. (2) and (3) *AKARI* coordinates in the *AKARI*/FIS all-sky survey bright source catalog version 2. (4) - (7): WISE W1, W2, W3, W4 magnitudes and their errors. These are the elliptical aperture magnitudes for the sources with $ext{fig} > 0$. (8) - (13): The *AKARI* flux densities at 9, 18, 65, 90, 140, and 160 $\mu$m, and their associated uncertainties from the *AKARI*/FIS all-sky survey bright source catalog version 2, and *AKARI*/IRC all-sky survey point source catalog version 1. (14): Galactic extinction corrected SDSS Petrosian $r$ magnitude. (15): Galactic extinction corrected $b_j$ magnitudes (AB mag) adopted from SuperCOSMOS all-sky galaxy catalogue (Peacock et al. 2016). (16): Galactic extinction corrected 2MASS $K_s$ magnitude (AB mag) from 2MASS Redshift Survey catalog (Huchra et al. 2012). (17): Redshift based on optical spectra. (18): Total IR luminosity between 8 and 1000$\mu$m measured from the SEDs fitting. (19): Best-fitted SED model number from Dale & Helou (2002) library.

| *AKARI* source name (AKARI-FIS-V2) | R.A. (J2000) | Decl. (J2000) | W1 | W2 | W3 | W4 | $F$(9 $\mu$m) | $F$(18 $\mu$m) | $F$(65 $\mu$m) | $F$(90 $\mu$m) | $F$(140 $\mu$m) | $F$(160 $\mu$m) | r | $b_j$ | $K_s$ | $z$ | log $(L_{IR}/L_{\odot})$ | SED model |
|-----------------------------------|-------------|-------------|----|----|----|----|--------------|--------------|--------------|--------------|--------------|--------------|----|-------|------|----|----------------|---------|
| 0042256+144201                    | 10.61       | 14.70       | -99| -99| -99| -99| 9.95±0.48    | 9.35±0.07    | 8.45±0.13    | 7.93±0.17    | 15.40        | -99          | -99| 0.04  | 10.74±0.00 | 64       |
| 0058485+283041                    | 14.70       | 28.51       | -99| -99| -99| -99| 9.38±0.08    | 8.28±0.10    | 7.84±0.18    | 16.62        | -99          | -99          | 0.11| 11.76±0.08| 64       |
| 0106247−014153                    | 16.60       | -1.70       | -99| -99| -99| -99| 9.17±0.29    | 9.64±0.12    | 9.99±0.48    | 7.20±0.09    | 16.61        | -99          | -99| 0.08  | 11.26±0.08| 64       |
| 0110267−084457                    | 17.61       | -8.75       | -99| -99| -99| -99| 11.47±1.45   | 9.51±0.12    | -99          | 7.47±0.11    | 15.86        | -99          | -99| 0.05  | 11.04±0.08| 64       |
| 0138528−102708                    | 24.72       | -10.45      | -99| -99| -99| -99| 7.14±0.06    | 6.87±0.01    | 7.40±0.06    | 7.81±0.15    | 16.13        | -99          | -99| 0.05  | 11.75±0.07| 25       |
| 0151233+130335                    | 27.84       | 13.06       | -99| -99| -99| -99| 9.77±0.68    | 9.27±0.11    | 8.44±0.15    | 7.83±0.19    | 14.75        | -99          | -99| 0.06  | 11.27±0.06| 64       |
3.2 Luminosity Functions

3.2.1 The 1/V_{max} method

We use 1/V_{max} method (Schmidt 1968) to compute LF for local IR galaxies. We prefer the 1/V_{max} method because it derives the LF directly from the data, without any model/parameter assumption on the LF shape. The 1/V_{max} technique is based on the galaxy number counts within a volume. The maximum comoving volume volume V_{max} = V_{max,i} - V_{mini,i} is calculated for each galaxy from the maximum redshift, z_{max}, at which it can be still detected in the considered surveys. In order to get the z_{max} for the F(90µm) flux limit, we compute the k-correction based on the same SEDs that the L_{8-1000} luminosities were measured. We obtain k-corrections of the SDSS r_{petro}, 6dFGS b_j and 2MASS K_s magnitudes by using the kcorrect code (+v4.3) of Blanton & Roweis (2007).

