BRIGHTNESS AND FLUCTUATION OF THE MID-INFRARED SKY FROM AKARI OBSERVATIONS TOWARD THE NORTH ECLIPTIC POLE

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ABSTRACT

We present the smoothness of the mid-infrared sky from observations by the Japanese infrared astronomical satellite AKARI. AKARI monitored the north ecliptic pole (NEP) during its cold phase with nine wave bands covering from 2.4 to 24 μm, out of which six mid-infrared bands were used in this study. We applied power-spectrum analysis to the images in order to search for the fluctuation of the sky brightness. Observed fluctuation is explained by fluctuation of photon noise, shot noise of faint sources, and Galactic cirrus. The fluctuations at a few arcminutes scales at short mid-infrared wavelengths (7, 9, and 11 μm) are largely caused by the diffuse Galactic light of the interstellar dust cirrus. At long mid-infrared wavelengths (15, 18, and 24 μm), photon noise is the dominant source of fluctuation over the scale from arcseconds to a few arcminutes. The residual fluctuation amplitude at 200″ after removing these contributions is at most 1.04 ± 0.23 nW m⁻² sr⁻¹ or 0.05% of the brightness at 24 μm and at least 0.47 ± 0.14 nW m⁻² sr⁻¹ or 0.02% at 18 μm. We conclude that the upper limit of the fluctuation in the zodiacal light toward the NEP is 0.03% of the sky brightness, taking 2σ error into account.

Key word: infrared; diffuse background

Online-only material: color figures

1. INTRODUCTION

Fluctuation in infrared sky brightness has been measured for various purposes depending on the wavelength regime. In the near-infrared, researchers have tried to discriminate the fluctuation by the cosmic near-infrared background (CNIRB) from those by other foreground sources. The CNIRB is the unresolved light from extragalactic sources including the radiation from first (Population III) stars, which reionized the universe (Santos et al. 2002). Recently, Matsumoto et al. (2011) found excess fluctuation on scales larger than ~100″ from the AKARI north ecliptic pole (NEP) survey at 2.4, 3.2, and 4.1 μm and interpreted it as CNIRB fluctuation. Their results are consistent with independent fluctuation measurements from Spitzer observations (Kashlinsky et al. 2005, 2007). In the far-infrared, the Galactic cirrus of interstellar dust is a prominent source of diffuse brightness and fluctuation. Far-infrared fluctuation measurements are used for studies of not only the Galactic cirrus but also the clustering of unresolved, high-redshift objects. The fluctuation by the cosmic far-infrared background has also been reported by several researchers (see Jeong et al. 2007; Matsuura et al. 2011, and references therein).

The zodiacal light (ZL) is a conspicuous probable source of infrared fluctuation because it dominates the sky brightness over a wide wavelength range of the infrared (Leinert et al. 1998). Ábrahám et al. (1997) analyzed five 0.5 × 0.5 images from 25 μm observations from the Infrared Space Observatory (ISO) and concluded that the upper limit of the ZL fluctuation is 0.2% of brightness, which corresponds to ~5 nW m⁻² sr⁻¹ toward the NEP. However, the ISO observation had a sparse resolution of 3′ and the 0.2% fluctuation is apparently too large when compared with modern CNIRB fluctuation measurements.

In this paper, we make use of the AKARI’s NEP Monitor Observations in six mid-infrared wave bands to measure the fluctuations in the sky brightness. We will concentrate on searching for residual fluctuation at around 200″ scale after eliminating the contributions from known fluctuation sources. Section 2 introduces the details of the observations and the image reduction and calibration processes. In Section 3, we attempt sinusoidal fits to the seasonal variation of the sky brightness, derived from the ZL. Section 4 shows the results from the fluctuation analysis and Section 5 discusses them. We summarize the paper in Section 6.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Monitor Observations

