DETECTION OF THE COSMIC FAR-INFRARED BACKGROUND IN AKARI DEEP FIELD SOUTH

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Received 2010 February 18; accepted 2011 May 9; published 2011 July 20

ABSTRACT

We report new limits on the absolute brightness and spatial fluctuations of the cosmic infrared background (CIB) via the AKARI satellite. We carried out observations at 65, 90, 140, and 160 μm as a cosmological survey in AKARI Deep Field South, which is one of the lowest cirrus regions with a contiguous area of the sky. After removing bright galaxies and subtracting zodiacal and Galactic foregrounds from the measured sky brightness, we successfully measured the CIB brightness and its fluctuations across a wide range of angular scales, from arcminutes to degrees. The measured CIB brightness is consistent with previous results reported from COBE data, but significantly higher than the lower limits at 70 and 160 μm obtained via Spitzer from the stacking analysis of selected 24 μm sources. The discrepancy with the Spitzer result is possibly due to a new galaxy population at high redshift obscured by hot dust or unknown diffuse emission. From a power spectrum analysis at 90 μm, two components were identified: the CIB fluctuations with shot noise due to individual galaxies in a small angular scale from the beam size up to 10 arcminutes, and Galactic cirrus emission dominating at the largest angular scales of a few degrees. The overall shape of the power spectrum at 90 μm is very similar to that at longer wavelengths, as observed by Spitzer and the Balloon-borne Large-Aperture Submillimeter Telescope (BLAST). Our power spectrum, with an intermediate angular scale of 10–30 arcminutes, gives a firm upper limit for galaxy clustering, which was found by Spitzer and BLAST. Moreover, the color of the CIB fluctuations, which is obtained by combining our data with the previous results, is as red as ultra-luminous infrared galaxies at high redshift. These galaxies are not likely to provide the majority of the CIB emission at 90 μm, but are responsible for the fluctuations. Our results provide new constraints on the evolution and clustering properties of distant infrared galaxies and any diffuse emission from the early universe.

Key words: cosmology: observations – diffuse radiation – infrared: CIB: diffuse background – infrared: galaxies – large-scale structure of universe

Online-only material: color figures

1. INTRODUCTION

Since the cosmic infrared background (CIB) was observed by the COBE satellite, it has been known that a large fraction of radiation energy in the universe is released in the infrared spectrum (Puget et al. 1996; Hauser et al. 1998). A compelling explanation for the CIB in the far infrared is the thermal emission of interstellar dust associated with high-redshift galaxies, heated by internal UV and optical radiation from young stars and active galactic nuclei (AGNs); the near-infrared background is dominated by starlight from extragalactic sources (Hauser & Dwek 2001; Kashlinsky 2005; Lagache et al. 2005). Thus, the far-infrared CIB is a powerful probe of dust-enshrouded star formation and AGN activity. Measuring the CIB in the far infrared may constrain dust emission powered by pre-galactic objects at very high redshift (Cooray & Yoshida 2004), such as the first generation of stars (Bond et al. 1986; Santos et al. 2002), which is expected to contribute to the near-infrared excess of the CIB (Matsumoto et al. 2005) and its spatial fluctuations (Kashlinsky et al. 2005; Matsumoto et al. 2010). The near-infrared excess problem is still controversial (Thompson et al. 2007), and the far-infrared observation is an important test for this issue.

In Figure 1, we summarize the results of all CIB measurements to date over the entire infrared and submillimeter wavelength range from previous space missions: COBE, the Infrared Telescope in Space (IRTS), Infrared Space Observatory (ISO), and Hubble Space Telescope (HST); Hauser et al. 1998; Fixsen et al. 1998; Finkbeiner et al. 2000; Matsumoto et al. 2005; Juvela et al. 2009; Thompson et al. 2007). For comparison, we also show various foreground emission components: zodiacal light (sunlight scattered by interplanetary dust), zodiacal emission (thermal emission from interplanetary dust), Galactic light (unresolved stars), diffuse Galactic light (DGL); starlight
scattered by interstellar dust), Galactic cirrus emission (thermal emission from interstellar dust), and the cosmic microwave background (CMB). Note that at mid-infrared wavelengths it is currently impossible to detect the CIB because the zodiacal emission is too bright. In the near infrared and far infrared, the foreground emission is relatively weak, and careful modeling and subtraction of the foreground enable one to extract the CIB from the measured sky brightness.

As seen in Figure 1, the CIB spectrum at wavelengths longer than 200 \( \mu m \) has been well constrained with the FIRAS instrument on COBE (Puget et al. 1996; Fixsen et al. 1998). However, results of photometric measurements at wavelengths shorter than 200 \( \mu m \) with the DIRBE instrument on COBE are divergent in the mean levels of the CIB brightness, mainly due to the strong and uncertain foreground contamination of zodiacal emission, which dominates the brightness of the entire sky, even though the Galactic foreground may be sufficiently weak in low cirrus regions (Hauser et al. 1998; Lagache et al. 2000; Finkbeiner et al. 2000). Although the CIB brightness was recently estimated using ISOPHOT data, independent of COBE data, the 90-\( \mu m \) data gave only an upper limit, and the measurement accuracy of the CIB brightness in the 150–180-\( \mu m \) range was in fact worse than that of COBE (Juvela et al. 2009). Figure 1 clearly shows a wavelength desert of the CIB measurement at shorter far-infrared wavelengths, i.e., <200 \( \mu m \). Hence, new measurements of the mean level of the CIB are required in this region.

In the last decade, many observational efforts were made to resolve the CIB into individual galaxies via far-infrared deep surveys with infrared space telescopes such as ISO, Spitzer, and AKARI (Kawara et al. 1998; Puget et al. 1999; Matsuura et al. 2000; Kawara et al. 2004; Dole et al. 2004; Frayer et al. 2006a; Matsuura et al. 2007; Shirahata et al. 2008), and consequently the origin of the CIB became clear. As shown in Figure 1, however, the detected galaxies account for only a small fraction (~10%) of the measured CIB brightness in the far infrared. Frayer et al. (2006b) claimed that they resolved more than half the model CIB at 70 \( \mu m \) into point sources in a single deep survey toward the GOODS-N field. In the mid-infrared, a lower limit of the CIB at 24 \( \mu m \) was derived from the integrated number counts, and this is thought to account for ~70% of the model CIB at 24 \( \mu m \) (Papovich et al. 2004). Dole et al. (2006) obtained lower limits for the CIB at 70 and 160 \( \mu m \) via a stacking analysis of detected sources at 24 \( \mu m \), finding that the mid-infrared sources contribute ~80% of the CIB in the far infrared, as shown in Figure 1 by the dotted line. In the submillimeter range, a similar stacking analysis of 24-\( \mu m \) galaxies against the deep surveys at 250, 350, and 500 \( \mu m \) by the Balloon-borne Large-Aperture Submillimeter Telescope (BLAST) experiment revealed that the 24-\( \mu m \) sources produce almost the entire CIB in the submillimeter range measured with FIRAS (Devlin et al. 2009; Marsden et al. 2009). Although these studies, using the Spitzer 24-\( \mu m \) surveys, provided strong constraints on the mean CIB level, the current limit of direct measurement of the CIB as diffuse emission in the far-infrared range is still high enough to allow the existence of new populations.

Measuring the spatial fluctuations (anisotropy) of the CIB is a powerful method of investigating the unresolved galaxy population below the detection limit and yields little contamination from the foreground. The CIB fluctuation analysis was pioneered for the COBE/DIRBE data (Kashlinsky et al. 1996a; 1996b). The angular power spectrum of the CIB fluctuations is an important observation to trace the distribution of star-forming galaxies with respect to the clustering bias in dark-matter halos. The fluctuation measurement is especially effective at longer wavelengths, where direct measurement of the
clustering of resolved galaxies is hampered by galaxy confusion due to the diffraction-limited resolution of current telescopes. In fact, power spectrum analysis of the CIB fluctuations has already been performed for large-area surveys in low cirrus regions: the FIRBACK survey at 170 \( \mu \text{m} \) by ISOPHOT (Puget et al. 1999; Lagache & Puget 2000), the MIPS/Spitzer data at 160 \( \mu \text{m} \) in the SWIRE/GTO field (Lagache et al. 2007), and the BLAST experiment (Viero et al. 2009). These results provided us with useful constraints on galaxy evolution and clustering. Information on the spectral energy distribution (SED) of the CIB fluctuations would be another important clue in the investigation of the CIB properties. However, the quality of previous CIB fluctuation measurements at shorter far-infrared wavelengths, such as the ELAIS/Lockman survey at 90 \( \mu \text{m} \) by ISOPHOT (Matsuura et al. 2000) and a new analysis of the IRAS map at 60 \( \mu \text{m} \) (Miville-Deschênes et al. 2007), is not sufficient to add new information beyond the MIPS and ISOPHOT results at 160 and 170 \( \mu \text{m} \).

Our aim in this work is to make the best measurements of the absolute brightness and fluctuations of the CIB since those of COBE, especially in the shorter far-infrared wavelength range, which is as yet not extensively explored. The far-infrared surveyor (FIS; Kawada et al. 2007) onboard the Japanese infrared satellite AKARI (Murakami et al. 2007) provides us with a valuable opportunity to investigate the CIB in the far infrared. The FIS has four far-infrared wavebands centered on 65, 90, 140, and 160 \( \mu \text{m} \), and a large-area survey to measure the sky fluctuations out to a large angular scale beyond the cosmic variance scale was carried out by this instrument. The CIB measurement was achieved by using the high sensitivity of the AKARI FIS to diffuse emission, high angular resolution that is powerful enough to remove the point sources down to low flux levels, and intensive selection of the survey field that provides minimum foreground contamination.