Once the k-corrections are obtained for each individual galaxy, it is moved to the redshift where F(90µm) and optical magnitudes (r_{petro} or b_j or K_s) reach their limits, respectively. We take into account the nominal survey limits that the surveys are complete; for the SDSS extinction corrected r_{petro} ≤ 17.7, 6dFGS extinction corrected b_j ≤ 16.75, and for 2MRS K_s ≤ 11.75. For AKARI we use F(90µm)=0.5 Jy flux limit where completeness is expected to be close to 80 per cent based on the completeness counts given for AKARI/FIS all-sky survey bright source catalog version 1 (Goto et al. 2011b). We use the detection completeness curve (Fig. 8 of Yamamura et al. 2010) to obtain the completeness of each source based on the 90µm flux density. If z_{max} exceeds the upper redshift limit of our local IR galaxy sample we set it to 0.3. We limit z_{mini} to be the minimum redshift limit of the considered sample.

We consider total infrared luminosity bins between log[L_{IR}/L_⊙] = 8 and 13, each bin has the size of 0.3 dex. In each luminosity bin, the LF is computed as

\[ \Phi(L) = \frac{1}{\Delta L} \sum_i \frac{1}{V_{max,i}} \]

where \( V_{max,i} \) is the comoving volume over which i-th galaxy could be detected, \( \Delta L \) is the size of each luminosity bin and \( w_i \) is the completeness correction factor for the i-th galaxy. This accounts for the IR detection incompleteness and the sky coverage correction, \( w_i = (1/\text{completeness})^*(\text{all} \text{sky area/} \text{survey} \text{area}) \). We adopt the effective survey areas estimated by the 6dFGS DR3 and 2MRS data releases (Jones et al. 2009; Huchra et al. 2012). The used effective survey areas of 6dFGS and 2MRS surveys are 13,572 and 37,000 square degrees, respectively. In order to estimate the SDSS DR 13 legacy spectroscopic sky coverage we produce a map of the specObj catalog program name = legacy sources with HEALPIX4 (Górski et al. 2005). We estimate the SDSS DR 13 spectroscopic effective survey area as 9,219 square degrees.

The uncertainties on the 1/V_{max} data points take into account only Poisson errors (depends on the number of sources); however the errors in the photometric fluxes propagate into uncertainties in the measured LF. We perform a Monte Carlo simulation in order to analyse this effect.

4 HEALPIX is hierarchical equal area isolatitude pixelization of a sphere, see https://healpix.jpl.nasa.gov for details.

Namely, we obtain the LF on 100 different mock galaxy catalogs following the same procedure as for the original sample. Each of the mock catalogs contains the same galaxies as the original sample, but we generate random fluxes from a Gaussian distribution around the measured flux with a dispersion of the measured uncertainties. As a result of the Monte Carlo simulation we obtain a Gaussian distribution of 1/V_{max} data points in each luminosity bin; we assign the standard deviation of the distribution as the Monte Carlo uncertainty. Then in our original 1/V_{max} results, the total uncertainty in each luminosity bin is the quadratic sum of the Poissonian error and the Monte Carlo uncertainty.

We derive LF for the AKARI–SDSS, AKARI–6dFGS and the combined AKARI–SDSS–6dFGS–2MRS samples separately. We list the 1/V_{max} data points in Table 2.

