MASSIVE QUIESCENT CORES IN ORION. VI. THE INTERNAL STRUCTURES AND A CANDIDATE OF TRANSITING CORE IN NGC 2024 FILAMENT

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ABSTRACT

We present a multiwavelength observational study of the NGC 2024 filament using infrared to submillimeter continuum and the NH$_3$ (1, 1) and (2, 2) inversion transitions centered on FIR-3, the most massive core therein. FIR-3 is found to have no significant infrared point sources in the Spitzer/IRAC bands. But the NH$_3$ kinetic temperature map shows a peak value at the core center with $T_k = 25$ K, which is significantly higher than the surrounding level ($T_k = 15-19$ K). Such internal heating signature without an infrared source suggests an ongoing core collapse possibly at a transition stage from first hydrostatic core (FHSC) to protostar. The eight dense cores in the filament have dust temperatures between 17.5 and 22 K. They are much cooler than the hot ridge ($T_H \sim 55$ K) around the central heating star IRS-2b. Comparison with a dust heating model suggests that the filament should have a distance of 3–5 pc from IRS-2b. This value is much larger than the spatial extent of the hot ridge, suggesting that the filament is spatially separated from the hot region along the line of sight.

Key words: ISM: clouds – ISM: individual objects (NGC 2024, Orion) – ISM: molecules – stars: formation – stars: low-mass

1. INTRODUCTION

Revealing the transition stage between prestellar cores and protostars is critical for understanding the entire star-forming process. The low- and intermediate-mass prestellar cores are supposed to initially stay in a hydrostatic equilibrium, referred to as a Bonnor–Ebert sphere (Bonnor 1955; Bonnor 1956). The density would gradually increase due to the self-gravity and external influences such as turbulence, compression flow, and velocity perturbation, which are usually presented in filamentary clouds (e.g., Gómez et al. 2007; Hennebelle & Chabrier 2011; Gong & Ostriker 2015). As the core becomes supercritical to the self-gravity, the “first collapse” would occur and generate a much denser object called the first hydrostatic core (FHSC, or first core). The FHSC has a density of $\sim 10^{13}$ cm$^{-3}$, so that the gas and dust become opaque to radiation (Larson 1969). The temperature in the FHSC would continuously increase due to the self-gravity and possibly ongoing accretion. Once the central temperature exceeds 2000 K, the heating would start to dissociate the $H_2$ molecules. The $H_2$ dissociation can provide an efficient coolant for the gas and largely reduce the thermal pressure support, thereby inducing the “second collapse.” In this process the FHSC would evolve into a protostar (Masunaga & Inutsuka 2000; André 2011).

Despite this delicately modeled evolutionary track, the observed examples for the transition stage between pre- and protostellar cores are still scarce. Up until now, only a few low-mass cores have been suggested to be FHSC candidates (e.g., Boss & Yorke 1995; Belloche et al. 2006; Chen et al. 2010; Pineda et al. 2011; Pezzuto et al. 2012). And a few properties are expected for the FHSCs based on their dust continuum emissions, including (1) low luminosity ($<10^{-1} L_\odot$), temperature ($<20$ K), (2) no significant emissions in far-infrared and shorter wavelengths ($\lambda < 70$ $\mu$m), and (3) dense and compact morphology in (sub)millimeter wavelengths.

At a distance of 415 pc (Menten et al. 2007; Sandstrom et al. 2007), the Orion molecular cloud is the closest and best-studied massive star-forming complex. Besides the regions with bright young stars, Orion contains a huge amount of cold, quiescent, and dense gas (e.g., Salji et al. 2015, and references therein). In our previous studies (Li et al. 2007, 2013; Velusamy et al. 2008; Ren et al. 2014), the quiescent cores in Orion A and Orion South have been selected and investigated. A large fraction of the cores were found to be unstable to the self-gravity and likely to have lower temperatures than their surroundings (Li et al. 2013). The candidate cores for the transition stage can be selected based on two requirements: the cores should be supercritical to the self-gravity and meanwhile have no detectable IR sources. Some likely candidates were examined but found to actually have faint embedded IR sources, and even the multiple stars that are associated with the core fragmentation (Ren et al. 2014). Subsequent studies should be performed over a larger field in order to enlarge the sample. And the evolutionary stages should be evaluated based on more evidences.

Located $\sim 4^\circ$ to the North of Orion A, NGC 2024 in the Orion B cloud contains extended gas structures with embedded cold dense cores. The major fraction of the gas is assembled in a compact filamentary structure (Mezger et al. 1992; also see Figure 1). A number of observations were performed to examine the physical properties therein (Gaume et al. 1992; Mauersberger et al. 1992; Mezger et al. 1992; Chandler & Carlstrom 1996; Watanabe & Mitchell 2008; Alves et al. 2011; Choi et al. 2015). These observations revealed that the dense filament is located behind the hot ionized gas and has complex structures. But the specific properties and evolutionary state of each core are still to be investigated. Gaume et al. (1992) presented Very Large Array (VLA) observations in the NH$_3$ lines, but only obtained average physical parameters for several regions owing to the limited velocity resolution and spectral sensitivity.