In this paper, we present the initial results of our CIB measurement with the AKARI FIS. In Section 2, we describe the FIS instrument and the observational method. The data processes used to produce the final calibrated image of the diffuse emission is presented in Section 3. In Section 4, we show how we subtracted the foreground from the observed brightness to measure the absolute brightness of the CIB as an isotropic residual. In Section 5, we present the power spectrum analysis of the final image used to decompose the CIB fluctuations into galactic and extragalactic components. In Section 6, we compare our results from the data analysis with previous studies of the CIB and present scientific discussion. Conclusions drawn from this work are given in Section 7.

2. OBSERVATIONS

2.1. The AKARI Satellite and Instrumentation

The AKARI satellite was launched on board JAXA’s M-V-8 launch vehicle on 2006 February 22, Japan standard time, as Japan’s first space mission dedicated to infrared astronomy (Murakami et al. 2007). AKARI is equipped with a cryogenically cooled telescope with an aperture of 68.5 cm in diameter and two scientific instruments, the FIS (Kawada et al. 2007) and the infrared camera (Onaka et al. 2007). AKARI’s orbit is Sun-synchronous, which dictates that any large surveys can only be carried out near the ecliptic poles. Although the primary purpose of the AKARI mission is the all-sky survey in the far infrared, much of the telescope’s time has also been used for slow-scan observations, which give much higher sensitivity than that of the all-sky survey, toward the targeted fields for specific scientific objectives (Kawada et al. 2007; Matsuura et al. 2007). A slow-scan observation is carried out as a mode of pointed observation via AKARI according to the Astronomical Observation Template (AOT) that specifies the observational parameters (see Section 2.3); there is a reset interval for the integration ramp to avoid saturation, and scan speed and step size in the cross-scan direction determine the total scan area in a single pointed observation for 10 minutes, a time period that is mainly determined by the limitation of the earth avoidance angle.

The FIS instrument consists of two cameras in short and long far-infrared bands, with colinear optics to collimate the beam from the telescope and a dichroic beam splitter to divide the beam into two, which focus on the two cameras. The dichroic beam splitter can be changed by a filter wheel to a wire-grid-polarized beam splitter for an additional function of the FIS, the Martin–Puplett Fourier-transform spectrometer (Kawada et al. 2007), which was not used for the observations described in this paper. Newly developed, two sets of 20 \( \times \) 3 Ge:Ga monolithic array detectors operated at 2.1 K (Matsuura et al. 2002; Fujiwara et al. 2003) and 15 stacks of five-elements-stressed Ge:Ga detectors at 1.8 K (Doi et al. 2002) with broad bandpass filters were used for the short-wavelength (SW) bands centered at 65 and 90 \( \mu \text{m} \) and the long-wavelength (LW) bands at 140 and 160 \( \mu \text{m} \), respectively. Pixel fields of view (FOVs) of the SW and LW detector arrays are 30 \( \times \) 30 arcsec and 50 \( \times \) 50 arcsec, respectively, which are comparable to the diffraction-beam size of the AKARI telescope.

The photocurrent of the detector is received by the cold read-out electronics of the capacitive trans-impedance amplifier and multiplexer, which are constructed with cryogenic MOSFETs at \( \sim 2 \) K; the buffered output signal from each array element is thus a charge integration ramp whose slope is, in principle, proportional to the input infrared power. Under the low-background condition in orbit, the sensitivity of the detector is mainly limited by the readout noise, and the signal-to-noise ratio is proportional to the exposure time of a single integration ramp at a fixed sky position; thus, slow-scan observations provide much higher sensitivity than that of the all-sky survey, which dictates fast scans.

2.2. Field Selection

The AKARI observations of the CIB were carried out for a far-infrared cosmological survey program (PI: S. Matsuura) as one of the core scientific programs of the AKARI project, known as Mission Programs (MP; Matsuura et al. 2006). The survey field called AKARI Deep Field South (ADF-S) is one of the lowest cirrus regions with a contiguous area in the sky (Schlegel et al. 1998), with an area of 12 deg\(^2\) near the South Ecliptic Pole; the field center is located at R.A. = 4\(^h\)44\(^m\)00\(^s\), decl. = −53\(^\circ\)20\prime\,00\″ (J2000). The survey field includes a nearby cluster of galaxies, DC 0428-53/Abell S0463 (Dressler 1980). The observation log of this survey is summarized in Table 1.

The ADF-S field is one of the best cosmological windows because of its low foreground emission, including a minimal galactic foreground and low zodiacal background. High visibility of this field to a polar-orbiting satellite such as AKARI is also important to achieve high sensitivity via long exposures. By comparison, the Lockman Hole (LH), the most popular low cirrus region as a cosmological window, has a relatively high zodiacal brightness and low visibility due to its low ecliptic latitude.
2.3. AOT and Parameters

In order to make a mosaic map of the entire survey field, a total of 200 slow-scan observations were obtained by a combination of AOTs, FIS–01, and FIS–02 (Kawada et al. 2007; Matsuura et al. 2007). These AOTs allow multiple pointings as footprints of the FOV along a scan path. The area covered by a single observation of FIS–01 or FIS–02 is 12 arcmin × 0.6 deg or 8 arcmin × 1.25 deg, respectively, for an exposure time of 10 minutes. Data in four photometric bands, centered at 65, 90, 140, and 160 μm, were simultaneously collected by a single observation, and the same sky was observed in all bands, except for a small difference in the FOV.

The AOTs include a calibration sequence, i.e., dark current measurements by closing the cold shutter and a responsivity check using an internal calibrator, during maneuvers before and after the observation and at the turning points of the round-trip scans. Such a highly redundant calibration sequence enabled us to correct any responsivity changes by referring to astronomical calibration data collected by the same AOT. After the first maneuver to the target position, the cold shutter was opened, the sky signals were monitored during a settling time for the attitude control while the telescope’s line of sight was oscillating around the target position, and the slow-scan observation started. Signal monitoring before the observation is useful to check for any signal drift, including time variation of any stray light (described in the next section).

To produce a mosaic image of the entire field with long-strip image segments, 200 slow-scan observations with field overlaps of half an FOV in the cross-scan direction were carried out. The survey was completed in one and a half years over three observational seasons, as summarized in Table 1. Making mosaics of the data collected in different seasons was not straightforward and required careful treatment of the time variation of zodiacal brightness.

2.4. Supplemental Observations

In addition to the ADF-S survey, supplementary observations using AOT FIS–01 were also made over small areas toward the LH and the North Ecliptic Pole (NEP), as shown in Table 1. One of the LH observations was a mini-survey to map ~1 deg² for the performance verification (PV) soon after the launch of AKARI (Matsuura et al. 2007), and another was included in the same MP as ADF-S to measure galaxy confusion and check the reproducibility of the measurement a year later. The NEP observation was a Director’s Time program to evaluate the confusion noise in a higher cirrus region than ADF-S, the lowest cirrus region. As described in later sections, these observations are useful to check the validity of the foreground estimate and evaluate the cirrus contribution to the sky brightness.

3. DATA PROCESSING AND CALIBRATION

In this section, we describe the methods of data reduction and analysis of the ADF-S data. The time series data are processed into a co-added image using the FIS slow-scan analysis tool (SS-Tool, Ver.20070914) (AKARI FIS Data Users Manual 2007). The SS-Tool includes dark-current subtraction, absolute calibration, flat fielding, stray light removal, and co-addition of multiple scans. The SS-Tool is described in detail in Matsuura et al. (2007), and therefore we describe it only briefly in the following sections.

3.1. Time Domain Analysis

The raw output of the FIS instrument is time series data, consisting of integration ramps for each detector pixel. Using the SS-Tool, we corrected the raw ramps for non-linearity and converted them to the average current values after removing spikes and glitches caused by cosmic-ray events and other discontinuities. The SS-Tool makes a dark-current subtraction, absolute calibration, flat fielding, stray light removal, and co-addition of multiple scans. Stray light was removed in the time domain by high-pass filtering the data with a window size of 90 s, which was determined to remove the slowest signal from the stray light but not to lose faster signals caused by astronomical emission. For the slow-scan observation, the time domain filter is equivalent to a spatial filter in the scan direction. We determined the window size of the filter in the scan direction to be equivalent to the FOV size in the cross-scan direction to ensure isotropy.
3.2. Flat Fielding

Flat fielding, i.e., correcting responsivity inhomogeneity in the detector array, was carried out by measuring the mean brightness of the scanned area for each observation. This method is based on the assumption that sky brightness, averaged over the observed area, is the same for all array pixels. Accordingly, this method is effective especially for the dark sky dominated by zodiacal emission, whose spatial fluctuation is known to be very small from mid-infrared observations, their smoothness in arcmin scales being better than 1% (Abraham et al. 1998).

According to the results of previous far-infrared missions, e.g., IRAS and COBE, sky brightness toward high galactic latitudes in the shorter AKARI bands at 65 and 90 μm should be dominated by zodiacal emission, even at high ecliptic latitude; the expected fractions are 90% at 65 μm and 70% at 90 μm, while at 140 and 160 μm, Galactic cirrus emission is more likely the major (>50%) component in many cases. Since the smoothness of Galactic cirrus emission depends on the angular scale and mean brightness, this flat fielding in cirrus regions is not as excellent as the method using the zodiacal emission. If we choose a sky with a brightness of about 10 MJy sr⁻¹, the smoothness of the cirrus emission can be better than 10%.

To construct a flat-field template for the SW bands, we carried out observations of zodiacal emission at ecliptic latitudes lower than 20° in the PV phase. For the LW bands, MADE cirrus observations at intermediate galactic latitudes of about 20°. However, the use of such a pre-measured flat suffered from the responsivity change induced by radiation effects and the degradation of detector properties, which may not be perfectly corrected.

