Spatial Distributions of Cold and Warm Interstellar Dust in M 101
Resolved with AKARI/Far-Infrared Surveyor (FIS)

Toyoaki Suzuki, Hidehiro Kaneda, Takao Nakagawa, Sin’itirou Makiuti, and Yoko Okada
Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency,
3–1–1 Yoshinodai, Sagamihara, Kanagawa 229–8510
suzuki@irsas.jaxa.jp
Hiroshi Shibai and Mitsunobu Kawada
Graduate School of Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464–8602
and
Yasuo Doi
Department of Earth Science and Astronomy, The University of Tokyo, 3–8–1 Komaba, Meguro-ku, Tokyo 153–8902

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Abstract

The nearby face-on spiral galaxy M 101 has been observed with the Far-Infrared Surveyor onboard AKARI. The far-infrared four-band images reveal fine spatial structures of M 101, which include global spiral patterns, giant H II regions embedded in outer spiral arms, and a bar-like feature crossing the center. The spectral energy distribution of the entire galaxy shows the presence of a cold dust component \(18 \pm 10\) K in addition to a warm dust component \(55 \pm 9\) K. The distribution of the cold dust is mostly concentrated near the center, and appears to be smoothly distributed over the entire extent of the galaxy, whereas the distribution of warm dust indicates some correlation with the spiral arms, and has spotty structures, such as four distinctive bright spots in the outer disk in addition to a bar-like feature near the center, tracing the CO intensity map. The star-formation activity of the giant H II regions that spatially correspond to the former bright spots is found to be significantly higher than that of the rest of the galaxy. The latter warm dust distribution implies that there are significant star-formation activities in the entire bar filled with molecular clouds. Unlike our Galaxy, M 101 is a peculiar normal galaxy with extraordinary active star-forming regions.

Key words: galaxies: individual (M101) — galaxies: structure — infrared: ISM — ISM: dust

1. Introduction

The characteristics of large-scale star formation are of great importance to understand the evolution of a galaxy. One of the open fundamental questions is the dependence of the global star formation rate (SFR) on the total gas content of a galaxy. Far-infrared (IR) dust emission can provide us with reliable estimates of SFR. In general, spiral galaxies have cold and warm dust, as first suggested by de Jong et al. (1984), and confirmed by ISO observations (see review of Sauvage et al. 2005 and references therein). The cold dust component \(T_d = 10–20\) K is associated with molecular and atomic hydrogen clouds, which is heated mostly by the general interstellar radiation field (ISRF) (Cox & Mezger 1989). The cold dust accounts for more than 90% of the total interstellar dust in mass, and can therefore be used to estimate the total gas distribution over a galaxy. The contribution of the warm dust component \(T_d = 25–40\) K can be used to estimate the SFR of massive stars \(\gtrsim 4 M_\odot\); since the warm dust component is heated by O and early B stars in H II regions (Cox & Mezger 1989), its luminosity can reasonably be considered to reflect the SFR of massive stars, providing that the escape fraction of non-ionising UV photons from the H II regions is properly taken into account (Popescu & Tuffs 2005; Hippelein et al. 2003). Hence, to properly address the question about the relation between the global SFR and the total gas content in spiral galaxies, it is crucial to separate the contributions of the cold and warm dust components and to discuss the spatially-resolved distribution of each component within a galaxy. Particularly for late-type spiral and irregular galaxies, most of the far-IR luminosity is carried by the cold dust primarily emitting longwards of the IRAS limit of 120 \(\mu\)m, and thus observations at wavelengths longer than 120 \(\mu\)m are essential to detect the cold dust component (Popescu et al. 2002; Vlahakis et al. 2005).