AKARI rotates around the Earth along a Sun-synchronous polar orbit of an altitude of 700 km (Murakami et al. 2007). Owing to frequent opportunities to observe the NEP over the whole mission period, it observed regions close to the NEP twice a month in order to check the detectors’ stability (Tanabé et al. 2008) and to study the CNIRB (Matsumoto et al. 2011). The Monitor Observations lasted from 2006 June to 2007 August. Because AKARI suffered from the impact of scattered Earth-shine during the northern hemisphere’s summer season (Verdugo et al. 2007; Pyo et al. 2010) we excluded the observations in that period. Table 2 lists the pointed
Figure 1. Monitor Fields in the ecliptic coordinates. The blue boxes with light borders (colored blue) are the fields observed by the MIR-S channels, while red ones with dark borders are the fields observed by the MIR-L. The uppermost red box corresponds to the MIR-L field of observation ID 5121014-001, and the ID increases in the clockwise direction (ref. Table 2). The background image is from the Improved Reprocessing of the IRAS Survey (IRIS; Miville-Deschênes & Lagache 2005) Atlas at 12 μm retrieved from the NASA/IPAC Infrared Science Archive. The center of the image is at the NEP, close to which the planetary nebula NGC 6543 is apparent.

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

Table 1

| IRC Mid-infrared Channels and Photometric Bands |
|-----------------------------------------------|
| Channel | MIR-S | MIR-L |
|---------|-------|-------|
| Band    | S7    | S9W   | S11   | L15   | L18W  | L24   |
| Wavelength (μm) | 7     | 9     | 11    | 15    | 18    | 24    |
| Bandwidth (μm)   | 1.75  | 4.10  | 4.12  | 5.98  | 9.97  | 5.34  |
| Pixel scaleb     | 2.54 x 2.34 | 2.51 x 2.39 |
| Field of viewa   | 9.1″ x 10.0″ | 10.3″ x 9.5″ |
| fdiffuseb (nW m⁻² sr⁻¹ ADU⁻¹) | 2.93  | 1.32  | 1.39  | 1.80  | 1.05  | 2.44  |
| fdiffuse/fpointc | 0.86  | 0.89  | 0.85  | 0.75  | 0.78  | 0.56  |
| 5σ detection limitd (μJy) | 47    | 46    | 64    | 105   | 91    | 173   |

Notes.

a Cross-scan × in-scan.
b Diffuse source calibration factor.
c Ratio of the diffuse source calibration factor to the point source. fpoint is taken from the third column of Table 4.6.7 in Lorente et al. (2008).
d Five times the standard deviation after the 3σ-clipping.

The observation data were reduced with the AKARI IRC Image Data Reduction Pipeline6 (version 20091022). To correct the dark currents in the exposure frames, the reduction pipeline by default subtracts the super-dark frames generated from the dark-current measurements in the Large Magellanic Cloud observations (Lorente et al. 2008). For our analysis, we modified the pipeline and subtracted the dark frame taken just before exposures in each pointed observation, the so-called self-dark. This modification mitigated the effect of the dark-current variation over long term in the exposure frames (Lorente et al. 2008).

AKARI provides IRC observers with five observation modes, the so-called Astronomical Observation Templates (AOTs). We selected AOT IRC03, which enabled us to obtain images in nine bands with a single pointed observation including the near-infrared channel. The near-infrared images simultaneously taken with MIR-S and MIR-L were separately studied by Matsumoto et al. (2011). In the IRC03 template, we have two or three exposures for each mid-infrared band, each of which consisted of one short-exposure (0.5844 s) and three long-exposure (LE; 16.3632 s) frames (Onaka et al. 2007; see Figure 2). We excluded short-exposure frames due to their low signal-to-noise ratio. On the other hand, the LE frames suffered from after-effects. The second and third LE frames show systematically

5 The observation data are available on the AKARI homepage (http://darts.isas.jaxa.jp/astro/akari) of the ISAS/JAXA Data Archives and Transmission System (DARTS) by querying with the observation IDs.

