AKARI Far-Infrared Spectroscopic Observations of the Galactic Center Region

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Abstract

We have observed the Quintuplet- and Arches-cluster regions with the Fourier Transform Spectrometer (FTS) of the Far-Infrared Surveyor (FIS) aboard AKARI to investigate the physical conditions of interstellar matter around the clusters. The FIS-FTS mapping data reveal differences in the spatial distribution among the far-infrared [OIII], [NII], and [CII] line emissions near the Arches cluster; the emission of an ionic line with a higher ionization potential is distributed closer to the Arches cluster. This clearly indicates that UV photons from the Arches cluster are ionizing the surface of nearby molecular clouds, and penetrating deeper to dissociate the cloud. We have estimated the effective temperature of the Arches cluster to be about 34000 K from the ratio of the [OIII]/[NII] lines.

Key words: Galaxy: center — infrared: ISM — ISM: general — ISM: H II regions

1. Introduction

In the Galactic center region, there are three clusters of young massive stars: the Central cluster, the Arches cluster, and the Quintuplet cluster. These clusters have been claimed to be main heating sources of the interstellar matter (ISM) in the Galactic center region (e.g., Cotera et al. 1996; Rodríguez-Fernández et al. 2001). Although they are important as local heating sources, Nakagawa et al. (1995) and Yasuda et al. (2008) suggested that numerous K- and M-type stars make larger contributions to the heating of diffuse gas in the large-scale Galactic center region as a whole, rather than OB stars forming the clusters, based on the small ratio of the [CII] line to the far-infrared (FIR) continuum.

The radio arc and molecular clouds at the Galactic center have been observed extensively in the FIR, submillimeter, and millimeter bands. In the radio arc region, one commonly distinguishes the straight, nonthermal filaments (Radio Arc) approximately perpendicular to the Galactic plane and the arched thermal filaments (Arched filament). Genzel et al. (1990) compared the spatial distributions of the [CII] line with those of molecular lines, suggesting that the [CII] emission may come from interfaces between the molecular clouds and the ionized zone. The Arches cluster was discovered in 1990 (Nagata et al. 1995) and in 1992 by Cotera et al. (1992), and since then it has been suggested that the Arched filaments are the edges of dense molecular clouds irradiated by UV radiation from the Arches cluster (Lang et al. 2001). However, there has been no direct evidence for a connection between the cluster, the molecular cloud, and/or the radio filaments. On the other hand, another young cluster, the Quintuplet cluster, has been known to be the main ionization source of the Sickle H II region (Simpson et al. 1997; Rodríguez-Fernández et al. 2001).

The FIR spectral region is rich with many spectral lines that are important for studying interstellar physics and chemistry. Among them, the atomic and ionic fine-structure lines [O I] 63 µm and [C II] 158 µm are dominant cooling lines for neutral interstellar gas, and ionic fine-structure lines, such as [O III] 88, 52 µm and [N II] 122 µm, are strong coolants in H II regions. These lines can be used as diagnostics to infer the physical conditions of interstellar gas, such as the temperature and density, as well as the intensity and hardness of the radiation field, by comparing the line ratios with those predicted by models of photodissociation regions (PDRs: e.g., Tielens & Hollenbach 1985; Wolfire et al. 1990; Hollenbach et al. 1991) and H II regions (Rubin et al. 1991). The properties of representative FIR fine structure lines are shown in table 1. With the FIR emission lines, which are free from dust extinction, we can directly probe the Galactic center region.

Infrared Space Observatory (ISO) detected various emission lines, which can be interpreted to be excited by UV radiation produced by the Quintuplet and the Arches cluster (Rodriguez-Fernández et al. 2001). Cotera et al. (2005) and Simpson et al. (2007) investigated the ionized emission lines and the distance to the Arches cluster with ISO in the FIR and Spitzer in the mid-infrared (MIR), respectively. They found that the ratio of the highly ionized to the lowly ionized lines decreased with the distance from the cluster. These results suggested that the Arches filaments were ionized by the Arches cluster. However, those observations covered very limited regions near the Arches cluster; the FIR spectrometer on board ISO has only a single beam.