3.2.2 Luminosity function of AKARI–SDSS galaxies

The IR LF of 4,705 AKARI–SDSS galaxies computed with the 1/V_{max} method is shown in Fig. 1 (open circles). The 90µm flux limit of AKARI at the median redshift of 0.036 is log[L_{IR}/L_⊙] ~10.0 and it imposes the completeness region of our sample. Therefore, we fit the 1/V_{max} data points starting from log[L_{IR}/L_⊙]=10.0. We simply fit the 1/V_{max} data points using a double power law (Babbedge et al. 2006) as follows:

\[ \phi(L)dL/L^* = \phi^*(L/L^*)^{1-\alpha}dL/L^*, L < L^* \]

(2)

and

\[ \phi(L)dL/L^* = \phi^*(L/L^*)^{1-\beta}dL/L^*, L > L^* \]

(3)

where, \( \phi^* \) is the normalisation factor in Mpc^{-3}, \( L^* \) is the characteristic luminosity (in units of \( L_⊙ \)) where the break between the faint and bright regions, \( \alpha \) is the faint-end slope and \( \beta \) is the bright-end slope. The obtained best-fitting parameters for the IR LF of AKARI–SDSS sample are \( \phi = 89 \pm 3 \times 10^{-5}, L^* = 4.85 \pm 0.01 \times 10^{10}, \alpha = 2.06 \pm 0.05, \beta = 3.1 \pm 0.3 \). We list the best-fitting parameters in Table 3. The best-fitting double power law is shown as the dashed line in Fig. 1.

Goto et al. (2011b) constructed LF of 2,337 IR AKARI–SDSS DR 7 galaxies. Our sample of SDSS DR 13 galaxies is almost twice as large as their AKARI–SDSS sample. Their results are shown as the red triangles in Fig. 1. Our counts are slightly higher compared to that of Goto et al. (2011b) in the faint-end. This difference is probably because we have a deeper, more complete AKARI catalog (ver2) that recovers the missing sources in Goto et al. (2011b), which used ver. 1. In fact the number of AKARI sources above the detection limit adopted in Goto et al. (2011b) is by a factor of 1.6 larger in ver. 2 than in ver. 1. This is one of the major causes of the difference in resulting LFs between these studies. In the bright-end part, our 1/V_{max} measurements in the log[L_{IR}/L_⊙]=12.65 bin is factor of 14 larger. This may explain the steeper bright-end slope (\( \beta = 3.54 \pm 0.09 \)) and the larger IR LF break (\( L^* \)) Goto et al. (2011b) obtain. Our faint-end slope is consistent with the one given by Goto et al. (2011b), within the two-sigma uncertainty level. The doubled sample size improves the underestimated high luminosity end measurement significantly.
3.2.3 Luminosity function of AKARI-6dFGS galaxies

We show the LF of 4,717 AKARI-6dFGS galaxies in Fig. 2. We fit the LF using the double-power law as expressed in Equations 2 and 3 using a χ² minimization. The best-fitting values are given in Table 2.

The green squares show the 1/Vmax measurements of the AKARI–SDSS galaxies (§3.2.2). In general, 1/Vmax data points measured for the SDSS sample are factor of 2 higher than that of the 6dFGS sample. This difference can be related to the different effective survey areas of the SDSS and 6dFGS samples. The 6dFGS sample has a factor of 1.5 larger effective area that results in a larger volume and a lower normalization. The number of galaxies in each luminosity bin is different for each sample; at the highest luminosity bin (log[LIR/L⊙] =12.95) there are no galaxies in the 6dFGS. Therefore we expect to have disagreement in some of the best-fitting values. While the faint- and bright-end slopes agree within four-sigma uncertainty level; the IR LF break of the 6dFGS sample is lower compared to the SDSS sample.

3.2.4 Luminosity function of AKARI-SDSS-6dFGS-2MRS galaxies

The 1/Vmax LF of the combined 15,638 AKARI–SDSS–6dFGS–2MRS galaxies is shown in Fig. 3. The best-fitting double power law is shown as the black solid line. SDSS and 6dFGS surveys are incomplete at bright magnitudes, due to the incompleteness below log[LIR/L⊙] =10.0 we cannot measure the faint-end of the IR LF. In order to extend the LF to lower luminosity bins with a complete sample of local galaxies we use the 2MRS sample. The addition of the 2MRS survey, especially the lower redshift (z < 0.01) galaxies in the sample allow us to probe the faint-end. However, we caution that below log[LIR/L⊙] =9.65 the completeness is not 100 percent and therefore the obtained LF represents a lower limit. Not surprisingly, the bright-end slopes of the combined sample agrees with the SDSS and 6dFGS samples within three-sigma uncertainty. Compared to these two samples, for the combined sample the IR LF break is at a lower luminosity of L′ = 2.60 × 10^{10}.