In this work, we present a new observational study for NGC 2024 using the continuum emissions from mid-infrared to...
submillimeter bands. We examined the mass and the temperature distributions of the entire filament. Moreover, to study the star-forming properties in the most massive core FIR-3 therein, we carried out new NH$_3$ observations with the Karl G. Jansky Very Large Array (JVLA). The results show that the dense cores on the filament tend to have young evolutionary stages and should be spatially separated from the hot gas and dust in the foreground. In Section 2, we describe the observation. In Sections 3 and 4, we describe the filament and dense core structures and their dust temperatures. In Section 5, we present the mass and temperature distributions within FIR-3 based on the high-resolution NH$_3$ spectral data. In Section 6, we discuss the core evolutionary state based on their physical parameters. A summary is given in Section 7.

2. OBSERVATION AND DATA REDUCTION

The observation of NGC 2024 FIR-3 was carried out with the NRAO$^4$ JVLA on 2014 September 6. The antennae were in D configuration. One baseline ($\lambda_{00}$/CO) was tuned at 23.9 GHz, in which two sub-bands were placed at the frequencies of the NH$_3$ (1, 1) and (2, 2) lines, respectively. Each subband had a bandwidth of 8 MHz. All the hyperfine components (HFCs) of the NH$_3$ (1, 1) lines are covered by the subband with a velocity resolution of 0.1 km s$^{-1}$. 3C 147, which has a flux density of 2.8 Jy in the $K$ band under the D configuration, was used as the bandpass and flux calibrator. The quasar J0541–0541 was adopted as the antenna gain calibrator. The total on-source integration time was 50 minutes.

The CASA program$^5$ was used for the data calibration analysis and imaging. Aladin sky atlas$^6$ was also used for inspecting the images. The synthesized beam size is $3.3 \times 2.8$, and the rms noise level is 7 mJy beam$^{-1}$ (1.2 K) per 0.1 km s$^{-1}$ channel.

In order to investigate the entire filament structure, the stellar emissions, and the spectral energy distribution (SED), we also obtained mid- to far-infrared images including (1) Spitzer/IRAC images from the Archive of the Spitzer Enhanced Imaging Products;$^7$ (2) the Herschel PACS 70, 100, and 160 $\mu$m bands, and SPIRE 250, 350, and 500 $\mu$m bands taken from the Herschel Science Archive;$^8$ (3) the MSX 12, 16.5, and 21 $\mu$m images from the MSX Image Server and Catalog Overlays v. 6.0;$^9$ and (4) the JCMT/SCUBA 450 and 850 $\mu$m continuum maps from the JCMT science archive.$^{10}$

The Herschel PACS and SPIRE images are Level-2.5 and Level-3 products, respectively. The PACS 100 and 160 $\mu$m images are from the “PACS-only” data and were mapped at a scan speed of 20$''$ s$^{-1}$ and Repetition factor of 6. The PACS 70 $\mu$m and all the SPIRE images are in parallel mode and have

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$^4$ The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

$^5$ http://casa.nrao.edu

$^6$ “Aladin sky atlas” is developed at CDS, Strasbourg Observatory, France (Boch & Fernique 2014).

$^7$ http://sha.ipac.caltech.edu/applications/Spitzer/SHA/

$^8$ Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA. http://www.cosmos.esa.int/web/herschel/science-archive

$^9$ http://irsa.ipac.caltech.edu/applications/MSX/MSX/

$^{10}$ The James Clerk Maxwell Telescope is operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the United Kingdom, the Netherlands Organization for Scientific Research, and the National Research Council of Canada. http://www.cadc.hia.nrc.gc.ca/jcmt/.
a scan speed of 60′′ s⁻¹. The Herschel images have sensitivities between 5 and 40 mJy pixel⁻¹ (see Table 6 in Appendix A.1), which are 2–3 orders of magnitudes smaller than the filament emissions. Therefore, the flux uncertainties should mainly come from the flux calibration and photometry processes, as described in Appendix A.1.

3. THE MASS DISTRIBUTION OF THE FILAMENT AND THE RIDGE

3.1. Dust Continuum Emissions

The Spitzer, MSX, Herschel, and JCMT/SCUBA images from mid-infrared to submillimeter bands are shown in Figure 1. Originally, the PACS 70, 100, and 160 μm images were in units of Jy pixel⁻¹, and the SPIRE and SCUBA images were in Jy beam⁻¹. In Figure 1, the intensity unit was scaled to Jy arcsec⁻² by dividing the original intensity scale by the pixel (PACS) or the beam (SPIRE and SCUBA) areas, in order to provide a fair comparison for the intensity scales throughout the wavelength range.

Figure 1(a) shows the SCUBA 450 μm emission (contours) overlaid on the red-green-blue (RGB) image of the IRAC 3, 5, and 8 μm bands. The brightest star and major heating source in this region is IRS-2b (Bik et al. 2003), which was estimated to have a spectral type between O8V and B2V. It is located at a projected distance of 30″ (0.05 pc) from the filament. The FIR cores (specified in Figure 2 and Section 3.2) are labeled with plus signs. The 8 μm emission (red) shows the extended emission over the entire region and a more prominent “hot ridge” structure going across FIR-5. The MSX RGB image (12, 16.5, and 21 μm bands, shown in Figure 1(b)) also evidently traces the hot ridge. In the MIPS 24 μm band (Figure 1(c)), the extended emission region is largely saturated over a spatial extent of 100″–200″ (0.2–0.4 pc), and its southern boundary is almost in parallel with the hot ridge. The extended emission and the ridge should represent the H II and the photodissociation region (PDR) around IRS-2b, respectively (Roshi et al. 2014); the ridge might be formed as the H II region is expanding and compressing the surrounding medium.