Here we present new far-IR images of the nearby galaxy M 101 obtained with the Far-Infrared Surveyor (FIS; Kawada et al. 2007) onboard AKARI (Murakami et al. 2007). M 101 is a face-on spiral galaxy with global spiral patterns, classified as Sc(s)I (Sandage & Tammann et al. 1981) with a distance of 7.4 Mpc (Jurcevic & Butcher 2006). The galaxy is an excellent candidate for this study, since it has a large optical size of 28' × 28' (Nilson 1973), well-developed spiral arms, and several conspicuous giant H II regions. Rice et al. (1988) and Devereux and Scowen (1994) presented 60 and 100 \(\mu\)m images of M 101 with IRAS; the latter found a spatial correspondence between the morphology of the far-IR and H\alpha luminosities. However, since the angular resolution of IRAS is rather poor, structures such as spiral arms and star-forming regions cannot be distinguished. As an early release of ISO observations, Hippelein et al. (1996a, 1996b) presented 60, 100, and 170 \(\mu\)m images of M 101 with ISOPHOT, which resolved the giant H II regions embedded in outer spiral arms, and a bar-like feature crossing the center. The spectral energy distribution of the entire galaxy shows the presence of a cold dust component \(18 \pm 10\) K in addition to a warm dust component \(55 \pm 9\) K. The distribution of the cold dust is mostly concentrated near the center, and appears to be smoothly distributed over the entire extent of the galaxy, whereas the distribution of warm dust indicates some correlation with the spiral arms, and has spotty structures, such as four distinctive bright spots in the outer disk in addition to a bar-like feature near the center, tracing the CO intensity map. The star-formation activity of the giant H II regions that spatially correspond to the former bright spots is found to be significantly higher than that of the rest of the galaxy. The latter warm dust distribution implies that there are significant star-formation activities in the entire bar filled with molecular clouds. Unlike our Galaxy, M 101 is a peculiar normal galaxy with extraordinary active star-forming regions.
regions. A better 100 μm image was later derived by Tuffs and Gabriel (2003). The far-IR colors are found to be surprisingly insensitive to the intensity of the ISRF, except for the two giant H II regions, NGC 5447 and 5461. The SEDs for the total galaxy and also for local specific fields show that a single blackbody model with a temperature of about 30 K can fit the observed SEDs.

Siebenmorgen, Krügel, and Chini (1999) observed 16 galaxies including active (Seyfert and starburst) and inactive (normal) galaxies. The SEDs of the active galaxies can be described by a single blackbody model at temperatures of 31.5 ± 2.8 K. The ratio of the far-IR luminosity to the gas mass, $L_{\text{FIR}}/M_{\text{gas}}$, is $\sim 90 L_{\odot}/M_{\odot}$. In contrast, the SEDs of the inactive galaxies require the presence of cold dust at temperatures of 12.9 ± 1.7 K in addition to warm dust at 31.8 ± 2.8 K, while $L_{\text{FIR}}/M_{\text{gas}}$ is $\sim 3 L_{\odot}/M_{\odot}$. From IRAS and ISO observations, M 101 is classified as an active galaxy in terms of its SED; however, it is an inactive galaxy considering its small $L_{\text{FIR}}/M_{\text{gas}}$ value (0.5 $L_{\odot}/M_{\odot}$) with a far-IR luminosity of $1.1 \times 10^{10} L_{\odot}$ (Rice et al. 1988) and a gas mass of $2.4 \times 10^{10} M_{\odot}$ (Kenney et al. 1991; Allen et al. 1973). Hence, the activity of M 101 is still controversial.