For the ADF-S survey, in fact, flat fielding with the observed sky itself yielded much better results than the pre-measured flat, because the responsivity change could be effectively corrected by the calibration sequence made during each observation. Thus, we constructed such “self-flat” data by averaging the time series data for each pixel after a 3σ rejection in time during the settling time for attitude control and the initial scan observation. The flat-field accuracy with this method was generally better than 5%, and the actual effect of the flat-field error for each observation was taken into account in the noise map derived from the signal variance for multiple scans over the same sky.

3.3. Absolute Calibration

3.3.1. Pre-flight Measurement in the Laboratory

Pre-flight measurements of the absolute gain, including detector responsivity, were carried out in all wave bands of AKARI in the laboratory, using an external blackbody source at temperatures ranging from 17 K to 30 K, with attenuators of 20–30 dB. The measured gain factors showed good agreement with each other, to within ±5%, and we adopted a mean value as the final gain factor.

To compare measurements done at different times and different conditions either in orbit or in the laboratory, we corrected the absolute gain value by referring to internal calibrator signals. The reproducibility of the calibrator signals was approximately ±5%, and this was also the limiting factor of calibration accuracy. In the SW bands at 60 and 90 μm, we estimated the accuracy of the pre-flight calibration to within ±7% by quadratically combining the above uncertainties.

While the monolithic Ge:Ga detectors for the SW bands had fairly good uniformity of responsivity over the array and showed high stability in orbit, the stressed Ge:Ga detector arrays for the LW bands showed considerably larger responsivity differences among pixels and strong radiation effects in orbit. These properties made it difficult to correct for responsivity in the LW bands, even with the internal calibrator (c.f. flat-field error), and caused additional calibration errors of ±6% and ±9% at 140 and 160 μm, respectively.

3.3.2. In-orbit Measurement

To measure the absolute gain of the detectors in orbit, we made observations of diffuse emission whose brightness had been previously accurately measured with COBE, as described in the last section.

For the SW bands, we observed the zodiacal emission at low ecliptic latitudes. To derive the gain factor, we compared our observed data with the COBE/DIRBE model of zodiacal emission, which is about 98% reliable at low ecliptic latitudes (Kelsall et al. 1998). In order to use this method to avoid the contamination from Galactic and extragalactic emission, we differentiated the sky brightness measured at different ecliptic latitudes in low cirrus regions with similar H1 column densities (N1H ~ 2 × 10¹⁹ cm⁻²) and compared the differential data with the zodiacal light model. The accuracy of this method is consequently limited by the calibration uncertainty of DIRBE, which is ~10% (Hauser et al. 1998).

For the LW bands, we observed Galactic cirrus emission and compared the measured brightness with the COBE/DIRBE annual average map (AAM). Sky brightness at low galactic latitudes in this wavelength range is dominated by Galactic cirrus emission; seasonal variation of zodiacal emission is smaller than 3%, and the AAM map is thus valid for this calibration. In addition to the calibration uncertainty of DIRBE, the low-frequency noise and instability of the detector during the observations increased the uncertainties to ±15% and ±19% at 140 and 160 μm, respectively.

3.3.3. Final Gain Factor and Uncertainty

For the SW bands, the absolute gain factor of AKARI from pre-flight measurements showed excellent agreement with that from the in-orbit calibration. The difference was only 5% at both 65 and 90 μm. It is noteworthy that this difference is smaller than both the uncertainties of the pre-flight and in-orbit calibrations. For the LW bands, the pre-flight measurement gave a slightly different gain from that of the in-orbit calibration; the difference was 13% and 25% at 140 and 160 μm, respectively, but they agreed with each other within the uncertainties.

In this work, we adopted our own gain factor from the pre-flight measurement to indicate the final result of the CIB brightness. For the foreground subtraction, however, we adopted the in-orbit calibration factor to compare our data directly with the DIRBE result. In summary, the absolute calibration uncertainties of our CIB measurements, taking all systematics into account, are ±7% at both 65 and 90 μm, ±9% at 140 μm, and ±13% at 160 μm. These numbers are sufficiently small for significant detection of the CIB. More details about the absolute calibration are described in a separate forthcoming paper (S. Matsuura et al. 2011, in preparation).

3.4. Co-added Image

Each slow-scan observation covers only a small patch of the sky, corresponding to the scanned area. To produce the final mosaic image of the entire ADF-S field from multiple scans, we co-added the time series data in grid cells of the sky coordinates,
foreground subtraction and show the final mosaic image of the entire ADF-S field. For accurate measurements of the CIB, estimates of the sky levels of multiple observations by subtracting the zodiacal foreground (lower data points). The sky brightness values are only for those dates when the fields were observed, rather than the entire length of the mission. The inset shows a magnified view of the data boxed with the dotted line.

Figure 2. Sky brightness at 65 μm in ADF-S and the LH and NEP fields, measured in various seasons (upper data points), and the residual brightness after subtraction of the zodiacal foreground (lower data points). The sky brightness values are only for those dates when the fields were observed, rather than the entire length of the mission. The inset shows a magnified view of the data boxed with the dotted line.

4. FOREGROUND SUBTRACTION

To produce the final mosaic image of the entire field by the co-addition of the time series data, we adjusted the mean sky levels of multiple observations by subtracting the zodiacal foreground. For accurate measurements of the CIB, estimates of the contribution from Galactic cirrus and external galaxies are also essential. In this section, we describe our methods of foreground subtraction and show the final mosaic image of the entire ADF-S field.

4.1. Zodiacal Emission

4.1.1. Seasonal Variation of Zodiacal Brightness

Although the seasonal variation of zodiacal brightness is sometimes an obstacle, it is rather useful to know the contribution of dust near Earth to zodiacal brightness. In fact, conventional models of the zodiacal cloud based on the IRAS and COBE observations have been constructed by relying on the local dust density and temperature derived from seasonal variation (Reach 1988; Kelsall et al. 1998). The amplitude of seasonal variation is not affected by any uncertainty from the isotropic component of zodiacal emission.

In Figure 2, the measured sky brightness at 65 μm at various locations in ADF-S is plotted as a function of days after launch. Figure 3 is the same plot but at 90 μm. The sky brightness values are only for those dates when the field was observed, rather than the entire length of the mission. Statistical errors of sky brightness from the rms fluctuation of the image are on the order of a few kJy sr⁻¹ (smaller than the size of the plot symbols). The sky brightness in the second season of winter, about a year after launch, was significantly lower than that in the first and third seasons of summer, as expected from a one-year period of the seasonal variation of zodiacal brightness.

For comparison, the sky brightness toward the LH and NEP, which has been measured as supplemental observations in previously well-explored fields, is also shown in Figures 2 and 3. The LH for both PV and MP is brighter than ADF-S because of the field’s higher zodiacal brightness, despite the similar density of the Galactic cirrus region. The NEP is brighter than ADF-S due to the larger contribution from the Galactic cirrus, even though it has the lowest zodiacal brightness.

4.1.2. Residual Brightness after Zodi-subtraction

To measure the absolute brightness of the CIB, we subtracted the zodiacal foreground from each observation by using the same COBE/DIRBE model as we used for the in-orbit calibration. The zodiacal brightness in the AKARI bands was calculated by interpolation from the DIRBE bands, with color correction assuming a blackbody spectrum. The zodi-subtracted data are composed of only the Galactic cirrus emission and CIB, assuming the zodi-model is correct.

In Figures 2 and 3, residuals after subtraction of the zodiacal foreground are compared with the raw data. The zodi-subtracted data for ADF-S taken in different seasons show good agreement with each other, not only in the mean levels but also in the
Figure 4. Top: diffuse map of ADF-S at 90 μm after subtraction of the zodiacal foreground, drawn as linear contours. The brighter the contour, the higher the surface brightness. The map size is approximately 6 deg × 2 deg. Bottom: the source-removed map after masking the sources down to ~20 mJy. The masked area is filled with zeros to the source locations clearly shown.

(A color version of this figure is available in the online journal.)

detailed structure, mainly due to the Galactic cirrus. In addition, the residuals for ADF-S and the LH agree with each other except for the detailed structure, while the NEP is much brighter than the others, especially at 90 μm, due to the larger contribution from the Galactic cirrus, as described later. At 65 μm, the difference in NEP brightness compared to the other fields is not very clear, since the sky brightness is dominated by zodiacal emission. The results indicate that the zodi-model is correct to an accuracy better than 5%, which is a typical value of the model’s uncertainty (Kelsall et al. 1998).

4.1.3. Zodi-subtracted Diffuse Map

The upper image of Figure 4 shows the final diffuse map at 90 μm produced by mosaicing the zodi-subtracted data. To obtain this mosaic image, destriping was made by first calculating the mean sky levels of the image strips taken by multiple scans, after removing bright sources via a 3σ rejection method, and then smooth filtering the time domain to the mean sky levels of multiple scans to correct any slight responsivity difference that may not have been perfectly corrected by the calibration sequence. Finally, all images were co-added. The window size used for the time-domain filter corresponds to three scan strips in the space domain. A large contiguous area was successfully mapped, except for small lost-data areas caused by problems with the ground station, such as the inlets in the upper part of the map. As clearly seen in the map, a large-scale structure from Galactic cirrus emission exists; the central region is darker than the surrounding area. Most bright spots can be attributed to nearby galaxies.

4.2. Stars and Galaxies

Each star or galaxy in the field does not contribute much to the overall sky brightness, but the total contribution, including faint sources down to the detection limit, is non-negligible for accurate measurements of the CIB. Moreover, point sources seriously affect the sky fluctuations more than the absolute brightness. Hence, we masked foreground stars and galaxies down to the 3σ detection limits of ~100 mJy at 65 μm and ~20 mJy at 90 μm from the diffuse map. The mask is a circular area around each source, with the radius normalized to be 1 arcmin at 100 mJy, increasing proportionally with increasing flux. The lower image in Figure 4 is the resultant 90-μm map after source removal. The masked areas are filled with zero values to make the source locations clear.