The PACS 70 μm image (Figure 1(d)) is also dominated by the hot-ridge emission. Among the seven major dense cores identified in Mezger et al. (1992), only FIR-4 is significantly seen. FIR-5 is totally blended with the ridge emission and cannot be separated. The PACS 100 μm image (Figure 1(e)) exhibits similar features but with the filament more evidently seen (in particular, FIR-2 and FIR-3), while the ridge becomes less intense. In PACS 160 μm, SPIRE 250 μm, 350 μm, and 500 μm, and SCUBA 450 μm and 850 μm bands (Figures 1(f)–(k)), the emissions are dominated by the filament and exhibit similar morphologies, while the ridge is much weaker in those bands.

3.2. Core Identification and Flux Measurement

The filament and FIR cores are best revealed in the SCUBA 450 μm band. On the 450 μm image, the dense cores were identified using the IDL routine Hyper (Traficante et al. 2015). Hyper will extract local emission peaks, identify the cores, fit the angular size and surface brightness of each core with a 2D Gaussian profile, and estimate the flux density within the core area. In this process, the background emission is subtracted through a 2D polynomial fitting. The best-fit core radii for the 450 μm cores are shown in Figure 2(a). Using Hyper, the seven FIR cores (Mezger et al. 1992) were all clearly extracted. In addition, FIR-5 was resolved into two objects (denoted as FIR-5a and 5b), which are consistent with the previous observations (Wiesemeyer et al. 1997; Lai et al. 2002). FIR-5a was further resolved into at least seven condensations in Lai et al. (2002).

As shown in Table 1, FIR-2, FIR-6, and FIR-7 are fitted to have large ratios of \( r_{\text{maj}}/r_{\text{min}} \). Such elongated core areas should be a result of confusion with the extended filamentary structures. As shown in Figure 2(a), the cores are evidently seen only above the 30% contour, while below this level, the emission is mainly from the filament. Figure 2 also shows that the elongations of the cores are altogether reasonably along the filament (at both 160 and 450 μm). To eliminate the confusion, we performed another fitting assuming each core to have a circular shape. The 450 μm emission contours and the cores are overlaid on the IRAC RGB image. The yellow stars indicate the protostars identified in the IRAC bands (Megeath et al. 2012). We note that at 70 μm, the core FIR-5 is blended with the hot dust emission; thus, the two sources should represent the emission peaks rather than dense cores.
Table 1
The Positions and Sizes of the Cores as Fitted by Hyper

| Object | Position at 450 μm (R.A., Dec.) | 70 μm Offseta | 160 μm Offseta | r_maha b | r_maha b | pab | r_cmb c |
|--------|---------------------------------|---------------|---------------|-----------|-----------|-----|---------|
| FIR-1  | 05:41:41.80-01:53:47.0          | unidentified  | (1.4, −3.6)   | 12        | 11        | 126 | 10/8.9 |
| FIR-2  | 05:41:42.50-01:54:06.0          | unidentified  | (0.7, −1.8)   | 16        | 9         | 157 | 9/7.8  |
| FIR-3  | 05:41:43.00-01:54:24.0          | unidentified  | (−0.4, −2.4)  | 15        | 10        | 146 | 10/8.9 |
| FIR-4  | 05:41:44.00-01:54:42.0          | (0.36, −4.68) | (0.4, −4.3)   | 13        | 9         | 147 | 9/7.8  |
| FIR-5a | 05:41:44.10-01:55:40.0          | (1.8,8.64)    | (2.9, −2.5)   | 14        | 10        | 269 | 11/10.0|
| FIR-5b | 05:41:44.80-01:55:32.0          | (0.36, −2.16) | (0.4, −4.7)   | 13        | 10        | 107 | 12/11.1|
| FIR-6  | 05:41:45.00-01:56:01.0          | (1.44, −2.16) | (1.8, −2.4)   | 16        | 11        | 157 | 12/11.1|
| FIR-7  | 05:41:44.90-01:56:15.0          | unidentified  | (2.5, 6.5)    | 16        | 9         | 184 | 10/8.9 |

Notes.
1. The R.A. and decl. offset at 70 and 160 μm bands relative to the core center positions at 450 μm. The cores unidentified by Hyper are not shown.
2. The major axes, minor axes, and position angles (pa). The pa values are counterclockwise to the north.
3. The best-fit core radius assuming a circular shape for the core area at 450 μm. The second value is the radius deconvolved with the beam size, i.e., r^2 = r^2_{obs} − (θFWHM/2)^2, where θFWHM = 9° is the FWHM beam size.