We report here on the first scientific result obtained with the Fourier Transform Spectrometer (FTS: Kawada et al. 2008) of...
the Far-Infrared Surveyor (FIS: Kawada et al. 2007) aboard AKARI (Murakami et al. 2007). We have observed the Arches- and the Quintuplet-cluster regions near the Galactic center with the AKARI FIS-FTS, which has two kinds of 2-dimensional detector arrays, and thereby we have obtained detailed line maps of the ionized sources and clouds around the clusters continuously, which contain important information on the ISM in the Galactic center region.

2. Observations and Data Analysis

The observations were performed in the AOT, FIS03 mode (Kawada et al. 2008), which is designed for spectroscopic observations with the FIS-FTS. This enables imaging spectroscopy over the full FIS wavelength range by the two wideband arrays (WIDE-S and WIDE-L; hereafter SW and LW, respectively). Two spectral resolution modes are provided for FIS-FTS observations: full-resolution mode and SED (Spectral Energy Distribution) mode. They are different only in the mirror scan path length and, accordingly, in the resultant spectral resolution (Kawada et al. 2008). The specifications of the FIS-FTS are given in table 2.

FIS-FTS observations of the Galactic center region were carried out in 2006 September and 2007 March. We used five pointings in total, the first one performed on 2006 September 19 and the others on 2007 March 17–18. For both observations, the full resolution mode was used with a reset interval of 0.1 s. The observation ID and the position of each observation are listed in table 3.

The observational region contains two massive star-forming young clusters in the Galactic center region, the Quintuplet and the Arches. The observational positions are shown in figure 1. The position of the first observation does not match well with those of the other later observations, as shown in figure 1, due to an unexpected misalignment of the fields-of-view (FOVs) of the two detectors (see figure 3 in Kawada et al. 2007, 2008), which was found later after the first FIS-FTS observation.

We overview the data analysis procedure of the FIS-FTS (see N. Murakami et al. 2009, in preparation, for details). We first applied the AKARI FIS-FTS official analysis tools (AKARI FTS Toolkit Manual) to the FIS Time Series Data (TSD). The analysis tools corrected any non-linearity of the integration ramp curves, removed reset anomalies and cosmic-ray glitches, determined the center burst position, and finally carried out a Fourier transformation of the interferogram to produce a spectrum.

Then, spectral correction functions (SCFs) were applied, and flux calibration was performed. The SCF is composed of two parts: a correction factor for the variations of the detector responsivity (flat correction) and a correction factor for the spectral response of each pixel. Ground measurement and internal calibration lamp data were used to correct any variations of the detector responsivity among the array pixels (N. Murakami et al. 2009, in preparation). In order to correct a variation of the spectral response among the pixels, we used ISO/LWS observations of the same regions that were observed by the FIS-FTS; all of the corresponding ISO/LWS data were taken from the archives. We also used FIS-FTS observations of planets, comparing them with their model prediction.

The absolute fluxes of the FIS-FTS were calibrated on the basis of observations of Uranus and Neptune (N. Murakami et al. 2009, in preparation). An absolute flux calibration was performed only for particular pixels, not for all of them. The other pixels were calibrated relative to the absolutely calibrated pixels through flat corrections. The absolute flux uncertainties are estimated to be no more than 40% for all of the pixels. The SW pixels suffer strong fringes in the spectra. The cause of these fringes is thought to be multiple reflection between the parallel surfaces of the detector monolith. Throughout the laboratory measurements, the fringe pattern remains the same, implying that it can be easily removed. The fringe pattern looks quite similar among different in-flight observations (Kawada et al. 2008). Another type of channel fringes exists in the FIS-FTS, which can be clearly seen in the LW interferograms. The observed fringes are well reproduced by a two parallel multi-reflection model with a 4.1-mm gap and about 20% reflectivity. A plausible cause of this phenomenon is two blocking filters put on the optical path just after the collimator mirror with a physical gap of about 4 mm (Kawada et al. 2008). We have utilized the predefined model patterns to reduce spectral fringes. However, we still have residual SW fringes and LW fringes in our SW and LW spectra, which are not strong, but still significant (see figure 2).