6 Available in the AKARI Observers Page (http://www.ir.isas.jaxa.jp/ASTRO-F/Observation/).
larger electron counts than the first (LE1) does, and are ignored. For the MIR-S bands, the LE1 frames in later exposures are also ignored, because they are systematically brighter than the one in the first exposure. In the case of the MIR-L bands, the situation is more complicated. The L18W band comes first in the sequence of the MIR-L channel exposures and the electron count is the largest in that band. The first L18W-band exposure significantly affects the following first L15- and L24-band exposures, which record higher counts than the second ones do. Therefore, we took the LE1 frames in the second exposures of the L15 and L24 bands, while the LE1 frame in the first exposure was chosen for the L18W band. Consequently, only one image of \( \sim 16 \) s exposure was taken for each band from every pointed observation. Therefore, the images used in this study are about \( \sqrt{6} \) or three times shallower than those obtained through the co-adding procedure of the reduction pipeline.

Parts of images affected by internal lamps and bright lines of pixels were masked out. Additionally, we masked the left half of the MIR-L channel frames, in which a pattern of internally scattered light was significant. The regions used in the analysis are shown in Figure 3.

The stars in the images were removed by masking the pixels whose values were larger than or smaller than three times the standard deviation with respect to the average, along with \( 3 \times 3 \) pixels surrounding them. The masking was repeated until there remained no more pixels to be clipped. The fractions of the masked pixels were \( \lesssim 6\% \) for the MIR-S bands, \( \sim 9\% \) for the L15 and L18W bands, and \( \sim 11\% \) for the L24 band. We did not combine the reduced images to investigate the seasonal variation of the brightness.

The dark frames were processed in the same way as the exposure frames except that we skipped the dark subtraction procedure. After the whole reduction processes, we obtained the average image of the dark frames for each channel and subtracted it from individual dark frames to strip the large-scale patterns in the dark current. The patterns were especially significant in the MIR-S channel dark frames and had an impact on the fluctuation measurements on scales larger than about \( 50'' \). These large-scale patterns were suppressed in the exposure frames when subtracting the dark frames from them pixel by pixel.

2.3. Absolute Calibration

We used the observations of the Diffuse Infrared Background Experiment (DIRBE) on board the Cosmic Background Explorer (COBE) as a reference for the absolute calibration of the diffuse light. The method is similar to that used for the calibration of the AKARI IRC All-Sky Survey (Pyo et al. 2010). If we assume that the sky brightness at mid-infrared wavelengths follows the blackbody spectrum (Leinert et al. 2002), the spectral energy distribution (SED) of the sky brightness \( I_s(\lambda) \) can be written as

\[
I_s(\lambda) = \tau B_\nu(\lambda, T),
\]

where \( \tau \) and \( T \) are the optical depth and the color temperature, respectively, and \( B_\nu(\lambda, T) \) is the Planck function at the wavelength \( \lambda \). The subscript \( v \) in \( I_s \) and \( B_\nu \) means that the unit of brightness is given in the per-frequency unit. Use of a per-frequency unit is not a mandatory rule, but is done to follow the convention of adopting the unit of MJy in the previous ZL.
studies. The assumption of wavelength-independent optical depth and color temperature is acceptable for the ZL-dominant background at the mid-infrared wavelengths (Leinert et al. 1998).

Our model SED, Equation (1), is a simple, empirical model and not a physically meaningful one. A physical model has to include (1) the ZL, (2) the integrated star light, (3) the diffuse Galactic light, and (4) the extragalactic background light (Leinert et al. 1998). For the absolute calibration, however, a detailed model of light sources is not necessary and an empirical shape of SED suffices. Thus, the temperature \( T \) in Equation (1) is not related to the temperature of the interplanetary dust (IPD), or of any other sources. On the other hand, Ootsubo et al. (1998, 2000) and Hong et al. (2009) modeled the infrared ZL spectra with the brightness integrals and suggested a two-temperature model of the IPD cloud in which the hot-dust component has a temperature of about 300 K or higher at 1 AU and the cold-dust component has a temperature of about 266 K or lower. But the hot-dust component is required to explain the part of the spectra at wavelengths shorter than \( \sim 6 \mu \text{m} \) and a single component model is sufficient at longer wavelengths (Reach et al. 2003).