A remarkable property of M 101 is its large, bright, and metal-poor H II regions (NGC 5447, 5455, 5461, 5462, and 5471) located in the outer disk of the galaxy. To explain the properties of the giant H II regions, Kenney et al. (1991) proposed that either the initial mass function is unusually enhanced in massive stars or the gas is consumed efficiently in these regions. For the former, Rosa and Benvenuti (1994) concluded that the initial mass function for stars with the masses larger than 2 $M_{\odot}$ is rather normal in M 101, similar to that in the solar neighborhood. For the latter, there was an indication that the star formation efficiency (SFE) of the massive stars in NGC 5461 is higher than a typical SFE observed in our Galaxy (Blitz et al. 1981). Giannakopoulos-Creighton, Fich, and Wilson (1999) detected CO emission from two giant H II regions (NGC 5461 and 5462); for NGC 5461, they found that the SFE is unusually high, as compared with that in star-forming regions of our Galaxy, concluding that higher SFE is likely to be the key to the formation of giant H II regions in M 101. Comparative research would however be necessary over the entire galaxy, not just restricted to the giant H II regions.

The four far-IR bands of the FIS have a great advantage over IRAS and Spitzer/MIPS in detecting both cold and warm dust components, which offers a unique capability to spatially and spectrally separate the two dust components determining the distribution of star-formation activity over a galaxy. The high spatial resolution of the FIS has an advantage over IRAS and ISO in resolving spiral arm and inter-arm regions, and identifying H II regions embedded in the arms. Furthermore, a large dynamic range in the signal detection is another advantage over MIPS; the FIS can observe a galaxy without being prevented by saturation effects at the brighter center and the H II regions. Therefore, AKARI/FIS observations are best suited for studying the luminous galaxy M 101.

2. Observations and Results

The observations were performed as part of the FIS calibration program on June 14 in 2006 by using one of the FIS observation modes, FIS01. The FIS was operated in a photometry mode with four bands: N60 (65 μm), WIDE-S (90 μm), WIDE-L (140 μm), and N160 (160 μm). The observations consist of two sets of round-trip slow scans with a shift in the cross-scan direction. The round-trip scan ensures data redundancy for any corrections of radiation effects. The user-defined parameters are the scan speed of 8′′ s⁻¹, the cross-scan shift length of 240″, and the reset time interval of 1.0 s.

The FIS01 scan sequence is shown in figure 1, which consists of (1) the first round-trip, (2) the cross-scan step, and (3) the second round-trip. In figure 1, the area inside the thick lines is scanned in the four bands. The total area scanned in the four bands is $15′×12′$. Details of the FIS instrument and its in-orbit performance/calibration are described in Kawada et al. (2007).

The FIS data were basically processed with the AKARI official pipe line modules. In addition to these, we applied a series of corrections for the radiation effects developed in Suzuki (2007). The long-term (several times $10^3$ seconds) gradual changes in the detector responsivity due to passage of the South Atlantic Anomaly were corrected by using a set of internal calibration signals. Then, cosmic-ray glitches were detected and their effects were corrected; spikes caused by ionizing radiation hits were removed and base-line fluctuations due to short-term (a few seconds) changes in the detector responsivity preceded by the spikes were restored at each detection point. The distortion of the fields-of-view of the FIS array detectors (SW and LW; Kawada et al. 2007) and their alignment were corrected. The positional offset uncertainty between the FIS detectors was estimated to be about $10′$ from observations of point sources, such as far-IR-bright asteroids. The focal-plane coordinate system was then converted into the equatorial coordinate system. Finally, the four-band images
Table 1. Flux densities of M101.

|        | N60 (65 µm) | WIDE-S (90 µm) | WIDE-L (140 µm) | N160 (160 µm) |
|--------|-------------|---------------|-----------------|--------------|
|        | 61 ± 12 Jy  | 168 ± 34 Jy   | 353 ± 106 Jy    | 522 ± 209 Jy |