### Table 1. Properties of FIR lines.

<table>
<thead>
<tr>
<th>Species</th>
<th>Upper level</th>
<th>Lower level</th>
<th>Wavelength (µm)</th>
<th>$E_{ul}$ (K)</th>
<th>$n_{cr}$ (cm$^{-3}$)</th>
<th>Ionization potential (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[C II]</td>
<td>$^2P_{1/2}$</td>
<td>$^2P_{3/2}$</td>
<td>157.7</td>
<td>92</td>
<td>$2.7 \times 10^3$</td>
<td>11.26</td>
</tr>
<tr>
<td>[N II]</td>
<td>$^3P_2$</td>
<td>$^3P_1$</td>
<td>122.0</td>
<td>120</td>
<td>$2.8 \times 10^2$</td>
<td>14.53</td>
</tr>
<tr>
<td>[O III]</td>
<td>$^3P_1$</td>
<td>$^3P_0$</td>
<td>88.4</td>
<td>160</td>
<td>$5.0 \times 10^2$</td>
<td>35.12</td>
</tr>
</tbody>
</table>

* Excitation energy.
† Critical densities. Collision partners are H for the [C II] line, and electron for the other lines (Tielens 2005).
‡ Ionization potential required to create the ion.

### Table 2. Specifications of the FIS Fourier Transform Spectrometer (FTS) from Kawada et al. (2007).

<table>
<thead>
<tr>
<th>Band</th>
<th>WIDE-S</th>
<th>WIDE-L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (µm)</td>
<td>60–110</td>
<td>110–180</td>
</tr>
<tr>
<td>Array size</td>
<td>20 × 3</td>
<td>15 × 3</td>
</tr>
<tr>
<td>Pixel size (&quot;)</td>
<td>26.8</td>
<td>44.2</td>
</tr>
<tr>
<td>Resolution (cm$^{-1}$)</td>
<td>0.36 (Full-resolution), 2.4 (SED)</td>
<td></td>
</tr>
</tbody>
</table>

* Resolution with apodization.

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Fig. 1. (Upper panel) positions of important sources located in the Galactic center region, and (lower panel) observational points of the AKARI/FIS-FTS (in bigger and small boxes) and the ISO/LWS (Cotera et al. 2005 in circles), overlaid on the 20 cm radio contour map (Yusef-Zadeh et al. 1984). The smaller and bigger boxes represent the pixels of SW and LW, respectively. It should be noted that LW covers a larger area than SW. The contour levels of the radio map are 0.014, 0.028, 0.07, 0.14, 0.42, 0.7, and 1.12 Jy sr$^{-1}$.
Table 3. Observation log.

<table>
<thead>
<tr>
<th>ID</th>
<th>Position (°)</th>
<th>Observing mode</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>5110023</td>
<td>0.1285 -0.0042</td>
<td>FIS03/Full-resolution</td>
<td>2006 Sep 19</td>
</tr>
<tr>
<td>5110042</td>
<td>0.1365 0.0089</td>
<td>FIS03/Full-resolution</td>
<td>2007 Mar 17</td>
</tr>
<tr>
<td>5110043</td>
<td>0.1229 -0.0114</td>
<td>FIS03/Full-resolution</td>
<td>2007 Mar 18</td>
</tr>
<tr>
<td>5110054</td>
<td>0.1051 -0.0387</td>
<td>FIS03/Full-resolution</td>
<td>2007 Mar 18</td>
</tr>
<tr>
<td>5110055</td>
<td>0.1497 0.0294</td>
<td>FIS03/Full-resolution</td>
<td>2007 Mar 18</td>
</tr>
</tbody>
</table>

Fig. 2. Examples of the FIS-FTS spectra. The left panel shows an SW spectrum, where the [O III] line is seen at a wavenumber of 113 cm\(^{-1}\). The right panel shows an LW spectrum, where the [C II] and [N II] lines are seen at wavenumbers of 163 cm\(^{-1}\) and 82 cm\(^{-1}\), respectively. In the LW spectrum, the OH absorption feature is also seen at a wavenumber of 84 cm\(^{-1}\). The residual fringes are recognized in both spectra (see text).