We compare our result with the IR LF derived by Sanders et al. (2003) from a complete sample of 629 60 µm selected IRAS galaxies (green crosses). This is the IRAS Revised Bright Galaxy Sample (RBGS). We also

Table 2. The IR LF of AKARI–SDSS, AKARI–6dFGS and AKARI–SDSS–6dFGS–2MRS galaxies obtained with the 1/Vmax method. N is the number of sources in each luminosity bin.

| log(LIR/L⊙) | φ (Mpc⁻³ dex⁻¹) | N | log(LIR/L⊙) | φ (Mpc⁻³ dex⁻¹) | N | log(LIR/L⊙) | φ (Mpc⁻³ dex⁻¹) | N |
|-------------|-----------------|---|-------------|-----------------|---|-------------|-----------------|---|
| 8.15        | 0.000           | 0 | 8.45        | 0.000           | 0 | 8.75        | 0.000           | 0 | 9.05        | 0.000           | 0 |
| 8.45        | 0.000 ± 1.074   | 3 | 8.75        | 0.000 ± 4.322   | 4 | 9.05        | 0.000 ± 2.682   | 4 |
| 9.05        | 0.000 ± 1.171   | 1 | 9.35        | 0.000 ± 2.682   | 1 | 9.65        | 0.000 ± 6.352   | 4 |
| 9.35        | 0.000 ± 2.682   | 4 | 9.65        | 0.000 ± 1.171   | 1 | 10.05       | 0.000 ± 2.682   | 4 |
| 9.65        | 0.000 ± 4.322   | 4 | 10.05       | 0.000 ± 1.171   | 1 | 10.35       | 0.000 ± 2.682   | 4 |
| 10.05       | 0.000 ± 6.352   | 4 | 10.35       | 0.000 ± 1.171   | 1 | 10.65       | 0.000 ± 2.682   | 4 |
| 10.35       | 0.000 ± 2.682   | 4 | 10.65       | 0.000 ± 1.171   | 1 | 10.95       | 0.000 ± 2.682   | 4 |
| 10.65       | 0.000 ± 6.352   | 4 | 10.95       | 0.000 ± 1.171   | 1 | 11.25       | 0.000 ± 2.682   | 4 |
| 10.95       | 0.000 ± 2.682   | 4 | 11.25       | 0.000 ± 1.171   | 1 | 11.55       | 0.000 ± 2.682   | 4 |
| 11.25       | 0.000 ± 2.682   | 4 | 11.55       | 0.000 ± 1.171   | 1 | 11.85       | 0.000 ± 2.682   | 4 |
| 11.55       | 0.000 ± 2.682   | 4 | 11.85       | 0.000 ± 1.171   | 1 | 12.15       | 0.000 ± 2.682   | 4 |
| 11.85       | 0.000 ± 2.682   | 4 | 12.15       | 0.000 ± 1.171   | 1 | 12.45       | 0.000 ± 2.682   | 4 |
| 12.15       | 0.000 ± 2.682   | 4 | 12.45       | 0.000 ± 1.171   | 1 | 12.75       | 0.000 ± 2.682   | 4 |
| 12.45       | 0.000 ± 2.682   | 4 | 12.75       | 0.000 ± 1.171   | 1 | 13.05       | 0.000 ± 2.682   | 4 |