Table 2
The Magnitude of the IR Sources Associated with the Cores in IRAC Bands and the Flux Densities of the Cores in MSX Bands

| Object | M_{3.6 μm} b | M_{4.5 μm} b | M_{5.8 μm} b | S_{1 μm} | S_{12 μm} | S_{25 μm} | S_{70 μm} |
|--------|--------------|--------------|--------------|------------|-----------|-----------|-----------|
| FIR-1  | 9.09         | 8.48         | N            | <0.2       | <0.5      | <0.6      | <3.0      |
| FIR-2  | 9.90         | 9.17         | N            | <0.2       | <0.5      | <0.6      | <3.0      |
| FIR-3  | N            | N            | N            | <0.2       | <0.5      | <0.6      | <3.0      |
| FIR-4  | 8.69         | 7.09         | N            | <0.2       | <0.5      | <0.6      | <3.0      |
| FIR-5b | N            | N            | N            | 43         | 50        | 65        | 325       |
| FIR-6  | N            | N            | N            | <0.2       | <0.5      | <0.6      | <3.0      |
| FIR-7  | N            | N            | N            | <0.2       | <0.5      | <0.6      | <3.0      |
| Ridge  | N            | N            | N            | 37         | 32        | 35        | 307       |

Notes.
1. The IRAC magnitudes in 3.6, 4.5, and 8.0 μm bands for the point source possibly associated with the FIR cores, from Megeath et al. (2012). The label "N" means nondetection and would indicate M_{3.6 μm} < 14.5.
2. FIR-5a and FIR-5b are blended; thus, the measured flux density should represent a total value of the two. The emission from the hot ridge is also included.
3. In the IRAC 8 μm and all the MSX bands, the flux density is an averaged value for the four box regions shown in Figure 3(b). The four regions are individually examined and found to have small differences in T_{d}(<±2 K).

Only FIR-1, FIR-2, and FIR-4 coincide with the IRAC sources, with the magnitudes of M_{3.6 μm} = 8.69 to 9.09, as listed in Table 2. The brightest IR source coincides with FIR-4. Based on the detection limit, the FIR cores absent of IRAC sources should have M_{3.6 μm} > 14.6.

The source extraction with Hyper was also applied for the PACS 70 μm and 160 μm images (Figures 2(c) and (d), respectively). The 70 μm image was examined for potential additional hot-dust sources, while the 160 μm image was adopted to compare with the 450 μm cores. As a result, FIR-4, FIR-6, and two other sources were identified at PACS 70 μm. But the two sources on the ridge should represent the emission peaks of the hot dust rather than dense cores. On the PACS 160 μm image, all the dense cores were identified, with the central positions consistent with the 450 μm values within 7" (see Table 1).

We adopted the 450 μm core areas (in the circular case) to measure the flux densities of all the cores except FIR-5a and FIR-5b. At 70 μm, the emission intensities within the FIR cores (except FIR-4 and FIR-5) range from 1 to 3 Jy arcsec^-2, which are much higher than the detection limit, but are comparable with the extended emission level (1.5 ± 0.9 Jy arcsec^-2). We thus suggested a marginal detection for these cores above the extended emission level. The flux measurement is described in more detail in Appendix A.1. We also selected five positions on the hot-gas ridge, including one at FIR-5 (Figure 3(b)), and measured the flux density at each position within a square region that covers the ridge width (d = 25°). On the Spitzer and MSX images (3.6–21 μm), there are no structures likely associated with the filament. The measured flux densities within the core areas should represent upper limits for the FIR cores. The flux densities of the cores in the IRAC and MSX bands are listed in Table 2, and the values of Herschel and SCUBA bands are shown in Table 3.

4. DUST TEMPERATURE DISTRIBUTION
4.1. The SED Fitting for the Cores and the Ridge

We estimated the dust temperature in the FIR cores and the ridge from their SEDs throughout the MSX, Herschel, and JCMT bands. The SED is fitted using a graybody emission model (Hildebrand 1983). Based on the radiative transfer, the flux density of the dust core is

\[ S_{ν} = \Omega B_{ν}(T_{d})[1 - \exp(-\tau_{ν})], \]

where S_{ν} is the flux density at the frequency ν, Ω is the solid angle of the core or the selected area, B_{ν}(T_{d}) is the Planck function of the dust temperature T_{d}. The optical depth \(\tau_{ν}\) is
is the mean molecular weight of the gas.\( n = \frac{\mu N_{\text{tot}}}{g} \),

where \( N_{\text{tot}} \) is the gas column density (mostly H+H\(_2\)), \( \mu = 2.33 \) is the mean molecular weight (Myers 1983), \( \mu H \) is the mass of the hydrogen atom, and \( g = 100 \) is the gas-to-dust mass ratio. \( \kappa_\nu \) is the dust opacity and is expected to vary with frequency in the form \( \kappa_\nu = \kappa_{230 \text{ GHz}}(\nu/230 \text{ GHz})^\beta \), with the reference value of \( \kappa_{230 \text{ GHz}} = 0.9 \) cm\(^2\) g\(^{-1}\), as adopted from the dust model for the grains with coagulation for 10\(^5\) yr with a cold and would also contribute to the total mass of the hydrogen atom, and \( n = 101.2 \) mm\(^2\) m. The Continuum Flux Densities in Units of Jy of the Cores and the Ridge in Herschel and SCUBA Wavebands

| Object | \( S_{70 \text{\mu m}} \) | \( S_{100 \text{\mu m}} \) | \( S_{160 \text{\mu m}} \) | \( S_{250 \text{\mu m}} \) | \( S_{350 \text{\mu m}} \) | \( S_{450 \text{\mu m}} \) | \( S_{850 \text{\mu m}} \) |
|--------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| FIR-1  | 130              | 285              | 683              | 295              | 121              | 49               | 65               |
| FIR-2  | 304              | 650              | 873              | 472              | 205              | 58               | 101              |
| FIR-3  | 330              | 743              | 1282             | 694              | 298              | 80               | 156              |
| FIR-4  | 1133             | 1620             | 1260             | 577              | 232              | 76               | 107              |
| FIR-5\(^a\) | 3571         | 3655             | 3951             | 1918             | 625              | 125              | 125/97           |
| FIR-6  | 313              | 660              | 922              | 646              | 268              | 58               | 111              |
| FIR-7  | 165              | 442              | 804              | 479              | 168              | 49               | 75               |
| Ridge\(^b\) | 2376           | 1182             | 497              | 141              | 37               | 10               | 15               |

Notes.