Fig. 2. Four-band images of M101 in the WIDE-S (top-left), N60 (top-right), WIDE-L (bottom-left), and N160 (bottom-right) bands. The center wavelengths of the four bands are 65 µm for N60, 90 µm for WIDE-S, 140 µm for WIDE-L, and 160 µm for N160. Contours are linearly spaced from 7% to 98% of the peak brightness at a step of 7%. Peak brightness is 60 MJy sr⁻¹ (WIDE-S), 70 MJy sr⁻¹ (N60), 100 MJy sr⁻¹ (WIDE-L), and 150 MJy sr⁻¹ (N160). Typical noise levels are 0.1 MJy sr⁻¹ (WIDE-S), 0.4 MJy sr⁻¹ (N60), 0.1 MJy sr⁻¹ (WIDE-L), and 0.3 MJy sr⁻¹ (N160). In each image, the PSF size in FWHM is shown in the lower left corner.
were created with grid sizes of 25" for the WIDE-L and N160 bands and 15" for the WIDE-S and N60 bands. The widths (FWHM) of the Point Spread Functions (PSFs) are ~ 60" for the WIDE-L and N160 bands and ~ 40" for the WIDE-S and N60 bands (Kawada et al. 2007).

The far-IR flux densities in the four bands were obtained by integrating the surface brightness within an aperture after subtracting the sky background level. Background levels were estimated from nearby blank skies and subtracted from images, which were observed in the beginning and at the end of the scan observation. To obtain the fluxes of the whole galaxy, the photometric aperture with a radius of 8" around the center was used, which was large enough to cover a dominant fraction of the far-IR emission from the galaxy without degrading the S/N. On the basis of the brightness profile along the scan direction, the loss of fluxes outside the aperture was estimated to be less than 20%. To obtain the fluxes in image bins (14" radius; see below) that are significantly smaller than the FIS beam sizes, appropriate aperture corrections were applied to the four-band data, as described in subsection 3.2. Color corrections were applied for the obtained flux densities. The resultant correction errors are estimated to be ~ 30% for the WIDE-L band, ~ 40% for the N160 band, and ~ 20% for the WIDE-S and N60 bands under the current stage of the FIS calibration, which are expected to improve with progress in the calibration. Table 1 gives the derived flux densities of M 101 in the four bands of the FIS.

Figure 2 represents the four far-IR band images of M 101. The images were smoothed with boxcar kernels with a width of 50" for the WIDE-L, N160 bands and 30" for the WIDE-S, N60 bands. At wavelengths longer than 120 μm, the WIDE-L and N160 band images clearly exhibit bright spots embedded in the arms in addition to the spiral patterns, as compared to the ISO 170 μm image (Hippelein 1996a). The conspicuous four bright spots spatially correspond to the four giant H II regions (NGC 5447, 5455, 5461, and 5462) and are even more emphatic in the WIDE-S and N60 band images. Among them, NGC 5461, which is located at 4.5 south-east from the center, is brightest, and even brighter than the center. Furthermore, as in the ISO 100 μm image (Tuffs & Gabriel 2003), a bar-like feature crossing the center can also be seen in the WIDE-S and N60 band images, which have a striking resemblance to the distribution of CO emission (Kenney et al. 1991).

3. Discussion

3.1. Presence of Cold Dust Component

The spectral energy distribution (SED) of the whole galaxy was obtained by integrating the surface brightness, as described in section 2. Figure 3 shows the resultant SED of M 101. Integrated flux densities in the four bands are shown by filled boxes, while those in the far-IR bands of ISOPHOT at 60, 100, and 170 μm, obtained with the latest calibration (Tuffs & Gabriel 2003), are shown by open boxes. As can be seen in the figure, our results with AKARI/FIS are consistent with the newly-calibrated ISOPHOT data. It is clear from the figure that a single-temperature blackbody spectrum cannot reproduce the observed SED. We therefore fitted the AKARI and ISO data with a double-temperature blackbody model modified by an emissivity power-law index of 1,