We have two unknown parameters, \( \tau \) and \( T \), in Equation (1). To fix these two parameters, the brightnesses at two wavelengths are sufficient; Pyo et al. (2010) used the DIRBE 4.9 and 12 \( \mu \text{m} \) bands to calibrate the AKARI All-Sky Survey at 9 \( \mu \text{m} \). In our case, we made use of the DIRBE 4.9, 12, and 25 \( \mu \text{m} \) bands, because the MIR-S and MIR-L channels cover the wavelength range from 7 to 24 \( \mu \text{m} \).

The DIRBE brightnesses were taken from the Calibrated Individual Observations (CIO) data set.\(^7\) For each AKARI MIR-S and MIR-L observation, we collected such DIRBE observations that satisfied the following conditions: (1) the difference in Earth’s heliocentric ecliptic longitude between DIRBE and AKARI observations is less than 5\(^\circ\) and (2) the separation between the observing coordinates of the two observations is less than \( \sim 10' \), half of the spatial resolution in the CIO. We collected the DIRBE observations for the MIR-S and MIR-L channels independently, because the lines of sight of the two

channels are separated from each other (Figure 1). The mission period of the COBE/DIRBE was shorter than one year and the DIRBE observations were not available for five AKARI observations of IDs from 5121016-001 to 5121020-001. For each AKARI observation, about 20 sets of DIRBE brightnesses were selected. We took the average of the selected brightnesses.

The DIRBE CIO data set provides the quoted brightness in which the calibration assumed that the source spectrum follows \( I_\nu \propto 1/\nu \). Because we assume a blackbody SED, we made the color correction on the DIRBE brightnesses, which depends on temperature only. For each set of three DIRBE brightnesses observed simultaneously, we determined the temperature \( T \) and the optical depth \( \tau \) with the least-squares fit using the following model:

\[
I_\nu \propto \tau B_\nu(\lambda_i, T)K_i(T),
\]

where the superscript \( i \) runs over three DIRBE bands and \( I_\nu^i, \lambda_i, \) and \( K_i \) are the quoted brightness, the effective wavelength, and the color-correction factor for the \( i \)th band, respectively. The equation for calculation of the color-correction factor is given in Hauser et al. (1998b). The quoted and color-corrected DIRBE brightnesses and the fitting blackbody SED corresponding to the AKARI’s observation ID 5121021-001 are shown in Figure 4 for instance.

Once the temperature and optical depth were determined, we calculated the sky brightnesses at the MIR-S and MIR-L bands’ reference wavelengths with Equation (1). The calculated brightnesses were divided by the ADU counts from the AKARI observations. Consequently, we obtained seven (MIR-S) or five (MIR-L) ratios between the calculated and measured brightnesses for each band and took their averages as the calibration factors. In Figure 4, the calibrated AKARI brightnesses are shown with green (for MIR-S channel) or red (for MIR-L channel) circles. The calibration factors used in this work are listed in Table 1.

The calibration factors for diffuse sky brightness are smaller than those for the point sources (Tanabé et al. 2008) by factors of about 0.85–0.89 for MIR-S bands and about 0.56–0.78 for MIR-L bands. The ratios between the diffuse and point source calibration factors are listed in Table 1. The difference of calibration factors between the point and the diffuse sources is

\(^7\) Available in the Legacy Archive for Microwave Background Data Analysis (LAMBDA) homepage (http://lambda.gsfc.nasa.gov) of NASA.
due to (1) the point-spread function (PSF) cutoff in the aperture photometry of the point sources and (2) the internal scattering and diffraction of light within a detector array (Arimatsu et al. 2011). The former causes the point source calibration factor to be overestimated, but does not cause a problem in point source photometry if a consistent aperture size is used for both the calibration and the photometry. On the other hand, the latter decreases the diffuse source calibration factor with respect to the “ideal” absolute calibration. As long as the internal scattering and diffraction of light within a detector array (Arimatsu et al. 2011) are taken into account, the systematic errors will not cause a problem in point source photometry if a consistent aperture size is used for both the calibration and the photometry. However, we will ignore those systematic errors because our central concern is to measure the fluctuation with respect to the sky brightness.