\(^a\) FIR-5a and FIR-5b are blended except at 450 \( \mu \)m. The \( S_{70 \text{\mu m}} \) values for the two cores are separately given, while \( S_\nu \) at other bands represent the total value of the two. At \( \lambda < 100 \) \( \mu \)m, the emission from the hot ridge is significant and would also contribute to the total \( S_\nu \).

\(^b\) In each band, the flux density represents an average value for the four box regions as shown in Figure 3(b). The four regions are individually examined and found to have a small difference of \( \Delta T_\nu \) (<2 K).

determined by other parameters as

\[
\tau_\nu = \kappa_\nu \mu H N_{\text{tot}}/g,
\]

The best-fit SEDs for the FIR cores are shown in Figure 3(a) (FIR-5 is put in Figure 3(b) to compare with the ridge). The physical parameters (\( \beta \) and \( T_\nu \)) are presented in Table 4. The cores were measured to have a small variation in both \( T_\nu \) and \( \beta \). FIR-4 has the highest temperature of \( T_\nu = 22 \) K, which is in agreement with the brightest infrared source therein. The total luminosities of the cores were estimated using \( L_{\text{core}} = \int 4\pi D^2 S_\nu d\nu \) and are also presented in Table 4. We note that FIR-3 was also observed in 1.2 mm continuum (Hill et al. 2005), with the flux density measured to be \( S_{1.2 \text{mm}} = 10 \) Jy. In comparison, by extrapolating the SED curve, we obtained a much lower value of \( S_{1.2 \text{mm}} = 6 \) Jy. The difference is probably due to the low resolution (24") and large mapping step (44") in the previous observation. The mapping step is larger than distances of FIR-1 and FIR-4 from FIR-3; thus, the cores would be poorly resolved and emissions from FIR-1 and FIR-4 might be largely included in the measured flux density. The \( \beta \) values in the filament are comparable to the highest \( \beta \) values among the other Orion regions (Goldsmith et al. 1997).

The SED within FIR-5 can be well fitted using two temperature components with \( T_\nu = 17.5 \) and 55 K, respectively (Figure 3(b)). The cold component is comparable to the other FIR cores and should represent the SED of FIR-5 itself. The hot component (\( T_\nu = 55 \) K) should represent the contribution from the hot ridge. The average flux densities of the four other positions on the ridge are also shown in Figure 3(b). The SED fitting resulted in \( T_\nu = 56 \) K and \( \beta \approx 1.6 \). We note that the \( \beta \) value for the hot component at FIR-5 is not well constrained because the Rayleigh–Jeans tail of the SED is dominated by the
cold component. We expect it to have a similar value of $\beta \approx 1.6$.

The optical depth for the hot component is optically thin throughout the observed wavelengths, with $\tau \approx 0.1$ at $\lambda = 70$ $\mu$m, while the cold dust becomes moderately optically thick at $\lambda < 100$ $\mu$m. At low optical depth, Equation (1) can be approximated as

$$ S_{\nu} = \frac{k_{\nu} B_{\nu}(T_d) \Omega \mu m_\text{H}_2 N_{\text{tot}}/g}{gD^2}, $$

where $D = 415$ pc is the source distance and $M_\Omega$ is the gas mass within $\Omega$. $N_{\text{tot}}$ was estimated from the 450 $\mu$m peak intensity (in Jy arcsec$^{-2}$), and the masses of FIR cores and the ridge (within the square aperture region) are calculated from their total 850 $\mu$m values. We note that FIR-5a and FIR-5b are resolved at 450 $\mu$m, so their masses can be separately obtained using the average $T_d$ and $\beta$ values for the two cores. The volume number density can be estimated from $N_{\text{tot}}$ as $n = N_{\text{tot}}/2R_{\text{core}}$. This value represents an average along the line of sight. The results are also presented in Table 4. We note that if the $k_{230 \text{GHz}}$ value is different, the core mass would vary with $k_{230 \text{GHz}}$ proportionally, while the temperature fit remains unchanged. For example, if adopting $k_{230 \text{GHz}} = 0.5$ cm$^2$ g$^{-1}$ (Preibisch et al. 1993), the core masses would increase by a factor of 0.9/0.5 $= 1.8$. The SED fitting is described in more detail in Appendix A.2.

For the hot component, the IRAC 8 $\mu$m and MSX 12.5 $\mu$m intensities are above the SED curve, suggesting a dust component with even higher temperature. Mezger et al. (1992) fitted the SED of the entire region and identified two cold components with $T_d = 19$ and 22 K, which are consistent with the temperature range for the FIR cores. But the hot component was measured to have $T_d = 45$ K, which is cooler than the hot ridge observed here. The difference is probably because the dust densities at shorter wavelengths ($\lambda < 350$ $\mu$m) were not included in their estimation.