$$F_{\text{FIR}}(v) = A_c v \pi B_v(T_c) + A_w v \pi B_v(T_w),$$

where $T_c$, $T_w$, $B_v(T)$, $A_c$, and $A_w$ are the temperatures of the cold and warm dust, the Planck function, and the amplitudes of the cold and warm dust components, respectively. The best-fit model thus obtained is indicated by the solid line in figure 3, while the dotted line and the dash-dotted line represent the warm and the cold dust components, respectively. The best-fit temperatures representative of $T_c$ and $T_w$ are 18$^{+14}_{-9}$ K and 55$^{+9}_{-23}$ K, respectively. The errors of the dust temperatures were derived from the 1σ confidence contour (Δ$\chi^2 = 2.3$) encompassed by the two parameters ($T_c$, $T_w$), while the other parameters ($A_c$, $A_w$) were fixed at the best-fit values. For the error in the warm dust temperature, since the upper error limit is not well determined by the data at wavelengths longer than 60 μm alone, the error is limited by combining the IRAS flux density at 25 μm (Rice et al. 1988). If we apply an emissivity power-law index of 2, the cold and warm temperatures to explain the resultant SED are 15$^{+2}_{-1}$ K and 37$^{+7}_{-11}$ K, respectively, which do not make significant differences from the above temperatures. Siebenmorgen, Krügel, and Chini (1999) showed that inactive spiral galaxies possess cold dust having temperatures of 12.9 ± 1.7 K and warm dust of 31.8 ± 2.8 K on the average, which are compatible to the two dust temperatures obtained for M 101 with the FIS. Hence, we have clearly confirmed the presence of the cold dust component in M 101.

By using the best-fit double temperature modified blackbody model, the far-IR luminosity of the cold dust component, $L_c$, and the warm dust component, $L_w$, can be calculated as

$$L_c = 4 \pi D^2 A_c \int v \pi B_v(T_c) dv$$

$$L_w = 4 \pi D^2 A_w \int v \pi B_v(T_w) dv.$$
Fig. 4. Spatial distributions of the cold dust (left), and warm dust (right) components of M 101. Contours are linearly spaced from 7% to 98% of the peak at a step of 7%. The peak luminosity is $3.6 \times 10^8 \, L_\odot \, \text{kpc}^{-2}$ for the warm dust component, and $3.1 \times 10^8 \, L_\odot \, \text{kpc}^{-2}$ for the cold dust component.

Table 2. Properties of the far-infrared dust emission in M 101.

| Dust component | Far-IR luminosity ($L_\odot$) | Dust mass ($M_\odot$) |
|----------------|-------------------------------|-----------------------|
| Cold dust      | $(1.6^{+0.5}_{-0.4}) \times 10^{10}$ | $(9^{+30}_{-5}) \times 10^{7}$ |
| Warm dust      | $(5.3^{+7}_{-6}) \times 10^9$ | $(1.1^{+40}_{-5}) \times 10^5$ |

where $D$ is the distance to M 101 (7.4 Mpc; Jurcevic & Butcher 2006). From table 2, the resultant total far-IR luminosity, $L_{\text{FIR}} (= L_c + L_w)$ is $(2.1^{+0.5}_{-0.4}) \times 10^{10} \, L_\odot$. The errors of the luminosities come from those of the temperatures and the amplitudes of the two dust components. Hence, $L_{\text{FIR}} / M_{\text{gas}}$ is estimated to be 0.9 $L_\odot / M_\odot$ with a total gas mass ($M_{\text{H}_2} + M_{\text{HI}}$) of $2.4 \times 10^{10} \, M_\odot$ (Kenney et al. 1991; Allen et al. 1973). By taking into account the presence of the cold dust component as well as the small $L_{\text{FIR}} / M_{\text{gas}}$ value, M 101 can be classified as an inactive galaxy.

The masses of the cold and warm dust components were estimated to derive the gas-to-dust ratio over the entire galaxy. We applied the grain emissivity factor given by Hildebrand (1983), an average grain radius of 0.1 $\mu$m, and a specific dust mass density of 3 g cm$^{-3}$. The mass of dust, $M_d$, becomes

$$M_d = 10^4 \left( \frac{L}{10^8 \, L_\odot} \right) \left( \frac{T_d}{40 \, \text{K}} \right)^{-5},$$

(4)

where $L$ is luminosity. Dust temperatures are set to be equal to those derived from the above SED fitting.