3. Results

3.1. Line Intensity Map of the Quintuplet and Arches Cluster Region

Three FIR fine-structure lines have been detected, [C II] 157 μm, and [N II] 122 μm from the LW spectra, and [O III] 88 μm from the SW spectra (table 1). Examples of the spectra are shown in figure 2. The line intensity was obtained by fitting the data with a Gaussian function plus a linear continuum for SW, and a sinc function plus a linear continuum for LW, where the line widths were fixed to those instrumental profiles. We used two types of line-fitting functions, because we applied the hanning apodization to the SW data, but not to the LW data before the Fourier transformation; the apodization to LW was found to make it more difficult to distinguish the line emissions from the fringes. Figure 3 shows line intensity maps thus obtained with the FIS-FTS. The maps of both SW and LW were created with a common grid size of 30′′. The positional information of the FIS-FTS data is correct within an accuracy of about 20′′.

Part of the [O III] bright region extending along the Galactic plane around (ℓ, b) = (0°15, −0°04) corresponds to the Sickle H II region. The resultant distribution of the line emission is consistent with the ISO/LWS observations (Rodríguez-Fernández et al. 2001). On the other hand, the [C II] emission shows a smoother distribution; the surface brightness decreases slightly away from the Galactic plane. In addition to the Sickle H II region, there is a bright region in the [C II], [N II], and [O III] maps around (ℓ, b) = (0°05–0°1, 0°0), which is adjacent to the Arches cluster. The positions of the peaks in [C II], [N II], and [O III] are, however, found to be significantly different from each other. The [C II] and [N II] emissions extend more toward the Galactic center than the [O III] line. The differences of these spatial structures are discussed in the following section.

Figure 3 shows that the Quintuplet cluster region is brighter in the [O III] emission than the Arches cluster region. The Arches cluster is younger than the Quintuplet cluster based on the color–magnitude diagrams with the Hubble Space Telescope observations (Figer et al. 1999). The difference in excitation was already known from a study of the Galactic center H II regions with Kuiper Airbone Observatory and ISO (Simpson et al. 2006 and their references), where it was suggested that the Arches cluster lies relatively far away from the gas emitting the observed lines. Our FIS-FTS results are consistent with their results.

3.2. Comparison with ISO/LWS Observations

We compared the FIS-FTS maps with the ISO/LWS data for the overlapping area. For the Quintuplet cluster, the observation area is partly overlapped with that of the ISO/LWS mapping observations (Rodríguez-Fernández et al. 2001). In the overlapping area of the FIS-FTS with the ISO/LWS, comparisons between the line intensities obtained by the FIS-FTS and the ISO/LWS have been made for each of the [O III], [N II], and [C II] lines (figure 4). We calculated the averages and standard deviations for the ratios of the line intensities obtained by the FIS-FTS to those with the ISO/LWS from the same position; the results are 1.33 ± 0.34 for the [O III] line,
Fig. 3. FIS-FTS line intensity maps. The top panel shows the [O III] line, the bottom left panel the [N II] line, and the bottom right panel the [C II] line. The color levels are linearly scaled in units of W m$^{-2}$ sr$^{-1}$. Typical 1σ noise levels are $3 \times 10^{-7}$ W m$^{-2}$ sr$^{-1}$, $2 \times 10^{-7}$ W m$^{-2}$ sr$^{-1}$, and $3 \times 10^{-7}$ W m$^{-2}$ sr$^{-1}$ for the [O III], [N II], and [C II] line maps, respectively.
Table 4. Comparison of the AKARI line intensity with the ISO/LWS (L01 mode) line intensity for the Arches region.*

<table>
<thead>
<tr>
<th></th>
<th>AKARI</th>
<th>ISO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Arches cluster</td>
<td>E1 filament</td>
</tr>
<tr>
<td>[O III]</td>
<td>1.48 ± 0.13</td>
<td>1.50 ± 0.14</td>
</tr>
<tr>
<td>[C II]</td>
<td>2.30 ± 0.07</td>
<td>1.86 ± 0.10</td>
</tr>
<tr>
<td>[N II]</td>
<td>0.81 ± 0.07</td>
<td>0.68 ± 0.08</td>
</tr>
<tr>
<td>Arches cluster</td>
<td>1.44 ± 0.04</td>
<td>1.66 ± 0.06</td>
</tr>
<tr>
<td>E1 filament</td>
<td>1.72 ± 0.04</td>
<td>1.46 ± 0.04</td>
</tr>
<tr>
<td>E2 filament</td>
<td>0.79 ± 0.02</td>
<td>0.73 ± 0.02</td>
</tr>
</tbody>
</table>

* The ISO results are obtained from staring observations with a single pixel (Cotera et al. 2005), while the AKARI results are obtained from the maps. Units are all given in 10⁻⁶ W m⁻² sr⁻¹.