It is also noteworthy that the ridge has a much lower $\beta$ than the values in the FIR cores. To examine the validity of this discrepancy, we attempted to fit the SED using a fixed value ($\beta = 2.7$) comparable to the FIR cores. In this case, the Rayleigh–Jeans tail ($\lambda = 200$ to 1000 $\mu$m) of the SED largely deviates from the observed values and cannot be reconciled by adjusting $\tau$ and $T_d$. The difference in $\beta$ may indicate different dust properties in the two components and support the trend that $\beta$ decreases with $T_d$ (Arab et al. 2012).

5. THE NH$_3$ GAS STRUCTURE AND TEMPERATURE DISTRIBUTION

5.1. The Gas Distribution

The NH$_3$ line spectra at the center of FIR-3 are shown in Figure 4, with the hyperfine structures (HFS) labeled on the lines. The NH$_3$ maps around FIR-3 are shown in Figure 5. The NH$_3$ (1,1) inner-satellite group (isg) has lower opacities than the main group (mg) and thus would better reveal the dense gas structures. Figure 5(a) shows the integrated emission of the isg, which is overlaid on the IRAC image. The NH$_3$ gas is located around the FIR-3 core center and aligned in parallel with the 450 $\mu$m filament, suggesting that NH$_3$ traces the densest gas component in the core.

Figures 5(b)–(d) show the integrated line emissions of the NH$_3$ (1,1)-mg, (1, 1)-isg, and (2, 2)-mg. The NH$_3$ (1,1)-mg and (1, 1)-isg show similar morphologies, except that the mg emission is somewhat saturated due to its higher optical depth. We also used Hyper to extract the compact sources in the NH$_3$ emission region (Figure 5(b)). As a result, four gas condensations were found in FIR-3, which are labeled as Cd-1, Cd-2, Cd-3, and Cd-4. Another two condensations in FIR-2 are labeled as Cd-n1 and Cd-n2. The physical parameters of the condensations are shown in Table 5, wherein the NH$_3$ column densities are estimated using Equation (4).

Figure 5(d) shows that the (2, 2) emission peak does not coincide with the (1, 1) peak but has a noticeable offset of $\approx 3''$ to the northwest. Since $(J, K) = (2, 2)$ level has a much higher excitation energy ($E_{u(2,2)} = 81$ K) than $(1, 1)$ ($E_{u(1,1)} = 24$ K), the (2, 2) emission peak may indicate a higher temperature at its emission peak.

5.2. The Temperature Distribution from NH$_3$

To investigate the temperature distribution from the NH$_3$ lines, we fitted the line profile using the fiducial radiative
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Figure 4. VLA NH$_3$ (1, 1) and (2, 2) spectra at the FIR-3 center. In each panel, the black solid line and the red dashed line represent the observed spectrum and the HFS fitting, respectively. The HFS is denoted on each emission peak, wherein “mg,” “isg,” and “osg” represent the main, inner-satellite, and outer-satellite groups, respectively.

The NH$_3$ rotational temperature can then be estimated from the (1, 1) and (2, 2) transitions using the method in Li et al. (2013). From the observed spectra we calculated the intensity ratio between isg and mg, $R_{\text{sm}} = \frac{\int T_b\text{isg}(1, 1)\,dv}{\int T_b\text{mg}(1, 1)\,dv}$, and the intensity ratio between the two transitions, $R_{\text{f2}} = \frac{\int T_b(1, 1)\,dv}{\int T_b(2, 2)\,dv}$. The rotational temperature is calculated from the two ratios as

$$T_{\text{rot}} = 41.5 \, \text{K}/\ln[1.06 \times C(1, 1) \times R_{\text{f2}}],$$

(4)

where $C(1, 1) = 0.003 + 2.26R_{\text{sm}} + 0.00032\exp(5.38R_{\text{sm}})$ is a correction factor for the (1, 1) optical depth. The uncertainty of the $T_{\text{rot}}$ is estimated to be $\delta T_{\text{rot}} \approx 1.5 \, \text{K}$ based on the noise level of the NH$_3$ lines and the method of Busquet et al. (2009, Equation (A.7) therein). We estimated the relation between $T_{\text{rot}}$ and the gas kinetic temperature $T_0$ based on the physical conditions in FIR-3 and using the RADEX program (vander Tak et al. 2007). The calculation is specified in Appendix A.3.

It resulted in a nearly thermalized population for (1, 1) and (2, 2) levels as mainly due to the high density in FIR-3. As a result, $T_{\text{rot}}$ is close to $T_0$.

As shown in Figure 5(e), the $T_0$ map has a noticeable peak with $T_0 \approx 25 \, \text{K}$, with the position coincident with the (2, 2) emission peak. Away from the peak, $T_0$ varies between 15 and 19 K, which are significantly lower than the peak value, but similar to the dust temperature in FIR-3. The temperature peak suggests an embedded YSO in condensation Cd-2. Since FIR-3 has no detectable IR point source, it is possible that the YSO is younger than Class 0 and the heating is mainly due to the accretion or core collapse. In this case the $T_0$ peak value may provide some constraint on accretion rate and core evolutionary state.