Table 2 shows that the warm dust mass occupies less than 1% of the total dust mass in M 101. The total gas-to-dust ratio is thus estimated to be 280, which is slightly larger than the accepted value of 100–200 for our Galaxy (Knapp & Kerr 1974).

3.2. Spatial Distributions of Cold and Warm Dust

In order to derive the distributions of the cold and warm dust components in the galaxy, the spatial resolutions of the WIDE-S and $N60$ images were reduced to match those of the WIDE-L and $N160$ images by convolving the former images with a Gaussian kernel with a width of 20″, which was performed before smoothing the images in figure 2. The images were then resized with the common spatial scale among the four bands: $25″ \times 25″$. As described in section 2, the flux densities at each image bin were derived from an aperture.
Fig. 6. (left) Far-ultraviolet ($\lambda = 1516$ Å) gray-scale image of M 101 (Gil de Paz et al. 2006) overlaid with the contour map of the warm dust emission. The far-UV image is convolved with the beam size, the same as in figure 4. The contour levels are the same as in figure 4. (right) CO contour map of the M 101 (Kenney et al. 1991) with the gray-scale map of the warm dust emission. The open box shows the area of the CO observation.

Fig. 7. Positions of seven local fields in M 101 indicated as the circles in the warm dust emission map (the same as the right panel of figure 4); for each region, the luminosity of the warm dust emission, the dust mass of the cold dust, and thus the ratio $L_w/L_c$ are obtained (see text for details).

radius of 14" with aperture-correction factors of 0.30 for the four bands. An individual SED constructed from the four-band fluxes at each image bin was then fitted with a two-temperature model, in which the temperatures were fixed at the values obtained for the SED of the whole galaxy; we could not well constrain the dust temperatures from fitting the four far-IR bands data if we set the temperatures to be free. Figure 4 shows the distributions of the dust emission thus spectrally deconvolved into the two components. The map of the warm dust is almost identical to the $N60$ image, which can be understood by considering that the contribution of the cold dust component to the $N60$ band intensity is negligible, as seen in the SED fitting of figure 3. The distribution of the cold dust, however, shows some differences from those of the other photometric band images, as seen in the giant H II regions, where the contributions of the two components may be intermixed to some extent.

As shown in figure 4, the cold dust component seems to be smoothly distributed over the entire extent of the galaxy, while the warm dust component indicates some correlation with the spiral arms. Figure 5 shows the $R$-band gray-scale image superposed on the contour map of the cold dust component. The cold dust may be heated by a diffuse heating source, such as an old stellar population or non-ionising UV photons escaping from H II regions. In the outer regions, the warm dust component is correlated with the spotty structures that belong to the spiral arms. The morphology of their warm and cold dust components seem to be consistent with those of other nearby galaxies found by ISO observations (Sauvage et al. 2005) and confirmed by Spitzer observations (Dale et al. 2005; Hinz et al. 2006; Gordon et al. 2006; Tabatabaei et al. 2007). The spots embedded in the outer arms are spatially related to the four giant H II regions, as shown in the far-ultraviolet (UV) map with GALEX (figure 6). However, in the giant H II regions (NGC 5455, 5461, and 5462), the far-UV peaks are somewhat located at the peripheries of the spots in the warm dust emission. NGC 5461 is located well outside the nuclear region, but still carries a significant fraction (1%) of the total far-IR luminosity of M 101. This situation is different from that in our Galaxy, where the far-IR emission from dust associated with H II regions contributes only a minor fraction; for example, the far-IR luminosity of the most active star-forming region, W 49A is 0.2% of the total far-IR luminosity of our Galaxy (Sievers et al. 1991; Bloemen et al. 1990).