3. SEASONAL VARIATION OF THE SKY BRIGHTNESS

The sky brightness observed on the Earth-bound orbit changes with time due to the annual variation of the ZL (Deul & Wolstencroft 1988; Reach 1988; Vrtilek & Hauser 1995; Kelsall et al. 1998; Kwon & Hong 1998; Pyo et al. 2010). For detailed studies of the solar system’s IPD cloud, such full models as those of Wright (1998) and Kelsall et al. (1998) are required. However, complete modeling of the IPD cloud is beyond the scope of this work. Instead, we tried simple sinusoidal fitting to the observed sky brightnesses, which assumes that the ZL at high ecliptic latitude is dominated by the smooth cloud component of the IPD cloud (Kelsall et al. 1998). The fitting function is given as a function of Earth’s heliocentric ecliptic longitude, \( \Lambda_{\odot} \), at the epoch of observation:

\[
I_s(\Lambda_{\odot}) = a \sin(\Lambda_{\odot} - b) + c, \tag{3}
\]

where \( a \), \( b \), and \( c \) are the amplitude, phase, and average brightness of the annual variation, respectively. In the fitting process, we fixed the period of the sine curve at 360°, which is a reasonable assumption. The results are plotted in Figure 5 and arranged in Table 3. For comparison, the results for the DIRBE 12 and 25 \( \mu m \) bands observations are shown. The DIRBE NEP brightnesses are retrieved from the CIO data set by collecting the observations pointing at an ecliptic latitude larger than 89°5 while avoiding the region within 0°5 of NGC 6543.

![Figure 4](image_url)

**Figure 4.** Calibration process for the MIR-S (a) and MIR-L bands (b). Data are plotted for the observation ID 5121021-001. Gray squares are the quoted DIRBE brightnesses at 4.9, 12, and 25 \( \mu m \) bands, corresponding to the AKARI observation configuration. The horizontal bars are the full widths at half-maximum (FWHM) of the spectral response curves of the DIRBE bands, while the vertical bars are the errors in the DIRBE brightnesses due to the gain uncertainty (Hauser et al. 1998a). The black squares are the color-corrected DIRBE brightnesses based on the SED drawn with blue (a) or red (b) dotted line. The SED is determined by fitting a blackbody SED to the quoted DIRBE brightnesses, while applying color correction. Note that the SED curves and the DIRBE brightnesses in (a) and (b) are slightly different from each other, because the observing coordinates of the MIR-S and MIR-L channels do not coincide. Blue (a) and red (b) circles are the calibrated AKARI brightnesses in the MIR-S and MIR-L bands, respectively.

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

| Channel | Band | \( a \) (nW m\(^{-2}\) sr\(^{-1}\)) | \( b \) (°) | \( c \) (nW m\(^{-2}\) sr\(^{-1}\)) | \( \sigma_{res} \) (nW m\(^{-2}\) sr\(^{-1}\)) |
|---------|------|------------------|------|------------------|------------------|
| MIR-S   | S7   | 126.93 ± 0.12    | 46.41 ± 0.08 | 1236.15 ± 0.12 | 4.91 (0.40%)     |
|         | S9W  | 237.74 ± 0.08    | 51.96 ± 0.03 | 2355.60 ± 0.09 | 4.86 (0.21%)     |
|         | S11  | 290.45 ± 0.09    | 54.45 ± 0.03 | 3034.43 ± 0.10 | 9.59 (0.32%)     |
| MIR-L   | L15  | 269.70 ± 0.13    | 61.12 ± 0.08 | 3211.98 ± 0.27 | 5.56 (0.17%)     |
|         | L18W | 229.03 ± 0.10    | 63.56 ± 0.06 | 2840.21 ± 0.19 | 4.61 (0.16%)     |
|         | L24  | 148.60 ± 0.14    | 69.74 ± 0.14 | 1984.60 ± 0.27 | 3.25 (0.16%)     |
| DIRBE   | 12 \( \mu m \) | 284.86 ± 0.03    | 55.05 ± 0.01 | 3171.88 ± 0.03 | 13.73 (0.43%)    |
|         | 25 \( \mu m \) | 179.46 ± 0.13    | 69.58 ± 0.05 | 1891.68 ± 0.10 | 11.73 (0.62%)    |

Note. \( \sigma_{res} \) Standard deviation of the residuals. Values in parentheses are the percentage of standard deviations with respect to the average brightnesses, \( c \).
The brightnesses within 5° intervals of Earth’s heliocentric ecliptic longitude are averaged and shown in Figure 5 with gray triangles. Error bars are the statistical errors of the averages.