We assumed that the central region originally had a similar temperature with its surroundings ($T_0 = T_{\text{avg}} = 18 \, \text{K}$) in the starless stage and was then heated to the current value ($T_0 = T_0\text{peak} = 25 \, \text{K}$) after the central object started to accrete mass. The luminosity increase at the second stage is then

$$\Delta L = (4\pi/g)M_{\text{peak}}\int k_e[B_e(T_{\text{peak}}) - B_e(T_{\text{avg}})]\,dv,$$

(5)

where $M_{\text{peak}}$ is the hot-gas mass associated with the $T_0$ peak. In Equation (5) we also assumed that $T_0$ can approximate the dust temperature. The $T_0$ peak is not resolved and thus would represent an average value within one beam; we thus consider the gas mass also within one beam area, that is, $M_{\text{peak}} = \pi R_{\text{beam}}^2N(\text{H}_2)\mu m_{\text{H}} = 0.3 \, M_\odot$. As a result, the luminosity increase is estimated to be $\Delta L \approx 50 \, L_\odot$.

On the other hand, the theoretical accretion luminosity is (Stahler et al. 1980)

$$L_{\text{acc}} = \frac{G M_* M_{\text{acc}}}{R_\odot},$$

(6)

where $M_*$, $R_\odot$, and $M_{\text{acc}}$ are the mass, radius, and accretion rate for the central object, respectively. The stellar mass can be estimated from its natal core mass assuming a star-forming efficiency of $\varepsilon = 0.3$ (Alves et al. 2007). Adopting Cd-2 as the natal gas condensation, we can obtain $M_\odot = \varepsilon M_{\text{Cd-2}} \approx 0.3 \, M_\odot$. We note that the spatial extent of the $T_0$ peak may only reflect the spatial range being heated, but is not to define a gas condensation, and thus was not used to estimate $M_\odot$. To estimate the accretion rate, we also assume that the accretion energy is eventually released mainly through the dust continuum emission so that $L_{\text{acc}} \approx \Delta L$.

In theory (e.g., Young & Evans 2005; Tomida et al. 2010), the YSO is expected to have $R_\odot = 10^2 - 10^3 R_\odot$ at the FHSC stage and then collapse into $R_\odot$ scale during the protostar formation (second collapse). We derived $M_{\text{acc}}$ for these two cases. First, if the central object is a first core with $R_\odot = 10^2 R_\odot$, the expected accretion rate would be $M_{\text{acc}} \gtrsim 6 \times 10^{-4} M_\odot \, \text{yr}^{-1}$. Alternatively, if the YSO has already collapsed into $R_\odot$ scale, it only needs to have $M_{\text{acc}} \approx 6 \times 10^{-6} M_\odot$ in order to maintain the observed $\Delta L$. The second $M_{\text{acc}}$ value is comparable to the average $M_{\text{acc}}$ for
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Figure 5. (a) Integrated NH$_3$ (1, 1)-isg emission (black contours) overlaid on the IRAC RGB image; the SCUBA 450 µm emission is also presented in white contours. The levels are 10%, 30%, 50%, 70%, and 90% of the maximum. The yellow dashed ellipses denote the FIR core areas fitted by Hyper. (b) Integrated NH$_3$ (1, 1)-isg emission (false-color image and contours). The contour levels are 4, 8, 12, 16, and 20 times the rms level (0.6 K km s$^{-1}$). The white circles indicate the condensation areas fitted by Hyper. (c) The (1, 1)-isg emission (contours) overlaid on the (1, 1)-mg emission (false-color image). (d) The (1, 1)-isg emission (contours) overlaid on the integrated (2, 2) emission (false-color image). (e) The T$_K$ map estimated from the (1, 1) and (2, 2) emissions. The contours are also (1, 1)-isg emission.

Table 5

| Object | Offset$^a$ | $T_K$ (arcsec) | Radius (arcsec) | Mass$^b$ ($M_\odot$) | N(NH$_3$) ($10^{15}$ cm$^{-2}$) |
|--------|------------|----------------|-----------------|----------------------|-------------------------------|
| Cd-1   | (~3.0, 7.0) | 18(2)          | 3.5(0.5)        | 1.2(0.8)             | 0.4(0.2)                     |
| Cd-2   | (~1.5, 4.0) | 25(2)          | 3.5(0.5)        | 1.0(0.7)             | 2.9                          |
| Cd-3   | (0.0)       | 19(2)          | 4.0(0.5)        | 2.0(1.5)             | 3.8                          |
| Cd-4   | (2.5, ~3.5) | 17(2)          | 4.0(0.5)        | 0.8(0.5)             | 2.7                          |
| Cd-n1  | (~7.5, 20.5)| 16(2)          | 3.5(0.5)        | 0.6(0.4)             | 2.3                          |
| Cd-n2  | (~6.5, 14.5)| 14(2)          | 3.5(0.5)        | 0.3(0.2)             | 1.7                          |

Notes.

$^a$ The R.A. and decl. offset from the C3-3. C3-3 is centered at R. A. = 05:35:26.53, decl. = -05:04:00.6. The condensations are shown in Figure 5(b).

$^b$ The C3-3 mass is assumed that its average column density is equal to the peak total column density in FIR-3 (Table 4), i.e., $M = \pi^2\mu m_0 N_{\text{tot,FIR3}}$. The masses of the other condensations are calculated by comparing with C3-3 and assuming that mass is proportional to NH$_3$ (1, 1)-isg integrated intensity, i.e., $M_{\text{C3-1}} = M_{\text{C3-3}}/(S_{\text{C3-3}}/S_{\text{C3-1}})$.