According to the point-spread function (PSF) previously measured for stars and asteroids as calibration standards (Shirahata et al. 2009), the remaining brightness in the out-of-mask region around a point source is less than 5% of the peak brightness, and the integrated flux in the out-of-mask region is 20% of the total flux. The integrated flux of the out-of-mask region of all sources down to the 3σ detection limit is less than half the total source flux. Consequently, the mean brightness of the zodi-subtracted map after removing sources is ~3% lower than the original value that included the sources, and the sky fluctuation power is also an order of magnitude lower. We also confirmed that the fluctuation power has the same value if we change the mask aperture by a factor of ±50%. This implies that the contribution of the out-of-mask fringes of the PSF to the total sky fluctuations is negligible.

4.3. The Galactic Cirrus

To estimate the Galactic foreground, we studied the correlation between the ADF-S map and the Schlegel, Finkbeiner, & Davis (SFD) dust map (Schlegel et al. 1998), which is widely used as a reliable map of the Galactic cirrus. A correlation method to subtract the Galactic foreground was previously performed based on COBE data (Arendt et al. 1998). In our study, this correlation may be scattered by point sources since the angular resolution of AKARI is much higher than that of the SFD map, which is based on IRAS and COBE data. In fact, many
bright galaxies in the field are resolved by AKARI, but in the SFD map they are left unresolved and instead recognized as part of the cirrus structure. Thus, we calculated the correlation for the zodi-subtracted map after removing bright galaxies and reducing the map resolution to that of the SFD map.

Figures 5 and 6 show the correlation between the SFD map at 100 μm and the ADF-S map at 65 and 90 μm, respectively. The 90-μm map correlates significantly with the SFD map, with a correlation coefficient of \( r = 0.43 \); the linear coefficient from the best-fit line, shown in Figure 6 as the dashed line, is \( I(90 \mu m)/I(100 \mu m) = 0.7030 \pm 0.0007 \). This color ratio corresponds to a dust temperature of \( T = 18.2 \) K for \( n = 2 \), where \( n \) is the emissivity index and \( I(\nu) \sim B(T) \nu^{-n} \), and is consistent with typical dust properties (Schlegel et al. 1998). The correlation of the 65-μm map was marginal, \( r = 0.05 \) and \( I(65 \mu m)/I(100 \mu m) = 0.283 \pm 0.002 \).

It is remarkable that the zero intercepts of the best-fit lines for the 65- and 90-μm data correlations show significantly finite values, implying a positive detection of an isotropic emission component of the CIB. To estimate cirrus brightness in the LW bands, we extrapolated the 90-μm brightness with a blackbody spectrum of \( T = 18.2 \) K for \( n = 2 \), because the map quality was not high enough to allow the same correlation analysis made for the SW bands.

5. POWER SPECTRUM ANALYSIS

5.1. Method

To carry out a fluctuation study of the CIB, we conducted a power spectrum analysis using the two-dimensional (2D) fast Fourier transform (FFT) for the final zodi-subtracted maps of ADF-S. The fluctuation of the surface brightness map is defined as \( \delta I(x) = I(x) - \langle I \rangle \), where \( x \) is the 2D coordinate in the sky and \( \langle I \rangle \) is the ensemble average. The 2D FFT of the fluctuation map, \( \delta I(k) \), is

\[
\delta I(k) = \int \delta I(x) e^{-j2\pi k \cdot x} d^2x, \tag{1}
\]

where \( k = (k_x, k_y) \) is the 2D wavenumber in the arcmin\(^{-1}\) unit, complementary to the map coordinate, \( x = (x, y) \), in the arcmin unit. The 2D power spectrum is \( P(k) = \langle |\delta I(k)|^2 \rangle \), and the power spectrum in one dimension is obtained from the average of the 2D power spectrum: \( P(k) = \langle P(k) \rangle, k = |k| \), where the average is calculated over all phase angles.

For the 2D FFT analysis, we first produced a co-added image of the entire field with Cartesian coordinates via a simple tangential projection. The image size is so small that the distortion by the projection does not affect the result (a spherical harmonics expansion with multipoles is required for power spectrum analysis at angular scales larger than \( 10^\circ \)). Next, we subtracted the mean offset level from the image, set the blank-data area outside the boundary of the observed area (the dark area in Figure 4) to zero, and set the source-masked regions to zero. Then, we applied a 2D FFT to the entire image. Finally, we corrected the raw power spectrum in the spectral domain by correction factors such as effective area, noise spectrum, and PSF, as described below.

5.2. Effective Area

As seen in Figure 4, the survey field has a non-rectangular shape, and the image includes zero-value data for the mask of bright sources, as described later. Such an irregular shape may distort the power spectrum, and the non-negligible number of zero-value data points decreases the amplitude of the power spectrum. To obtain the real power spectrum and avoid such artifacts, we corrected the power spectrum by multiplying it by a correction factor corresponding to the effective area of the field.

To derive this correction factor, we used a random-noise simulation method by generating noise images of the same shape and area as the survey field, so that the rms noise of all images had a constant value. Then, we calculated the power spectra of the noise images by using the 2D FFT. Since the simulated noise image should have a flat power spectrum, i.e., white noise, we can find any effects due to image irregularity by noting a change in distortion and amplitude of the noise power spectra. The correction factor was actually calculated as the ratio of the original white noise spectrum to the mean power spectrum of the simulated noise images.

The resultant correction factor was constant, with no significant spectral distortion in the entire spectral range. This result is reasonable, because the masked pixels for bright sources and bad pixels in the observed area occupy only a small fraction (4%) of the entire image, and the masked area in the margin...
The largest angular scale. The map’s center is the coordinate origin, which corresponds to (arbitrary unit). The map’s center is the coordinate origin, which corresponds to the largest angular scale.

The estimated noise is mainly due to instrumental noise, but may include systematic errors of the zodi-model uncertainty surrounding the observed area does not change the shape of the power spectrum but rather its amplitude, which is corrected by the masking fraction.

5.3. Angular Power Spectrum

Figure 7 shows the power spectrum of the 90-μm map, including bright galaxies as a function of wavenumber. The amplitude is corrected by the effective area, as described above. Shown in Figure 8 is the logarithmic contour map of the 2D power spectrum \( P(k) \) for phase angles in a coaxial ring of each wavenumber bin. The wavenumber bin width is approximately 0.003 arcmin\(^{-1}\), corresponding to the inverse of the angular size of the map. The error bars of the power spectrum denote the standard error that was calculated from the standard deviation and number of data points in each radial bin.

Figure 7. Raw power spectrum of the zodi-subtracted ADF-S map at 90 μm, including bright sources (filled triangles), and the PSF-corrected power spectrum after subtracting instrumental noise (thin line). The diamonds represent the measured power spectrum of instrumental noise, and the dashed line is the result of a polynomial fit to the noise spectrum. The dotted line is the power spectrum of the average (A+B) map from the data used for the noise evaluation (see the text).

Figure 8. Map of the 2D power spectrum for the source-removed map in Figure 4. The contour is logarithmic, and the coordinates are in wavenumbers (arbitrary unit). The map’s center is the coordinate origin, which corresponds to the largest angular scale.

(A color version of this figure is available in the online journal.)

\begin{equation}
C(\theta) = 2\pi \int P(k)J(2\pi k\theta)kd\theta
\end{equation}

and compared it with the directly calculated two-point correlation function, which is not affected by zero-value pixels. For this analysis, we reduced the image resolution to make it three times worse than the original resolution via pixel binning, because the computational process for two-point correlations is much slower than the FFT method, and the run time is limited. Figure 9 shows the obtained two-point correlation functions of the image as functions of the angular separations of pixel pairs. The correlation function from the power spectrum shows good agreement with that directly calculated from the image, which means the FFT method is fairly valid for our analysis.

5.4. Noise Estimate

To obtain the astronomical fluctuation power, subtraction of instrumental noise is necessary. We estimated the noise power spectrum from the difference of two subset maps made in the same field but in different epochs (seasons); two maps for the data collected in the first epoch in 2006 (map “A”), and, six months later, the second epoch in 2007 (map “B”) (see Table 1). Shown in Figure 10 are the two maps (A and B), the difference (A−B), and the mean (A+B). We used the A−B map to estimate the noise power spectrum, including all noise and artifacts, and used the A+B map to confirm the noise reduction via averaging. The obtained noise power spectrum is shown in Figure 7. The noise is dominated by low-frequency noise, as fitted by polynomials with terms of \( 1/f \) and \( 1/f^2 \). For noise subtraction from the raw power spectrum, we used the result of the polynomial fit scaled by the number of observations \( N_{\text{obs}} \), rather than the noise data, to avoid adding error arising from the data scatter. It is noteworthy that the power spectra of the average (A+B) map and the entire map after noise subtraction show good agreement with each other, as shown in Figure 7.

The estimated noise is mainly due to instrumental noise, but may include systematic errors of the zodi-model uncertainty.
and the responsivity correction. The seasonal variation of small-scale structures of zodiacal emission may also contribute to the noise, but its contribution is also subtracted from the measured power spectrum as a noise component. This noise level gives an upper limit of residual fluctuations of zodiacal emission of smaller than 0.5% of the mean level at an angular scale of $\sim 1$ arcmin, while the previously reported upper limit at the same angular scale was 1% (Abraham et al. 1998).