Part of the [O III] distribution obtained from the FIS-FTS observations spatially correspond well to the eastern filament (the upper left panel of figure 5), which is consistent with a previous study (Timmermann et al. 1996). Although the [N II] line also traces the ionized regions, the [N II] distribution has a peak at a position different from that of the [O III] distribution, spatially corresponding to the western filament (the upper middle panel of figure 5). The [C II] distribution, tracing PDRs and the H II region, shows two peaks, which is consistent with a previous [C II] observation (Genzel et al. 1990). The two peaks are located near the the peaks of the [O III] and [N II] lines.

The difference among the [O III], [N II], and [C II] distributions can be explained by the difference in the ionization potentials of the emission species. The O⁺ has a higher ionization potential (~35.1 eV) than those of N (~14.5 eV) and C (~11.3 eV). Thus, the [O III] line traces highly ionized regions with strong UV radiation fields, but the [N II] line traces lower ionized regions, and the [C II] is expected mostly from neutral PDRs. The FIS-FTS results show that the emission of an ionic line with a higher ionization potential is distributed closer to the Arches cluster. The implications of these results are discussed later in detail.

Figure 6 shows a brightness profile cut in parallel to the array direction of the FIS-FTS through the Arches cluster, where the errors were estimated by fitting the lines with the continua. The origin of the projected distance corresponds to the position of the Arches cluster. In deriving the projected distance, 8.5 kpc is adopted as the distance to the Galactic center. This brightness profile clearly shows the differences among the [O III], [N II], and [C II] distributions in the area near the Arches cluster. The [O III] line peak is located at ~2 pc away from the Arches cluster, while the [N II] line peak is located at ~11 pc. This result shows that high-energy photons (~35 eV) created by ionizing sources are absorbed in the surfaces of clouds, and lower energy photons (~14 eV) permeate the clouds more deeply. The [C II] profile has two peaks near the [O III] peak and the [N II] peak. We consider that the [C II] line arises from PDRs associated with the respective H II regions which the [O III] line and the [N II] line come from. In fact, as can be seen in figure 6, the two [C II] peaks are a little farther away from the Arches clusters than the [O III] peak and the [N II] peak.

Figure 5 compares the AKARI results with those of Midcourse Space Experiment (MSX: Mill et al. 1994). The MSX observed the Galactic center region with higher resolution and sensitivity than those of previous large-scale mapping of the RAFLG survey (Little & Price 1985) and IRAS (e.g.,

1.01 ± 0.16 for the [N II] line, and 1.27 ± 0.27 for the [C II] line.

Apart from the Quintuplet cluster region, the ISO/LWS observed the area surrounding the Arches cluster (Cotera et al. 2005). However, the observations were performed only for several points by a single beam in a staring mode, not in a mapping mode. Among them, 3 ISO/LWS data points are included in the area covered by the FIS-FTS map (figure 1). The line intensities of the FIS-FTS map were then compared with the ISO/LWS line intensities at the 3 points after smoothing the FIS-FTS image with the ISO/LWS beam size (table 4). The FIS-FTS and the ISO/LWS data show an overall consistency. Since the observed point on the E2 filament is located on the edge of the FIS-FTS map, the FIS-FTS result for this point is relatively uncertain.

By considering calibration errors, these AKARI/FIS-FTS results are consistent with the ISO/LWS results.