As can be seen in Figure 5 and in Table 3, the sine curves well describe the seasonal variation of the NEP brightnesses. The residuals after subtracting the fitting sine curves from the observed brightnesses are within ~0.4% of the average brightnesses for the AKARI observations. We plotted the residuals with respect to Earth’s heliocentric ecliptic longitude, as shown in the right panels of Figure 5. A clear dependency of the residuals on the longitude was not found. Meanwhile, the residuals of the bands in the same channel are correlated to each other, but no correlation is found between different channels. Therefore, we conclude that the residuals are caused by an instrumental effect, but not by the temporal variation of the sky brightness. At least for the MIR-L bands, it is arguable that the residuals are not related to the dark current, because the residuals from three bands are consistent with each other in the sense of the ratio relative to the average brightnesses. In the current analysis, it is difficult to clearly pinpoint the cause of the residuals. The observed brightnesses and the fitting parameters in the S11 and L24 bands are, respectively, consistent with those in the DIRBE 12 and 25 μm.

Our observation fields deviated slightly from the exact position of the NEP, as shown in Figure 1. By the means of the IPD cloud model of Kelsall et al. (1998), we examined how much difference in brightness between the NEP and the AKARI Monitor Fields is introduced by the deviation. The model was evaluated for the NEP and the AKARI Monitor Fields at the observation epoch for each observation ID listed in Table 2, and then the difference between the two brightnesses was obtained. We calculated the model at the wavelengths of the two IRC bands, S9W from MIR-S and L18W from MIR-L. To evaluate the model at the wavelengths of 9 and 18 μm, we turned off the inverse color correction required to obtain the DIRBE quoted brightness. The emissivity modification factors at those wavelengths were obtained by logarithmically interpolating the values given in Kelsall et al. (1998). Earth’s heliocentric coordinates required for the model calculation were retrieved from the HORIZONS ephemeris computation service operated by the Jet Propulsion Laboratory. The calculation results are shown in Figure 6.
The model calculation shows that the difference changes with time and is coupled with the solar elongation, one of the parameters most relevant to the ZL brightness. Though the observing coordinates of the MIR-S channel are fixed at a celestial coordinates, the solar elongation slightly changes because the Earth revolves around the Sun. As can be seen in Figure 6, we have brightness dimmer than that of the NEP if the solar elongation is larger than 90°, and vice versa. In the case of the MIR-S channel, the difference becomes almost zero for the observation ID 5121021-001, at which the solar elongation is closest to 90°. For this channel, the brightness difference relative to the NEP is always smaller than or comparable to the standard deviation of the sinusoidal fitting residuals (Table 3). For the MIR-L channel, the moving line of sight in the celestial coordinates introduces another modulation to the solar elongation, in addition to that caused by Earth’s motion. That celestial coordinates introduces another modulation to the solar elongation, in addition to that caused by Earth’s motion. That celestial coordinates introduces another modulation to the solar elongation, in addition to that caused by Earth’s motion. That celestial coordinates introduces another modulation to the solar elongation, in addition to that caused by Earth’s motion.

5. DISCUSSION

At mid-infrared wavelengths the sky is very bright due to the ZL and the electron counts recorded in the IRC detector pixels are copious, usually larger than two thousands. Thus, the photon noise is one of the major sources of fluctuation. To estimate the photon-noise contribution to the fluctuation, we artificially generated a pseudo-image filled with the values from a Poisson distribution whose mean is fixed at the average electron count of an exposure image. The electron count is calculated by multiplying ADU values by the instrument gain of 6.4363 e− ADU−1. We generated 100 pseudo-images for each image, calculated the fluctuation spectra of the pseudo-images, and took the average over 100 spectra. The photon-noise fluctuation spectrum is individually calculated for each exposure image because the sky brightness relevant to the average electron count changes with time, as discussed in Section 3. The average of 10 fluctuation spectra of the photon noise for each band is shown in Figure 7 with a gray line.