5.5. Beam Correction

The steep decrease in fluctuation power toward large wavenumbers is obviously due to low-pass filtering by the PSF, which has a beam size of approximately 30 arcsec in FWHM. To reproduce the intrinsic power spectrum of the map, we divided the raw power spectrum by the normalized power spectrum of the PSF constructed from sources in ADF-S (self-measured PSF). Although the pre-measured PSF of bright stars as calibration standards could also be used for this purpose, observations of calibration stars using the same AOT parameter as that used for the ADF-S survey were not available because the calibration sources are too bright.

Figure 11 shows two kinds of power spectra for the self-measured PSF; one is a statistical PSF spectrum from the difference between two spectra of the source-removed map and the original map, and the other is the average PSF spectrum of only bright sources in the field. To obtain the average PSF spectrum, we cut out postage stamps with a size of $40 \times 40$ arcmin$^2$ around the bright sources with signal-to-noise ratios higher than 30. The statistical PSF spectrum is normalized at small wavenumbers, and the average PSF spectrum is scaled to fit the overall range. The two methods show good agreement with each other in the range of 0.1–0.8 arcmin, though a large discrepancy appears at large wavenumbers. Since this paper focuses on the power spectrum at large angular scales, we adopted the statistical PSF because it actually provides a better result when reproducing the power spectrum of the map at large wavenumbers, and it is also known that transient effects are stronger for brighter sources (Shirahata et al. 2009).

5.6. Resultant Power Spectrum

5.6.1. Raw Power Spectrum

The power spectrum after noise subtraction and PSF correction is shown in Figure 7. There exist two major components in
the power spectrum. One is a constant component dominating at wavenumbers larger than 0.1 arcmin\(^{-1}\), and the other shows a steep rise toward the smallest wavenumber following a \(k^3\) power law. The former is regarded as the shot noise (Poisson noise) mainly due to bright galaxies in the field, and the latter can be identified as Galactic cirrus fluctuations, as discussed in the following section.

We carried out a power spectrum analysis for the 65-\(\mu\)m data in the same way we did for the 90-\(\mu\)m data. However, the obtained power spectrum was not significant compared to noise power, suffering from low sensitivity. It was also difficult to obtain a significant power spectrum at 140 and 160 \(\mu\)m because of the presence of low-frequency noise originating from the responsivity change induced by cosmic-ray hits.

5.6.2. Bright-source Removal

The raw power spectrum in Figure 7 is obviously contaminated by shot noise, with a flat spectrum at larger wavenumbers originating from randomly distributed bright galaxies in the field. To investigate the fluctuations originating from underlying faint galaxies (the building blocks of the CIB), we derived the power spectrum by removing the point sources down to the detection limit of AKARI, \(\sim 20\) mJy.

Figure 12 shows the PSF-corrected power spectra before and after point-source removal. The shot noise power, in contrast to the cirrus component, decreases to 10% of the value before source removal. The increased power at \(\sim 1\) arcmin\(^{-1}\) may be a signature of the small-scale correlation between galaxies and source confusion, or it may be due to the uncertainty of the PSF, as seen in Figure 11. Study of the power spectrum at these small angular scales is reserved for future work. At the other wavelengths, we only obtained upper limits for the shot noise, which are not as meaningful as lower limits.

6. RESULTS AND DISCUSSION

6.1. Mean CIB Levels

6.1.1. Absolute Brightness Toward ADF-S

The resultant CIB brightness was measured as the zero-intercept of the correlation between the zodi-subtracted map and the SFD map, as shown in Figure 13, and summarized in Table 2 with statistical and calibration errors and an uncertainty in the zodiacal emission model of 5% (Kelsall et al. 1998). In Table 2, the mean brightnesses of zodiacal emission and Galactic cirrus emission over the entire ADF-S are also shown as components of the measured total sky brightness. The measured brightnesses in Table 2 are all color corrected, assuming a flat spectrum. Although the zero-point offset of the SFD map may cause a systematic uncertainty in the CIB brightness, such uncertainty has been estimated to be smaller than 0.1 MJy sr\(^{-1}\) at 100 \(\mu\)m (Finkbeiner et al. 2000), which does not significantly alter the results. In conclusion, we can say that we significantly detected the CIB in the SW bands. We also tentatively detected the CIB at 140 and 160 \(\mu\)m by extrapolating the cirrus brightness from 90 \(\mu\)m to each wavelength, assuming a \(T = 18.2\) K blackbody spectrum.

To obtain a more robust result we adopted another zodi-model with a very powerful assumption about the celestial signal—called the “very-strong no-zodi” principle, i.e., no extrasolar emission at 25 \(\mu\)m exists at high ecliptic latitudes (Wright 1998; Wright 2001; Levenson et al. 2007)—in which the zodi-model brightness becomes \(\sim 10\%\) higher than what was assumed for our foreground subtraction (L. Levenson, private communication). On this assumption, the residual background decreases to zero at 65 \(\mu\)m but still remains at 90 \(\mu\)m, at a significantly positive value of 0.50 MJy sr\(^{-1}\), because of the bluer color of zodiacal emission. This lower limit of the CIB at 90 \(\mu\)m is shown in Figure 13. In the LW bands, the zodi-model difference changes the residual background by at most 10%, which is smaller than the statistical error.

6.1.2. Isotropy

In Table 3, we summarize the zodi-subtracted sky brightness in various fields as a mean value, with the error estimated from...
the brightness variance for a number of observations in each field. The error does not include the calibration error or the zodi-model uncertainty. The table also indicates the residual brightness after subtracting the cirrus brightness, which was estimated from the H\textsubscript{i} 20-cm line map of the Leiden–Argentina–Bonn (LAB) survey as a systematic uncertainty of 10\textsuperscript{19} cm\textsuperscript{-2} (Kalberla et al. 2005; Bajaja et al. 2005). The cirrus brightness was obtained by assuming a conversion factor from the H\textsubscript{i} column density to the 100-\textmu m brightness of 0.6\pm0.1 MJy sr\textsuperscript{-1}/10\textsuperscript{20} cm\textsuperscript{-2}, as the median value of various COBE-based results with their variation as an uncertainty (Boulanger et al. 1996; Arendt et al. 1998; Reach et al. 1998; Schlegel et al. 1998; Lagache et al. 2000). For the wavelength conversion from 100-\textmu m to the AKARI bands, we used the correlation coefficients in Figures 5 and 6. Since the angular resolution of the H\textsubscript{i} data is 10 arcmin, which is much larger than that of our data, we used the mean brightnesses of our data and the H\textsubscript{i} data in each field. The residual brightnesses after subtracting the cirrus brightness in different fields agree with each other within the error bars, at both 65 and 90-\textmu m including the systematic uncertainty of the H\textsubscript{i} column density.

The ratio of the H\textsubscript{i} column density to the far-infrared brightness assumed above may be an overestimate, because it tends to be determined by the data in the brighter cirrus regions. In low cirrus regions, the ratio could be smaller due to the contribution of uncorrelated components, such as dust associated with ionized gas. In fact, the mean residuals for the three fields in Table 3 are slightly smaller than the results in Table 2 from the correlation of the ADF-S and SFD maps, though they are consistent with each other within the total error, including the calibration error. The contribution of cirrus emission can be more accurately estimated in the LW bands, where cirrus emission is brighter. However, we did not make the same analysis as we did for the SW bands, because accurate measurement of the CIB is possible only in ADF-S, which has highly statistical samples.

### 6.1.3. Comparison with Previous Observations

As seen in Figure 13, our results in the four photometric bands are in agreement with previous CIB measurements from COBE/DIRBE at 60, 100, and 140-\textmu m (Hauser et al. 1998; Wright 2004; Odegard et al. 2007) within their measurement accuracies. They are also consistent with an upper limit from IRAS at 60-\textmu m (Miville-Deschênes et al. 2002) as well as an upper limit at 90-\textmu m and the measured CIB level in the 150–180-\textmu m range measured by ISO (Juvela et al. 2009).

The integrated galaxy counts (Dole et al. 2004; Matsuura et al. 2007; Shirahata et al. 2008) account for only a few
percentage points of the CIB brightness. A stacking analysis of the \textit{Spitzer} 24-\textmu m sources (Dole et al. 2006) substantially extended the lower limits at 70 and 160\textmu m from the prediction of the galaxy evolution model presented in Lagache et al. (2004). Our measured CIB brightness at 90\textmu m is obviously higher than the \textit{Spitzer} result, and our result implies the existence of many unknown sources, which may have been missed in the stacking process since they were too faint to be detected at 24\textmu m with \textit{Spitzer}.

A hypothetical source with such an excessive brightness should have peculiar spectra, with a peak around 100\textmu m, that make only a small contribution to the CIB in the other wave bands. High levels of the CIB at 100\textmu m already have been seen with \textit{COBE} (Hauser et al. 1998; Finkbeiner et al. 2000) but have been thought to be due to calibration errors and foreground uncertainties (Dole et al. 2006). The 140- and 240-\textmu m bands of the DIRBE instrument on board \textit{COBE} can be cross-calibrated with the FIRAS instrument, and the DIRBE result of the CIB brightness is reduced to 0.6 times if the DIRBE data are transformed to the FIRAS photometric system and corrected for the zero-point difference (Hauser et al. 1998; Odegard et al. 2007). It is remarkable that this work corroborates the uncorrected DIRBE result using a different instrument.

6.1.4. Possible Origins of the Excess Emission

If the excess emission at 90\textmu m originates from an isotropic component of the Galactic cirrus emission, which may not be accounted for in the SFD map, it should be tightly constrained by the previously measured H\textsc{i} column density, unless the gas-to-dust ratio is extraordinary. If the excess brightness at 90\textmu m of \sim 0.4 MJy sr\textsuperscript{-1} is associated with neutral hydrogen, the corresponding H\textsc{i} column density must be \(N_{\text{H}} = 1 \times 10^{20} \text{cm}^{-2}\). This is much higher than the measured H\textsc{i} column density toward ADF-S (see Table 3) and also unlikely, judging from the uncertainty of the H\textsc{i} observation. Moreover, if the temperature of such an isotropic dust emission is \sim 17 K, similar to the bulk of the Galactic cirrus emission, the emission should appear at longer wavelengths as a strong excess, but this result is not significant in our data. Therefore, it is difficult to explain the excess brightness by dust emission associated with neutral hydrogen.