Figure 1. The IR LF of 5,388 AKARI–SDSS galaxies. The dashed line is the best-fitting double power law. The black open circles are the 1/Vmax data points obtained in this work. The uncertainties are the sum of Poisson errors and the errors computed using 100 Monte Carlo simulations. The triangles are the results for 2,357 AKARI–SDSS galaxies obtained by Goto et al. (2011b).
show the $1/V_{\text{max}}$ data (red diamonds) of the IRAS RBGS from Goto et al. (2011a). Our results are in agreement with the results of Sanders et al. (2003) and Goto et al. (2011a). Goto et al. (2011a) follow a similar procedure to obtain $L_{\text{IR}}$ and the $1/V_{\text{max}}$ measurements, also they include 160 $\mu$m band in estimating $L_{\text{IR}}$. When the RBGS data are added, we obtain a very similar fit (dashed magenta line in Fig. 3). Compared to Goto et al. (2011a) we obtain flatter faint- and bright-end slopes and a lower $L^*$. This shows that by increasing the number of local IR galaxies more than 20 times, we obtain the most accurate LF which is consistent with the results of previous studies (Sanders et al. 2003; Goto et al. 2011a). The most significant effect of the larger sample size is the much smaller statistical uncertainties (i.e., root mean square error is $(\sum V_{\text{max}}^{-2})^{0.5}$) in each luminosity bin. However, this does not necessarily decrease the uncertainties of the best-fitting parameters.

We note that due to the lack of complete (optical or IR) datasets that could provide AGN and star forming galaxy (SFG) separation for the combined 15,638 AKARI–SDSS–6dFGS–2MRS galaxies, we do not attempt to separate individual galaxies into AGN/SFG. Therefore, the LFs presented in this work includes the contribution from AGN. We also note that in far-IR, the contribution from the warm dust of AGN is expected to be small, and the emission is expected to be dominated by star-formation activity.

### 3.3 Total Infrared Luminosity Density

We integrate the measured LFs to estimate the total IR luminosity density, $\Omega_{\text{IR}}$. For each sample we integrate the best-fitting double power law. We list the obtained total luminosity densities in Table 3. The total luminosity density of the combined sample of 15,638 IR galaxies is $\Omega_{\text{IR}} = 1.19 \pm 0.05 \times 10^8 L_\odot $ Mpc$^{-3}$. In order to estimate the uncertainty we add and subtract the 1$\sigma$ error from the best-fitted double power law, we take the largest difference as the error. Only a small fraction of $\Omega_{\text{IR}}$ is produced by luminous IR galaxies and ultra luminous IR galaxies; 9.3 per cent and 0.9 per cent, respectively. This is consistent with the results of previous studies (e.g., Soifer & Neugebauer 1991; Goto et al. 2011b) that quantified the contribution of U/LIRGs to $\Omega_{\text{IR}}$ as small.

### 4 CONCLUSIONS

In our aim to derive the most accurate local IR LF, we have cross-matched the AKARI all-sky survey with the SDSS, 6dFGS and 2MRS to find 15,638 IR galaxies with spectroscopic redshifts. We have measured $L_{\text{IR}}$ by SED fitting based on the six AKARI, the four WISE IR photometry bands. Especially, the far-IR photometry that cover the peak of the dust emission SED allow us to have accurate $L_{\text{IR}}$ measurements compared to the ones based on a bolometric conversion factor. Our main conclusions are:

(i) We obtain the most accurate local (median $z = 0.027$)
IR LF for the largest sample studied so far. Our local IR LF will be a reliable benchmark for future investigations of total IR LF evolution at higher redshifts.

(ii) Compared to the previous study of Goto et al. (2011b), we have doubled the AKARI–SDSS sample size. Our LF with better high luminosity-end measurements, is consistent with that of Goto et al. (2011b).

(iii) Our analysis of the LF of different samples agree with each other. Particularly we measure a similar bright-end slope for different samples. With much greater precision they are also consistent with the previous measurements.

(iv) For the combined sample of 15,638 IR galaxies, we compute the local IR luminosity density as \( \Omega_{IR} = 1.19 \pm 0.05 \times 10^8 \) L\(_\odot\) Mpc\(^{-3}\). In the local Universe, the contribution of LIRGs and ULIRGs to \( \Omega_{IR} \) is very small; 9.3 per cent and 0.9 per cent, respectively.

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