One of the sky brightness components that may explain the fluctuation is the Galactic cirrus emission by interstellar dust. The fluctuation spectrum of the Galactic cirrus is known to have a power-law index in a range from 2.5 to 3.1 (Jeong et al. 2005; Miville-Deschênes et al. 2007). To evaluate the real fluctuation spectrum of the cirrus, we used the AKARI Far-Infrared Surveyor observation of the NEP field (Matsuura et al. 2011) at the wavelength 90 μm. After removing the point sources, we measured the fluctuation of the image. To exclude the shot noise due to faint galaxies and the effect of large pixel size (∼30″), we used fluctuations at scales larger than 85″. Assuming that the structure of the Galactic cirrus is the same in other wavelengths, we converted the fluctuation measured at 90 μm to the fluctuations in the mid-infrared bands by using the SED of the Galactic cirrus. Regarding the cirrus SED, we adopted the most recent results from the Herschel and Spitzer Space Telescope observations by Compiĕgne et al. (2010). The cirrus fluctuation spectra are plotted in Figure 7 with magenta diamonds.
Another source of fluctuation is the shot noise due to faint sources. We estimated the fluctuation $F_{\text{src}}$ produced by the sources with flux fainter than the detection limit with the formula $F_{\text{src}} = \int S^2 (dN/dS) dS$, where $S$ is the flux and $dN/dS$ is the differential source count. The source-count functions are taken from the deep observations of the NEP with AKARI (Wada et al. 2007 at 7 $\mu$m; Pearson et al. 2010 at 15 $\mu$m) and the deep field observations with the Spitzer Space Telescope (Papovich et al. 2004 at 24 $\mu$m). Regarding the other wavelengths, we interpolated the source-count function. The detection limits are determined by five times the standard deviation of the pixel values after $3\sigma$-clipping and shown in Table 1. We accept $5\sigma$, rather than $3\sigma$, as the detection limit because of uncertainties involved in (1) the difference of source detection or removal methods between the source-count papers and this work, (2) the difference of calibration factors used in this work from those for point sources, and (3) the systematic errors ($\sim 10\%$) in the calibration factors inherited from the COBE/DIRBE calibration. The fluctuation spectra of the faint sources are drawn in Figure 7 with cyan dotted lines. The spectra decrease below the scale $\sim 15''$ due to the PSF. Quadratic summation of the photon noise, the cirrus, and the shot-noise spectra are also shown with black dashed lines. In Table 4, we arrange the fluctuations of dark current, sky brightness, photon noise, Galactic cirrus, and shot noise in six mid-infrared bands at the scale of 200''.

The residual fluctuations at 200'' after removing the photon noise, the Galactic cirrus, and the shot-noise contributions from the sky-brightness fluctuations were calculated and are listed in Table 4. We note that the photon-noise contributions were individually subtracted from the corresponding sky-brightness fluctuations and then the photon-noise-removed fluctuations were averaged after rejecting the maximum and minimum values, because photon noise depends on the changing sky brightness. The cirrus and the shot-noise contributions were subsequently subtracted. Subtracting operations were done in a quadratic sense, that is, we calculated the square root of the difference between the squares of operands. The errors were properly propagated.

For the MIR-S bands, the fluctuations at the scales $\lesssim 100''$ were well described by the photon noise. At larger scales, the slope of the spectrum becomes shallower, because the Galactic cirrus emission surpasses the fluctuation due to the photon noise. Owing to polycyclic aromatic hydrocarbon features, the cirrus emission is stronger in the short mid-infrared wavelengths than in longer wavelengths. The contribution of the cirrus emission decreases with the wavelength and becomes negligible in the MIR-L bands. The photon noise dominates the sky-brightness fluctuation in the MIR-L bands at all the scales considered in this study. The residual fluctuation appears at scales larger than 100''. At a few arcminutes scale, the residual fluctuation is detected at all mid-infrared bands.