Unexpectedly large amounts of ionized gas at high Galactic latitudes in the form of a warm ionized medium (WIM) comprise another possible candidate for the excess emission. In fact, dust emission from a WIM was detected by the WHAM H\textsc{a} survey, though the observed areas were limited to relatively dense regions at low Galactic latitudes (Lagache et al. 2000). The DIRBE results at high Galactic latitude regions show that the WIM component contributes little to the total dust emission and does not change much of the residual CIB brightness (Arendt et al. 1998; Odegard et al. 2007), though the far-infrared emissivity per H\textsuperscript{+} atom shows very large field variance.

Large differences in the residual brightnesses of different fields listed in Table 3 may be caused by the contribution of dust associated with a WIM. In fact, ADF-S is darker than the LH in the far infrared, while the H\textsc{i} column density toward ADF-S is higher than that toward the LH. However, any WIM could be dust-poor compared to the Galactic plane, because grain destruction is expected to occur in low-density regions of the interstellar medium, while the ionized hydrogen column density, in order to account for all excess brightness, must be higher than that of neutral hydrogen. Just as for neutral hydrogen, the dust temperature must be high enough to have an emission peak around 100\textmu m while not producing a significant excess at longer wavelengths, but the existence of such hot dust at high Galactic latitudes has not been reported. Future measurements of the H\textsc{a} emission and other interstellar lines in ADF-S would give a firm limit of the WIM’s contribution to the excess.

Star-forming galaxies at high redshift are another possible cause of the CIB excess in the far infrared. In Table 2, the measured CIB brightness is compared with the range predicted from a selection of galaxy evolution models that take the contribution of a population of luminous infrared galaxies peaking at \(z \sim 1\) and ultra-luminous infrared galaxies (ULIRGs) peaking at \(z > 2\) into consideration (Lagache et al. 2004; Pearson et al. 2007; Franceschini et al. 2008; Takeuchi & Ishii 2010). Most of these galaxy evolution models give a lower brightness than our measured CIB at 65 and 90\textmu m, but the models agree with our results at 140 and 160\textmu m, the stacking analysis of \textit{Spitzer} data at 70 and 160\textmu m, and the \textit{COBE} results at wavelengths other than 100\textmu m, within the data uncertainties. A model prediction from Takeuchi & Ishii (2010) in Figure 13 shows a fairly good agreement with the measured CIB at wavelengths shorter than 140\textmu m, but it gives too high a brightness at longer wavelengths, especially in the submillimeter range (Puget et al. 1996; Fixsen et al. 1998). It is obvious that our results, especially at 90\textmu m, provide a tight constraint on galaxy evolution models.

In contrast to the CIB measurement, the source counts at 90\textmu m with \textit{AKARI} are much lower than those predicted by contemporary galaxy evolution models, while the galaxy counts at 65 and 140\textmu m are consistent with the models and the \textit{Spitzer} results at 70 and 160\textmu m (Matsuura et al. 2007; Shirahata et al. 2008). Such low counts at 90\textmu m have also been found by \textit{ISO} (Rodighiero et al. 2003; Héraudeau et al. 2004), and it has been reported that many galaxy evolution models fail to reproduce the 90-\textmu m counts (Chary & Elbaz 2001; Serjeant et al. 2004). At 90\textmu m, the integrated galaxy counts down to the detection limit of \textit{AKARI}, \sim 20 mJy, can only account for less than 10% of the CIB brightness (Matsuura et al. 2007). To reproduce the CIB brightness, a strong increase in the galaxy counts below the detection limit is necessary. If we assume a single power law with a power index of \sim −1.5 (Euclidian) for the cumulative galaxy counts, \(dn/dS \sim S^{−1.5}\), the power law needs to extend to 0.01 mJy. Such high counts require an extraordinary evolution scenario because conventional galaxy evolution models predict a steep drop in differential 90-\textmu m counts toward the faint end below 1 mJy.

Recently, Berta et al. (2010) reported the result of far-infrared deep surveys to resolve the CIB with \textit{Herschel}/PACS (the PEP survey); they claimed that about half the CIB at 100 and 160\textmu m was resolved into point sources by integrating the source counts down to 3 mJy, and that the fraction increased to more than half by stacking the 24-\textmu m sources. Altieri et al. (2010) obtained source counts much deeper levels, \sim 1 mJy at 100\textmu m, toward the cluster lens Abell 2218, but the resolved CIB fraction remained similar to that of the PEP survey. Therefore, a much deeper far-infrared survey is still required to resolve the CIB excess.

To explain the previous \textit{COBE} result of high CIB levels at 60 and 100\textmu m, the possible contribution of a new population at high redshift \((z = 2-3)\), with high dust temperatures \(T_d \sim 60\text{ K}\) heated by AGNs, or accretion onto a black hole has already been discussed (Finkbeiner et al. 2000; Blain & Phillips 2002; Blain et al. 2004). If this is true, our finding of the CIB excess at 90\textmu m could also be explained by such high-\(z\) hot
suggest that LIRGs and ULIRGs at $z \sim 1$, rather than AGNs at high redshift, constitute the main bulk of the CIB, and the contribution of AGNs to the CIB is thought to be at most 10% (Treister et al. 2006; Devlin et al. 2009). Therefore, the CIB excess is more likely to be composed of high-$z$ hot sources of new galaxy populations than known, obscured AGNs, which can be detected at 24 $\mu$m. If the hot source is so heavily obscured that dust extinction is strong even in the mid-infrared, and if the dust grains are so small that the emissivity index is at a maximum, $\lambda^{-2}$, at longer wavelengths, then they can contribute to the CIB selectively at short far-infrared wavelengths.

Another possibility to explain our finding that the CIB at 90 $\mu$m is very smooth is the contribution of unknown diffuse emission, such as radiative decay of relic particles of the early universe, e.g., the cosmic neutrino background or dark matter particles (Bond et al. 1986; Ressell & Turner 1990). If the particle decay time is longer than the age of the universe, the decay photon-energy spectrum can have a clear SW cutoff, which may result in a spectral peak in the CIB at the decay energy.

6.1.5. Energetics and Cosmological Implications

The total integrated energy of the CIB excess in the AKARI bands is estimated to be $\sim 10$ nW$m^{-2}$ sr$^{-1}$, which is comparable to the CIB energy associated with the 24-$\mu$m galaxies of 24 nW$m^{-2}$ sr$^{-1}$ (Dole et al. 2006). If we assume a constant star formation rate (SFR) over cosmic history of $z > 1$, the excess energy corresponds to the SFR of $0.1 M_\odot$ yr$^{-1}$ Mpc$^{-3}$, which is an order of magnitude higher than that in the local universe (Hauser & Dwek 2001). If the radiation energy is produced by a starburst at $z$, the total hydrogen mass fraction converted to metals in this epoch is estimated to be $\Delta X \sim 0.004(1 + z)$. For a redshift of $z > 1$, more than 1% of the baryon mass density need to be converted to metals. A starburst at high $z$ values as the origin of the CIB excess may cause overproduction of metals beyond the metal abundance in the local universe. Black hole accretion may play an important role in generating background radiation at high redshift (Finkbeiner et al. 2000).

In the near infrared, the CIB excess that cannot be explained by the integrated flux of known galaxy populations has been reported, and the origin of the excess has been posited as first stars, or proto-galaxies, at $z \sim 10$ and discussed in terms of the spectral signature of the redshifted Ly-\alpha in the CIB near 1 $\mu$m, as seen in Figure 1 (Kashlinsky 2005; Matsumoto et al. 2005). Findings of the CIB excess in both the near and far infrared lead us to consider the connection; the UV light from the first massive stars, which produce the near-infrared excess, might be partly absorbed by the self-produced dust, re-emitted in the mid-infrared, and redshifted into the far-infrared band at present. Accretion to the first black hole as a remnant of the first star explosion might also be the hot source at high redshift. Dust production by the first stars and successive black hole formation and accretion are little understood, and this research would be furthered by future observations of infrared galaxies and many details of the CIB.

6.2. Fluctuations of the CIB

6.2.1. The Galactic Cirrus

In order to obtain information on the CIB fluctuations from the measured power spectrum, it is necessary to estimate the fluctuation power of the foreground, such as zodiacal emission and the Galactic cirrus. Zodiacal emission, the most dominant foreground component, has been known to have a very smooth distribution, and its fluctuations in the mid-infrared have been measured with ISO to be smaller than 1% of the mean brightness at angular scales of 1 arcmin (Abraham et al. 1998). This value is already much smaller than the shot noise level in unresolved galaxies. Although an unexpected time-varying residual of zodiacal emission, after zodi-model subtraction, may contribute to the power spectrum over a broad range of angular scales, it has already been subtracted as part of the noise power estimated from the difference of the two sub-maps, as described in the last section. Thus, the main foreground is the Galactic cirrus, especially at large angular scales.