The bar near the center was first discovered by CO ($J = 1–0$)
observations (Kenney et al. 1991), and the R-band image reveals an oval distortion in the stellar distribution, which is offset in the position angle from the bar by \( \sim 25^\circ \). The AKARI/FIS shows that the warm dust component traces the bar region, spanning 2' in length in the central region of M 101. This bar is not seen in the distribution of cold dust, but can also be traced in the far-UV emission (Gil de Paz et al. 2006). Numerical simulations of interstellar gas with barred potentials can produce this position angle offset due to their dissipative nature (Huntley et al. 1978); gas is concentrated on the leading edge of the barred potential by a shock wave. Hence, we conclude that the warm dust component traces the concentration of the interstellar medium along the bar potential near the center, and that there is active star formation not only in the center, but also throughout the bar. Near the end of the bar region labeled in figure 7, however, figure 6 shows significant deviations of both warm dust and far-UV distributions from the CO distribution; the warm dust emission is still bright beyond the leading edge of the CO emission, tracing the complex far-UV emission in the developed spiral arm. The difference in the spatial distribution between the warm dust emission and the CO emission may be interpreted as evidence of star formation induced by a spiral density wave (Rand et al. 1992; Loinard et al. 1996).

On the basis of the spectrally-deconvolved dust emission maps in figure 4, we derive the far-IR luminosity ratio between warm and cold dust \( (L_w/L_c) \) in various regions, which consist of seven local fields in M 101: the four giant H II regions, the center, the bar, and the inter-arm region, as shown in figure 7. The results are given in table 3. It is found from the table that the ratios of the four giant H II regions are significantly higher than those of the center and the bar, and 20–40 times as high as that of the inter-arm region. The cold dust component is associated with gas content, while the warm dust component is associated with the SFR of massive stars. Thus, the ratio \( L_w/L_c \) is physically related to star-formation activity. Systematic errors in the ratio are likely to be dominated by the assumption of constancy in the warm dust temperature; the dust temperature can be higher than the fixed one, particularly in the giant H II regions. However, higher temperature results in a larger \( L_w \), thus making the difference in \( L_w/L_c \) between the giant H II regions and the other regions even larger. Therefore, the result in table 3 may indicate that the star-formation activity of the four giant H II regions are highest in the galaxy. As a result of a past encounter of M 101 with its companion galaxy, NGC 5477, intergalactic H I gas may fall in the outer disk near at least NGC 5461 and 5462 (van der Hulst & Sancisi 1988). Therefore, such external effects may promote the formation of the giant H II regions. As for the bar, the ratio of the entire bar is similar to that of the center.

### Table 3. Far-infrared luminosity ratios between cold and warm dust components \( (L_w/L_c) \) in various regions in M 101.

| Region       | Center | Bar end | NGC 5447 | NGC 5455 | NGC 5461 | NGC 5462 | Inter arm |
|--------------|--------|---------|----------|----------|----------|----------|-----------|
| \( L_w/L_c \)| 0.6 ± 0.1 | 0.8 ± 0.2 | 1.6 ± 0.4 | 3.0 ± 0.7 | 2.6 ± 0.6 | 1.9 ± 0.4 | 0.07 ± 0.02 |

3.3. **Color Temperature of Dust in Various Regions**

Since it is not easy in practice to accurately estimate \( T_c \) and \( T_w \) for each image bin, temperatures of the cold (18 K) and warm (55 K) dust components are kept to be constant over the galaxy for simplicity in the above discussion. Nevertheless, the far-IR colors constructed from any combination of the FIS four-band fluxes can be robust indicators of the temperatures of the warm and cold dust for each region in M 101. Figure 8 shows the color–color diagram \( \log(F140/F160) \) versus \( \log(F160/F90) \) of the above seven local fields and the whole galaxy in figure 3 by using an average over each region. \( F65, F90, F140, \) and \( F160 \) show the flux densities of the \( N60, WIDE-S, WIDE-L, \) and \( N160 \) bands, respectively. In figure 8, \( F65/F90 \) ratio is significantly higher in the four giant H II regions, the center, and the bar as compared to that of the galaxy as a whole. The higher \( F65/F90 \) colors can be interpreted as higher warm dust temperatures, i.e. more active star formation. Therefore, the star-formation activities in the six regions are more intense than those in the rest of the galaxy. In particular, the four giant H II regions show the most active star formation in M 101. Hence, the results show an overall consistency with the ratio \( L_w/L_c \) listed in table 3.