We think that the residual fluctuation is related to an instrumental effect, but not to a celestial object. If we divide the residual fluctuations in Table 4 by the calibration factors in Table 1 to convert the unit to ADU, the fluctuations are about 0.7 ADU for the MIR-S bands except for the S7 band, and about 0.4 ADU for the MIR-L bands. For the S7 band, the fluctuation
stage, we conclude that the residual fluctuation plus two times as such as ghost images or fluctuation of flat patterns. In the current fluctuations measured in this work to the instrumental effect, are consistent to each other in the unit of ADU. Although it ignore the S7 band, the fluctuations at the bands of each channel 200 toward the NEP at each band. The most stringent upper limit at is the least, about (0.26 ± 0.24) ADU, but has large error. If we 0.01 nW m⁻² sr⁻¹ over a scale range from 5 to 200 arcsec. The fluctuation is measurable in this work after correction for the dark current, within a factor of two over a scale range from 5 to 200 arcsec. Fluctuation spectra are comparable to the photon-noise spectra 0.03% of the brightness at 18 μm. This limit is applicable to the ZL at near-infrared wavelengths, at which the sunlight scattered by the IPD particles is important (Matsumoto et al. 2011).

### Table 4

| Channel | Band  | Fluctuation (nW m⁻² sr⁻¹) |
|---------|-------|--------------------------|
|         | Dark Current | Sky Brightness | Photon Noise | Cirrus | Shot Noise | Residual |
| MIR-S   | S7     | 0.80 ± 0.05 | 1.71 ± 0.30 | 0.71 ± 0.01 | 1.32 ± 0.03 | 0.40 | 0.77 ± 0.09 (0.174%) |
|         | S9W    | 0.36 ± 0.02 | 1.54 ± 0.09 | 0.66 ± 0.01 | 1.01 ± 0.02 | 0.31 | 0.96 ± 0.15 (0.054%) |
|         | S11    | 0.38 ± 0.02 | 1.35 ± 0.15 | 0.76 ± 0.01 | 0.71 ± 0.02 | 0.31 | 0.99 ± 0.24 (0.049%) |
| MIR-L   | L15    | 0.25 ± 0.03 | 1.31 ± 0.18 | 0.88 ± 0.01 | 0.46 ± 0.01 | 0.29 ± 0.01 | 0.84 ± 0.30 (0.045%) |
|         | L18W   | 0.15 ± 0.02 | 0.89 ± 0.07 | 0.63 ± 0.01 | 0.37 ± 0.01 | 0.22 ± 0.01 | 0.47 ± 0.14 (0.027%) |
|         | L24    | 0.34 ± 0.04 | 1.28 ± 0.16 | 0.80 ± 0.01 | 0.26 ± 0.01 | 0.27 ± 0.01 | 1.04 ± 0.23 (0.076%) |

### Notes.

a The exact scale for the fluctuation measurements is 193’05 for the MIR-S channel and 203’31 for the MIR-L.
b Obtained by taking the average of the Galactic cirrus fluctuations between 100 and 300 arcsec scales after rejecting the largest and the smallest values. Error is the statistical error of average.
c Errors less than 0.01 nW m⁻² sr⁻¹ are omitted.
d Value in parentheses is the percentage of the fluctuation plus two times error with respect to the average brightness (c in Table 3) over the seasonal variation.

### 6. CONCLUSION

We made use of the AKARI IRC NEP Monitor Observations to examine the fluctuation in the sky brightness at the mid-infrared wavelengths. The fluctuation is measured by the power-spectrum method. After correction for the dark current, the fluctuation in the sky brightness is retrieved at six IRC mid-infrared bands. At wavelengths 7, 9, and 11 μm, the photon noise dominates the fluctuation spectra up to the arcminute scale, while the Galactic cirrus component dominates above that scale. At longer wavelengths (15, 18, and 24 μm), the sky-brightness fluctuation spectra are comparable to the photon-noise spectra within a factor of two over a scale range from 5 to 200 arcsec. Residual fluctuations are detected at scales larger than 100' after removing the noise and cirrus contributions from the measured sky-brightness fluctuations. We take the smallest fluctuation, ~0.03% of the sky brightness at the wavelength of 18 μm, as the upper limit of the sky-brightness fluctuation toward the NEP in the mid-infrared range.

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