A $k^3$ power law of the fluctuation spectrum of the Galactic cirrus has been reported by many authors, e.g., Miville-Deschênes et al. (2007), but it is remarkable that this work confirmed the same power law at very low flux levels at 90 $\mu$m. The power spectrum of the cirrus fluctuations can be expressed as

$$P_{\text{cirrus}}(k) = P_0(k/k_0)^{-\gamma},$$

where $k$ is the wavenumber in arcmin$^{-1}$ and $P_0$ is the power normalized at $k_0 = 0.01$ arcmin$^{-1}$, $\gamma$ is the power-law index, ranging from 2.5 to 3.1, and is known to be close to 3 for the optically thin case at low cirrus regions (Schlegel et al. 1998; Jeong et al. 2005; Miville-Deschênes et al. 2007). As shown in Table 4, our result gives a cirrus power at 90 $\mu$m of $P_0 = (5.5 \pm 0.5) \times 10^4$ Jy$^2$ sr$^{-1}$, and the power at 100 $\mu$m is derived to be $P_0 = (1.1 \pm 0.1) \times 10^5$ Jy$^2$ sr$^{-1}$ from the correlation coefficient between the ADF-S and SFD maps.

At high values of $k$, the power-law index may not always be the same as the value derived at low $k$, where the cirrus component dominates the total fluctuation power. In previous work with the ISO observations, it has been proved that a single power law for the cirrus power spectrum is valid up to $k \sim 0.3$ arcmin$^{-1}$, though this result is certain only in relatively bright regions. Since there is no strong reason to change the power-law index at higher $k$, we assume a single power law over the entire wavenumber range to estimate the cirrus power.

It has been reported that the fluctuation power of the cirrus emission scales with the mean brightness as a power law, with an index of 2–3 depending on the brightness. According to Miville-Deschênes et al. (2007), the cirrus fluctuation power at 100 $\mu$m in the low-brightness regime ($B < 10$ MJy sr$^{-1}$) is given by

$$P_0 = 2.7 \times 10^6 B^{1.9} \text{Jy}^2 \text{sr}^{-1},$$

Table: Small-scale Fluctuations of Foregrounds and the CIB

| Zodiacal | Cirrus | CIB $P_{\text{shot}}$ | Models | ISO |
|----------|--------|----------------------|--------|-----|
| $<0.6 \times 10^2$ | $<0.1 \times 10^2$ | $3.6 \pm 0.2 \times 10^5$ | $(1.1-7.2) \times 10^5$ | $2 \times 10^5$ |

Notes.

a) Power spectral density at 90 $\mu$m in Jy$^2$ sr$^{-1}$.

b) $<1\%$ of the mean brightness at an angular scale of 1 arcmin (Abraham et al. 1998).

c) Cirrus fluctuation power at $k > 0.2$ arcmin$^{-1}$ estimated from the measured $P_0$.

d) The mean shot noise level from $k = 0.2-0.8$ arcmin$^{-1}$ after point-source removal.

e) The galaxy evolution models of Lagache et al. (2004), Jeong et al. (2006), Pearson et al. (2007), Franceschini et al. (2008), and Takeuchi & Ishii (2010).

ISO result at 90 $\mu$m after removing galaxies brighter than 30 mJy (Matsuura et al. 2000).
where $B$ is the mean brightness at 100 $\mu$m. If this is the case, our measured power of the cirrus fluctuations corresponds to the mean brightness of 0.14 MJy sr$^{-1}$ at 90 $\mu$m, which is slightly lower than the value in Table 2. The relation between the fluctuation power and the mean brightness may not be valid under such low cirrus conditions. The result implies that it is dangerous to estimate the mean CIB brightness from the fluctuation power.

### 6.2.2. Shot Noise of Unresolved Galaxies

We have derived the shot noise of unresolved galaxies, from the source-removed power spectrum in Figure 12, as the mean power level over a range of 0.2–0.8 arcmin$^{-1}$, where the PSF is relatively accurate, to be $P_{\text{shot}} = (3.6 \pm 0.2) \times 10^{-2}$ Jy$^2$ sr$^{-1}$ at 90 $\mu$m. In Table 4, we summarize our results for the foreground estimates at small angular scales, where the shot noise dominates. The fluctuations of zodiacal emission were estimated to be negligible, as discussed in the last section. The cirrus component following a $k^3$ power law is negligible at such small angular scales ($k > 0.2$ arcmin$^{-1}$). Therefore, the remaining shot noise can be attributed to the fluctuations from unresolved galaxies.

In Table 4, we compare our results with the previous work at 90 $\mu$m using ISO-PHOT (Matsuhara et al. 2000) and with a range of shot noise levels predicted by various galaxy evolution models. Since the detection limit of AKARI for point sources is better than that of ISO, the AKARI result shows lower fluctuation power than the ISO result. We estimated the shot noise level for each galaxy evolution model by simply integrating the squared flux, $S^2$, with the differential source counts, $dN/dS$, as

$$P_{\text{shot}} = \int S^2(dN/dS)dS,$$  \hspace{1cm} (5)

for fluxes below 20 mJy. The measured shot noise power is three to five times lower than any other model predictions, which is clearly due to the high source counts of the models near the detection limit. The result implies that the main bulk of the CIB at 90 $\mu$m consists of sources much fainter than the detection limit.

Since the shot noise is the squared flux integrated with the source counts, it is more sensitive to the number density of bright sources than the mean CIB level, which is a linear integration of the flux. As described in the last section, the mean CIB level provides constraints on the source counts at the very faint end below the point-source detection limit. In contrast, shot noise can provide constraints on the source counts near the detection limit.

The measured shot noise level can be reproduced by measured source counts that are extended down to 1 mJy with a Euclidian power law (a constant for the differential counts). In such a simple scenario, sources fainter than 1 mJy have little contribution to the fluctuations but become the main contributor to mean brightness. To resolve the bulk of the CIB into point sources, future infrared telescopes with detection limits much better than 1 mJy at ~100 $\mu$m will be required.

### 6.2.3. Cosmic Variance

Since ADF-S covers a large contiguous area of 12 deg$^2$, the field contains various regions of different sources and cirrus densities. The power spectrum shown in Figure 12 gives the average properties of the entire field, but it can be biased by strong features of specific regions on the map.

To check for cosmic variance, we carried out power spectrum analyses for sub-maps with an area of 1 x 1 deg$^2$ cut from various positions, as shown in Figure 14. The first is the central region, with the minimum cirrus level and source densities; the second region contains the rich cluster of galaxies called DC 0428-53 (Abell S0463) (Dressler 1980); and the third is a relatively high cirrus region with a moderate source density. As shown in Figure 15, the power spectrum obtained from the cluster region is about an order of magnitude higher than the others. The central region shows the minimum fluctuation power, as expected, and the high-cirrus region has slightly higher power than the central region, though the point source contribution seems to be more prominent than the cirrus fluctuations. This result implies that the power spectrum is severely affected by the point source contribution and biased by high source-density regions.

To estimate the effect of point sources on the power spectrum in detail, we made the same comparison of the three sub-maps after removing point sources. The result is shown in Figure 16. All power spectra at different sky positions show excellent agreement with each other, at an accuracy better than 5% in the overall range of the wavenumber. This result implies that the power spectrum that resulted after removing point sources is not affected by cosmic variance, such as the clustering of nearby galaxies, and can be regarded as a universal function of the CIB fluctuations.
and directly derived the bias factor for structure formation in a
power spectra for the sub-maps (same as Figure 15) after point-
Figure 16.

Figure 15. Power spectra of the three maps in Figure 14. Circles, triangles, and
diamonds represent data points for the central region, the cluster of galaxies, and
the high-cirrus region, respectively. These power spectra are raw data without
noise subtraction or PSF correction.

Figure 16. Power spectra for the sub-maps (same as Figure 15) after point-
source removal.

6.2.4. Limits on the Galaxy Clustering Component

In the measured power spectrum in Figure 12, a small hump of $\sim 10^3 \text{ Jy}^2 \text{ sr}^{-1}$ is seen in intermediate range of
0.03–0.1 arcmin$^{-1}$, and its $k$-dependence seems to be less
steep than the $k^3$ power law of the Galactic cirrus. A possible
interpretation of such an excess fluctuation at an intermediate
angular scale is the clustering of star-forming galaxies, e.g.,
Perrotta et al. (2003). Lagache et al. (2007) reported finding
galaxy clustering in the power spectrum at 160 $\mu$m with Spitzer
after removing point sources brighter than 200 mJy. In Figure 17,
we plot the Spitzer result from Lagache et al. (2007), multiplied
by a scaling factor of 0.01, with our power spectrum. They
claimed their power spectrum shows an excess component in
the range of $k \sim 0.03–0.1$ arcmin$^{-1}$ and a dip around $k \sim 0.02$ arcmin$^{-1}$, which may show an oscillatory
structure of matter distribution. Such concordance between
the results of two independent observations with different
instruments and in different fields leads us to conclude that the
fluctuations in both the AKARI and Spitzer power spectra
have the same origin.

It has been reported that galaxy clustering was clearly found
by the BLAST experiment in the submillimeter range (Viero
et al. 2009). Since the BLAST bands are on the Rayleigh–Jeans
side of the dust emission in the rest-frame galaxy, BLAST bands
can be more sensitive to high-redshift galaxies than those of
AKARI and Spitzer, with less contamination by the Galactic
cirrus. The power spectrum analysis for the BLAST map with
an area of 6 deg$^2$ found a strong signature of galaxy clustering,
with the power spectrum showing a $k^2$ power law over the
range of $k \sim 0.03–0.1$ arcmin$^{-1}$ in all BLAST bands. Their
power spectra show a very similar shape to those measured
by AKARI and Spitzer even though the limiting fluxes for the
source removal for these three missions are different—AKARI:
$\sim 20$ mJy, Spitzer : $\sim 200$ mJy, and BLAST: $\sim 500$ mJy.