3.3. Spatial Distributions of Emission Lines near the Arches Cluster

The Arched filaments, as shown in figure 1, which contain eastern (E1 and E2) and western (W1 and W2) filaments (e.g., Yusef-Zadeh et al. 1984), are thought to be the edge of dense molecular clouds (Lang et al. 2001), and are probably excited by hot stars in the Arches cluster (Cotera et al. 2005). As described in subsection 3.1, we can see displacements among the [O III], [N II], and [C II] distributions in the area near the Arches cluster.

By fitting the lines with the continua, the line errors were estimated. The eastern (E1 and E2) and western (W1 and W2) filaments (e.g., Yusef-Zadeh et al. 1984), are thought to be the edge of dense molecular clouds (Lang et al. 2001), and are probably excited by hot stars in the Arches cluster (Cotera et al. 2005). As described in subsection 3.1, we can see displacements among the [O III], [N II], and [C II] distributions in the area near the Arches cluster.

Figure 4 shows a correlation of the AKARI line intensity with the ISO line intensity. The triangles indicate the [O III] lines, the squares are the [N II] lines, and the diamonds are the [C II] lines.

Fig. 6. Spatial brightness profile obtained from the FIS-FTS observations. The two peaks are located near the the peaks of the [O III] and [N II] lines.

The difference among the [O III], [N II], and [C II] distributions can be explained by the difference in the ionization potentials of the emission species. The O⁺ has a higher ionization potential (~35.1 eV) than those of N (~14.5 eV) and C (~11.3 eV). Thus, the [O III] line traces highly ionized regions with strong UV radiation fields, but the [N II] line traces lower ionized regions, and the [C II] is expected mostly from neutral PDRs. The FIS-FTS results show that the emission of an ionic line with a higher ionization potential is distributed closer to the Arches cluster. The implications of these results are discussed later in detail.

Part of the [O III] distribution obtained from the FIS-FTS observations spatially correspond well to the eastern filament (the upper left panel of figure 5), which is consistent with a previous study (Timmermann et al. 1996). Although the [N II] line also traces the ionized regions, the [N II] distribution has a peak at a position different from that of the [O III] distribution, spatially corresponding to the western filament (the upper middle panel of figure 5). The [C II] distribution, tracing PDRs and the H II region, shows two peaks, which is consistent with a previous [C II] observation (Genzel et al. 1990). The two peaks are located near the the peaks of the [O III] and [N II] lines.
Fig. 5. FIS-FTS line intensity maps. The [O III], [N II], and [C II] line maps are shown in the left, middle, and right columns, respectively. The color levels are the same as those in figure 3. In the top panels, the contour map of radio 20 cm emission is overlaid, where the contours levels are 0.014, 0.028, 0.07, 0.14, 0.042, 0.7, and 1.12 Jy sr$^{-1}$ (Yusef-Zadeh et al. 1984). In the middle panels, the contour map of mid-infrared 6.8–10.8 $\mu$m emission obtained from MSX is overlaid, where the contours are logarithmically scaled from $2 \times 10^5$ to $7 \times 10^5$ W m$^{-2}$ sr$^{-1}$. In the bottom panels, the contour map of mid-infrared 11.1–13.2 $\mu$m emission obtained from MSX is overlaid, where the contours are logarithmically scaled from $1 \times 10^5$ to $7 \times 10^5$ W m$^{-2}$ sr$^{-1}$.

Cox & Laureijs 1989). The MSX 8 $\mu$m band traces PAH emitting the 7.7 $\mu$m and 8.6 $\mu$m emission features well, while other MSX bands are dominated by the emissions of hot dust (Egan et al. 1998). Simpson et al. (1999) showed the spectrum of the Arched filament region obtained with the MSX Michelson interferometer (see figure 4 in Simpson et al. 1999). Both PAHs and hot dust emissions require excitation by UV radiation.

Figure 5 shows that the spatial distribution of the [O III] line emission coincides well with that of the hot dust emission, while that of the [C II] line does not (bottom panels). A good spatial correlation of the [O III] line emission with the hot dust emission is consistent with the results of the ISO observations (Rodríguez-Fernández et al. 2001), indicating that the dust is heated by radiation from young stars in the Quintuplet and Arches clusters that ionize the gas. On the other hand,
the MSX 8 μm band intensity (i.e. PAH emission) is bright not only in the region with strong [O III] line emission, but also in the region with strong [C II] line emission (middle panels of figure 5). The distribution of the [N II] line emission shows a less clear spatial correspondence with that of the hot dust emission. This difference between [O III] and [N II] can reflect that the [O III] emission traces the H II regions with intense UV radiation, while the [N II] emission traces more lowly ionized H II regions. The emission of the warm dust with temperatures lower than 40 K is almost invisible in the MSX bands.