On the other hand, the \( F140/F160 \) colors do not show significant variations among various regions, except NGC 5455. Since the \( F140/F160 \) color can be related to the cold dust temperature, variations in the cold dust temperature are significantly smaller than that in the warm dust temperature over the galaxy. This fact is consistent with the idea derived by Shibai, Okumura, and Onaka (1999), which also justifies the above assumption of constant temperature for cold dust. One exception is NGC 5455, which shows a significantly higher \( F140/F160 \) color than the other giant H II regions. As shown
in figure 9, the oxygen abundance \([12 + \log(O/H)]\) in the four giant H II regions is lower (35–60\%) than that of the solar system (Kennicutt et al. 2003); the metallicity in NGC 5455 is the lowest among the four giant H II regions. Madden et al. (2006) present that low metallicity regions indicate intense ISRF. Therefore, the higher F140/F160 color of NGC 5455 may be explained by the more intense ISRF in NGC 5455.

Although the IRAS observations have unexpectedly shown that the far-IR colors are insensitive to a change of the ISRF intensity over the galaxy (Devereux & Scowen 1994), the AKARI/FIS has demonstrated that there are significant variations in the far-IR colors among the seven regions with the four photometric bands and high spatial resolution. Although M 101 is classified as an inactive galaxy, unlike our Galaxy, the extraordinary active star-forming regions are located in the outer disk (10–16 kpc from the center; Israel et al. 1975). M 101 is thus considered to be a peculiar inactive galaxy.

4. Conclusions

The spatial structure of M 101 is well resolved in the four bands with the AKARI/FIS. The resultant SED of the whole galaxy shows the presence of a cold dust component (18 \pm 3 K) in addition to a warm dust component (55 \pm 2 K). Considering its small \(L_{\text{FIR}}/M_{\text{gas}}\) value of 0.9 \(L_\odot/M_\odot\), M 101 is classified as an inactive galaxy. We deconvolved the cold and warm dust emission components spatially, by making the best use of the multi-band photometric capability of the FIS. The difference in the distribution between the cold and warm dust is more clearly revealed than in the separate images in each of the four bands. The distribution of the cold dust is mostly concentrated near the center, and appears to be smoothly distributed over the entire extent of the galaxy, whereas the distribution of the warm dust indicates some correlation with the spiral arms, and has spotty structures, such as four distinctive bright spots in the outer disk in addition to a bar-like feature near the center, tracing the CO intensity map. The former bright spots are spatially related to the four giant H II regions. The latter feature implies that there is active star formation throughout the bar filled with molecular clouds.

On the basis of the distributions of the warm and cold dust components, we have derived \(L_w/L_c\) as a robust measure of star-formation activity in the various regions in M 101. Star-formation activity of the four giant H II regions is significantly higher than that of the rest of the galaxy. External effects, such as the infall of intergalactic gas, may promote the formation of the four giant H II regions. The color–color diagram constructed from any combination of the FIS four-band fluxes has revealed the temperature variations of the warm and cold dust in the various regions. The four giant H II regions show significantly higher warm dust temperatures in M 101, which supports the active star formation. The warm dust temperature shows large variations over the galaxy, whereas the cold dust temperature shows a comparatively narrow range of variations, which suggests relatively constant ISRF intensities over the galaxy. Hence, unlike our Galaxy, M 101 is considered to be a peculiar inactive galaxy with extraordinary active star-forming regions.

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