To test if the hump structure seen in the AKARI power
spectrum could be real and to compare the AKARI data with the
results of other missions regarding the galaxy clustering
component using the same method, we made a model fit to our
power spectrum using a $k^2$ power law for galaxy clustering, in
addition to shot noise and cirrus fluctuations, i.e.,

$$P_2(k) = P_{\text{cirrus}} + P_{\text{shot}} + P_{\text{cluster}}$$

and

$$P_{\text{cluster}} = P_c (k/k_c)^{-2},$$

where $k_c = 0.03$ arcmin$^{-1}$. However, such a simple model cannot
reproduce the complex structure seen in the measured spectrum.
For the case shown by the thin solid line in Figure 17, we
obtained the best-fit parameters: $P_{\text{cirrus}}(0.01) = (5.0 \pm 0.4) \times$
$10^4 \text{ Jy}^2 \text{ sr}^{-1}$ for $\gamma = 3.0 \pm 0.1$, $P_{\text{shot}} = (3.7 \pm 0.01) \times$
The upper limit obtained by assuming there is no cirrus contribution to the measured power spectrum at $k = 0.03 \text{ arcmin}^{-1}$, as described in the last section. The upper limits on the CIB fluctuations at $k \sim 0.02 \text{ arcmin}^{-1}$ from the DIRBE analysis (Kashlinsky & Odenwald 2000) are also indicated. For comparison, the measured mean CIB levels and the model CIB by Lagache et al. (2004) are also shown in Figure 18.

If the CIB fluctuations measured by AKARI, Spitzer, and BLAST originate from the same underlying galaxies, the combined spectrum should be comparable to the SED of the most dominant galaxy population. In Figure 18, we compare the combined spectrum of the measured CIB fluctuations with the SED of Arp220 from Klaas et al. (2001), which is redshifted at $z = 2$ and vertically scaled to fit the CIB fluctuation data for shot noise (upper) and galaxy clustering (lower).

Figure 18. SED of the CIB fluctuations measured with AKARI at 90 $\mu$m, Spitzer at 160 $\mu$m (Lagache et al. 2007); and BLAST at 250, 350, and 500 $\mu$m (Viero et al. 2009) for shot noise levels at $k = 0.33 \text{ arcmin}^{-1}$ (filled triangles) and galaxy clustering at $k = 0.03 \text{ arcmin}^{-1}$ (open triangles). Note that the AKARI data point for the clustering component is the upper limit (see the text). The upper limits from the DIRBE analysis (Kashlinsky & Odenwald 2000) are also indicated by horizontal bars with arrows. The fluctuation power is converted to a linear brightness scale as the fluctuation amplitude, $\delta I(k) = \sqrt{2k^2 P(k)}$. The fluctuations are compared with the absolute CIB levels, $I_\nu$, the same as Figure 13; AKARI (filled circles); COBE/DIRBE (open diamonds, filled diamonds, and filled squares); Spitzer; and BLAST (open circles). The model CIB by Lagache et al. (2004) is also displayed (dotted line) as a reference SED of the CIB composed of 24-$\mu$m sources, which are stacked with the Spitzer and BLAST data to obtain the mean CIB levels. The dashed lines with data points (filled squares and open squares) are SEDs of Arp220 from Klaas et al. (2001), which are redshifted at $z = 2$ and vertically scaled to fit the CIB fluctuation data for shot noise (upper) and galaxy clustering (lower).

It is notable that the CIB distribution at 90 $\mu$m, after removing the point sources to a faint flux level, is unexpectedly smooth. It is also noteworthy that the AKARI data are of high enough quality to detect such very low fluctuation levels.

6.2.5. SED of the CIB Fluctuations

A study of the SED of the CIB fluctuations should give constraints on the redshift distribution and SED of the underlying galaxies and provide important information on their origins. Figure 18 summarizes the CIB fluctuations measured with AKARI, Spitzer (Lagache et al. 2007), and BLAST (Viero et al. 2009) for shot noise levels at $k = 0.33 \text{ arcmin}^{-1}$ and galaxy clustering at $k = 0.03 \text{ arcmin}^{-1}$, with the fluctuation amplitude $\delta I_\nu$. The AKARI data point for the clustering component is the upper limit obtained by assuming there is no cirrus contribution to the measured power spectrum at $k = 0.03 \text{ arcmin}^{-1}$, as described in the last section. The upper limits on the CIB fluctuations at $k \sim 0.02 \text{ arcmin}^{-1}$ from the DIRBE analysis (Kashlinsky & Odenwald 2000) are also indicated. For comparison, the measured mean CIB levels and the model CIB by Lagache et al. (2004) are also shown in Figure 18.

If the CIB fluctuations measured by AKARI, Spitzer, and BLAST originate from the same underlying galaxies, the combined spectrum should be comparable to the SED of the most dominant galaxy population. In Figure 18, we compare the combined spectrum of the measured CIB fluctuations with the SED of Arp220 taken from Klaas et al. (2001), which is redshifted to $z = 2$ and scaled to fit the data. Although there is a non-negligible discrepancy between the two spectra, the overall colors are very similar. Therefore, the fluctuating component is likely to be formed by such red galaxies at redshifts of $z > 1$, which are all resolved at 24-$\mu$m and account for $\sim 100\%$ of the CIB in the submillimeter range (Devlin et al. 2009; Pascale et al. 2009; Viero et al. 2009). This result is consistent in that the color of the CIB fluctuations is very similar to the color of the mean CIB flux in the Spitzer 160-$\mu$m band and the BLAST bands, and it is also consistent with the mean CIB levels in those bands, which agree well with the model CIB for the selected 24-$\mu$m galaxies.

A remarkable result on the SED of the CIB fluctuations is that the relative fluctuation amplitude at 90 $\mu$m, $\delta I_\nu / \langle I \rangle$, is quite small compared with those at other wavelengths. This is caused...
by both the very red color of the CIB fluctuations and the high CIB level at 90 μm, which is exceeds the integrated flux of the selected 24-μm galaxies and can account for the mean CIB levels at longer wavelengths. According to this result, the CIB should have a spectrum peaking around 90 μm if it does not contribute much at 160 μm and cannot be detected at 24 μm. The underlying galaxies building the CIB should also be individually faint and numerous to keep the mean CIB levels high while keeping the CIB fluctuations low.

Although hot high-z sources with far-infrared luminosities on the order of \(10^3 \, L_{\odot}\), discussed in Blain et al. (2004), can considerably contribute to the CIB at 90 μm, such very luminous and less numerous galaxies would largely contribute to the CIB fluctuations rather than the mean CIB flux. According to the measured CIB properties as discussed above, the bulk of the CIB may consist of hot high-z sources of lower luminosity but higher surface density. A simple way of reducing the CIB fluctuations without an SED change is to assume higher redshifts and higher temperatures by keeping \(T_d/(1 + z)\) a constant, and this could be the case of our result.

As described in the previous section, a more exotic source than galaxies, such as the radiative decay of the relic particles of the early universe, may also contribute to the CIB. To obtain a definite conclusion to the origin of the CIB excess in the AKARI band, further investigation is required. To prove the hot high-z source and/or decaying particle hypothesis, large-aperture space telescope missions, such as SPICA (Nakagawa 2008), are required to resolve the far-infrared CIB into point sources at very low flux levels (below 0.1 mJy; Swinyard & Nakagawa 2009). Spectral measurement of the continuous SED of the CIB over a wide infrared range would also be a powerful discriminator of the origin. Such observations can be simply made with a small-aperture telescope on a small satellite or sub-orbital missions, such as rocket experiments. Future space missions to obtain a direct measurement of the mid-infrared CIB while mitigating the contamination by zodiacal emission require out-of-ecliptic missions or deep space missions beyond the asteroid belt (as the source of zodiacal dust), which will be powerful enough to probe into the underlying galaxies or particles that compose the CIB excess (Matsuura 2002).

7. CONCLUSIONS

As a result of a cosmological survey in ADF-S, we successfully measured the absolute sky brightness in the four photometric bands of AKARI: 65, 90, 140, and 160 μm. AKARI’s high sensitivity to diffuse emission, field selection to minimize the foreground, and careful foreground estimates enabled us to detect the CIB as an isotropic emission component. The high angular resolution of AKARI was also essential for removing the foreground galaxies as point sources.

The measured CIB brightness in all AKARI bands is consistent with the previous COBE/DIRBE results, and the 90-μm brightness is higher than a simple interpolation from the Spitzer results at 70 and 160 μm obtained by a stacking analysis of selected 24-μm sources. The result suggests the existence of new populations with high-temperature spectra in addition to the previously explored infrared galaxy population. Using a power spectrum analysis of the 90-μm map after removing the point sources down to ~ 20 mJy, we found the shot noise component resulting from the underlying galaxies. We also obtained a firm upper limit of the fluctuation amplitude of galaxy clustering, which was found at longer wavelengths with Spitzer and BLAST. The SED of the CIB fluctuations obtained by combining the AKARI, Spitzer, and BLAST results is as red as that of ULIRGs at high redshifts, and the main bulk of the CIB may be composed of another galaxy population that contributes little to the fluctuations, and/or an unknown diffuse source.

Our results provide new information on the properties of infrared galaxies and also a constraint on radiative decay of the relic particles in the far-infrared energy range. To obtain a definite conclusion about the origin of the CIB, further investigation is required, e.g., a detailed study of the SEDs of infrared galaxies and a cross-correlation study with multi-band images. Resolving the excess brightness into point sources and measuring the CIB spectrum continuously over a wide range should be the main target of ongoing and future infrared missions: Herschel, SPICA, and other satellites; deep space missions; and sub-orbital programs.

We thank L. Levenson for his help with calculating the zodiacal foreground in the far infrared, based on the model in Wright (1998). A.P. has been supported by the research grant of the Polish Ministry of Science Nr N N203 51 29 38. This research is based on observations with AKARI, a JAXA project with the participation of ESA. This work was supported by KAKENHI (19540250 and 21111004).

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