The [C II] line emission arises mostly from a warm neutral medium, and is thus expected to show a weaker correlation with hot dust emission. On the other hand, the PAH emission is expected to arise from regions with a much weaker radiation field than the hot dust emission, such as PDRs, which is supported by the observed correlation between the [C II] and PAH emissions. This may also suggest the importance of photoelectric heating of gas by PAHs in PDRs.

4. Discussion

A more quantitative discussion on the H II regions associated with the Arches cluster is presented in this section.

First, we compare the extent of the distribution of the line emission with that predicted by previous single-beam observations. Rodríguez-Fernández, Martín-Pintado, and de Vicente (2001) discussed the influence of radiation from the Arches cluster using the ratio [N III]/[N II] observed by ISO. Their measurements suggested that the influence of the radiation from the cluster could be considered to be up to a distance of 7–13 pc by combining the results with the CLOUDY simulation (Ferland 1996). They assumed the number of incoming UV photons to be $Q(H) = 10^{51.4} \text{s}^{-1}$ and the electron density to be $n_e = 10^2 \text{cm}^{-3}$ in a CLOUDY simulation. The ionization potential of N is similar to (a little higher than) that of H (table 1); thus, the [N II] emission can be regarded to arise from almost the same region as an H II region. The brightness profile in figure 6 shows that the distribution of the [N II] line extends away to a distance of $\sim 15$ pc from the Arches cluster. Hence, our measurements show a little larger distribution than the model prediction ($\sim 7–13$ pc) by Rodríguez-Fernández, Martín-Pintado, and de Vicente (2001), implying that the gas is not uniformly distributed around the cluster (see below).

Next, we estimate the effective temperature of the Arches cluster from the ratio of the integrated line intensities of [O III] 88 μm ($I_{88}$) to [N II] 122 μm ($I_{122}$) using the following equation:

$$\frac{I_{88}}{I_{122}} = \frac{\frac{h\nu}{\lambda_{88}}} \frac{A_O}{A_N} \frac{\int \delta_O \frac{n_{O^{++}}}{n_O} f_O n dl}{\int \delta_N \frac{n_{N^+}}{n_N} f_N n dl} = \frac{\lambda_{122} A_O \delta_O Q(O) f_O}{\lambda_{88} A_N \delta_N Q(N) f_N}$$

(1)

where $f$ is the fraction of these ions occupying the emitting state, which depends mostly on the electron density; we have derived $f_O$ and $f_N$ by solving balance equations between the relevant 3 fractional populations for O $^{++}$ and N $^+$, respectively (Emery & Kessler 1982). Here, $n_{O^{++}}/n_O$ and $n_{N^+}/n_N$ are the ionization fractions. For the calculation, an electron density of $10^{2.7} \text{cm}^{-3}$ was assumed and the abundances of O and N were $\delta_O = 5 \times 10^{-4}$ (Tielens & Hollenbach 1985) and $\delta_N = 1 \times 10^{-4}$ (Stenberg & Dalgarno 1995), respectively. The hydrogen density, $n$, was assumed to be constant through the integrated region. The Einstein A coefficients of $2.7 \times 10^{-3} \text{s}^{-1}$ and $7.5 \times 10^{-6} \text{s}^{-1}$ were adopted for [O III] 88 μm and [N II] 122 μm (Tielens 2005), respectively. $Q(O)$ and $Q(N)$ in equation (1) are the numbers of ionized photons, all of which were assumed to come from the Arches cluster. By using the measured $I_{88}/I_{122}$, we could obtain $Q(O)/Q(N)$ from equation (1). On the other hand, we predicted $Q(O)/Q(N)$ with the CMFGEN model (Martins et al. 2005), and compared the measurement with the calculation to obtain $T_{eff}$. The line emissions of N $^+$ and O $^{++}$ were integrated over distances of 0 to 13 pc from the Arches cluster, and the observed ratio ($I_{88}/I_{122}$) was used to obtain the effective temperature of the Arches cluster. The effective temperature ($T_{eff}$) thus derived is $\sim 34000 \text{K}$, which corresponds to those of O6–O7 stars. Since the calibration errors are $\sim 40\%$ for the [O III] line and $\sim 30\%$ for the [N II] line, the systematic uncertainty of $T_{eff}$ errors is estimated to be $\pm 1500 \text{K}$. One should note that the line brightness profiles observed by AKARI in figure 6 show that the [N II] emission extends significantly beyond a distance of 13 pc from the Arches cluster, which is the boundary of the [O III] line map, while most of the [O III] emission associated with the Arches cluster is contained within 13 pc.

This result is consistent with earlier studies. For example, Erickson et al. (1991) suggested that the typical ratios of [S III] 33 μm and [O III] 88 μm in the E2 filaments obtained by their observations with Kuiper Airborne Observatory were well explained by numerous embedded stars with $T_{eff} \sim 35000 \text{K}$. Using the ratios of [O III] 52 μm/[S III] 33 μm, Cotera et al. (2005) calculated the effective temperatures of the Arches cluster with the CLOUDY model, which were 35000–37000 K for the Kurucz stellar model. Cotera et al. (2005) derived $T_{eff}$ from discrete single-beam observations at three positions (the Arches cluster, the E1 filaments, and the E2 filaments) with
the ISO/LWS. Serabyn, Shupe, and Figer (1998) discussed that the stellar population of the Arches cluster consisted of hot, massive O stars, pointing out that a total number of ~120 of massive O stars is required to explain the fluxes (see figure 3 in Serabyn et al. 1998). The effective temperature of O stars ranges from 51200 K for an O3 star to 35900 K for an O9 star (Tielens 2005). Hence, the above results suggest that the color of the total flux from the ensemble of the clusters can be approximated by late O-type stars; we obtained $T_{\text{eff}} = 38000$ K when we assumed the Salpeter initial mass function (Salpeter 1955) with a mass range of O5–O9.

Now that we have obtained $T_{\text{eff}}$ of the Arches cluster from the above calculation, we can estimate the radius of the H II region ($R_{\text{H II}}$) excited by the Arches cluster. We assume that the average electron density of the cloud is $10^{2-3}$ cm$^{-3}$ (Cotera et al. 2005) and that the number of the stars contained in the cluster is ~150 (Serabyn et al. 1998; Figer et al. 1999) with the same effective temperature, $T_{\text{eff}} = 34000$ K. We then obtain $R_{\text{H II}} = 5.71$ pc. The calculated radius of $R_{\text{H II}}$ is considerably smaller than the observed spatial distributions of the [N II] line emission. The difference between the calculation and the observation implies that the gas is not uniformly distributed around the cluster, while the gas density was assumed to be constant in the above calculation. In fact, the radio observations revealed filamentary structures around the cluster (Yusef-Zadeh et al. 1984; Lang et al. 2001), suggesting that the gas density is far from being constant. Continuous spatial coverage of the Arches cluster region by our observations also reveals a rather non-uniform distribution of the [C II] and [N II] line emissions, supporting the complicated structure of the ISM around the cluster.

5. Summary

We have presented AKARI FIS-FTS observations of the Galactic center region in FIR fine-structure lines ([O III] 88 μm, [N II] 122 μm, and [C II] 158 μm) to investigate the condition of the ISM around the massive young star-forming Quintuplet and Arches clusters. We obtained three line maps, and found differences in the spatial distributions among the [O III], [N II], and [C II] emission lines near the Arches cluster. The results demonstrate that the gas phase changes with the distance from the Arches cluster, which is direct evidence that UV photons from the Arches cluster are ionizing the surface of nearby molecular clouds, forming the radio filament and penetrating deeper to dissociate the clouds. We have estimated the effective temperature of the Arches cluster to be ~34000 K, from the ratio of [O III]/[N II]. The results suggest that the color of the total flux from the ensemble of the clusters can be approximated by late O stars.

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