5.3. The Gravitational Instability

The possibility for the core collapse can also be evaluated through the Jeans mass, which is

$$M_J = \frac{\pi}{6} \frac{c_s^3}{G^3/2\rho^{1/2}}$$

$$= 2M_\odot \left( \frac{\sigma^2}{0.2 \text{ km s}^{-1}} \right) \left( \frac{n}{10^3 \text{ cm}^{-3}} \right)^{-\frac{1}{2}}.

(7)$$

$M_J$ represents the highest mass that can be sustained by the internal pressure related to the velocity dispersion $\sigma$. FIR-3 has $n \geq 10^4$ cm$^{-3}$, and the velocity dispersion is $\sigma_{\text{obs}} = \Delta V/\sqrt{8 \ln(2)} \approx 0.42$ km s$^{-1}$. These parameters lead to $M_J \approx 0.5 M_\odot$, which is smaller than the Cd-2 mass, suggesting that the collapse of Cd-2 is possible unless there is additional support such as magnetic field. Besides FIR-3, FIR-4, FIR-5, and FIR-6 were also suggested to be unstable based on the observed H$_2$CO line widths (Watanabe & Mitchell 2008).

Using the NH$_3$ kinetic temperature, the velocity dispersion due to the thermal motion is estimated to be $\sigma_{\text{th}} = k_B T_K/\mu m_0 = 0.25 - 0.33$ km s$^{-1}$ as $T_K$ varies between 19 and 27 K. The nonthermal contribution is $\sigma_{\text{nt}} = \sqrt{\sigma_{\text{obs}}^2 - \sigma_{\text{th}}^2} \approx 0.2 - 0.3$ km s$^{-1}$. The $\sigma_{\text{nt}}$ value is in the subsonic range but tends to be higher than the values in the cold dense gas (e.g., $\sigma \approx 0.1 - 0.2$ km s$^{-1}$; Pineda et al. 2010). Based on the current data, it is uncertain whether the FIR cores are experiencing a turbulence decay or, oppositely, becoming more turbulent due to the ongoing star-forming activities (e.g., Fontani et al. 2012). We examined the NH$_3$ line width over the emission region and found no significant variation. A velocity field over a larger area mapped by a single dish may help better reveal the origin of the turbulence.

6. The EVOLUTIONARY STATE OF THE FIR CORES

6.1. Mass–Luminosity Relation

The relation between the luminosity and mass can also provide an estimate for the core evolutionary state (Molinari et al. 2008; Elia et al. 2013). The mass–luminosity diagram is shown in Figure 6. The cores except FIR-4 are quite closely aligned in a power law of $L \propto M^p$ with the index $p = 1.0$. The deviation of FIR-4 is expected due to its higher dust temperature. Besides the IRAC source, active star formation in FIR-4 is also indicated by the radio continuum and maser emissions therein (Choi et al. 2015). FIR-1, FIR-2, and FIR-6 may also have protostars as due to the presence of IRAC sources or outflows (Chandler & Carlstrom 1996). But for these three cores, the stellar emissions should still be too weak to significantly increase the total luminosities. It is also possible that the IR sources at FIR-1 and FIR-2 are just foreground stars.

Figure 6 also shows the $M$–$L$ distribution for the other four samples with specified evolutionary stages, including Class 0 protostars (Andre et al. 2000, p. 59), prestellar cores (Elia et al. 2013), starless cores (Strazzella et al. 2015), and recently identified FHSC candidates (with respective references shown in the figure caption). As the figure shows, the more evolved samples do not necessarily have higher absolute luminosities, but instead show steeper slopes for their $M$–$L$ relations, namely,
higher $p$ values. The NGC 2024 cores have a similar slope to the prestellar sample ($p = 1.0$).

From integration of Equation (1) we can obtain $L_{\text{core}} \propto M_{\text{core}}^{4+\beta}$. This indicates that luminosity $L_{\text{core}}$ can be sensitively affected by $T_d$. A sample would have $L \propto M_{\text{core}}^{4}$ only if the cores have quite similar temperatures. If $T_d$ varies with the core mass, the $L \propto M$ relation would be different. Assuming a power law of $T_d \propto M^q$, we can have $L_{\text{core}} \propto M_{\text{core}}^{4+q(4+\beta)}$. The starless and prestellar samples exhibit relatively flat power laws, probably because the more massive cores are more shielded from the external heating, leading to $q \approx 0$. In contrast, the protostellar cores might have higher $T_d$ in more massive cores ($q > 0$) because the massive ones would preferentially become the birthplace for the high-mass stars and/or multiple systems. As a result, the relation would become steeper than $L_{\text{core}} \propto M_{\text{core}}^{4}$. The core sample collected from different regions might also be affected by the variation in $\beta$, which could be more complicated, and is not discussed here.

In fact, NGC 2024 should be distinguished from other samples by the presence of strong external heating, which regulates cores into similar temperatures, and moreover, increases their absolute luminosities to be even higher than the Class 0 sample. In such a case, the absolute luminosities of the individual cores would not effectively trace the evolutionary stages. Similarly, the 70 $\mu$m emission would not indicate embedded protostars as it works in cold isolated regions (e.g., Pineda et al. 2011). In particular, the hot ridge has $T_d \approx 55$ K and strong 70 $\mu$m emission, but should be solely illuminated by the external radiation and have no star formation at all. In comparison, as a confirmed protostellar core, FIR-4 only has $T_d = 22$ K. It could be heated to much higher temperatures if located closer to IRS-2b. In this case, the internal emission can be hardly discerned.

6.2. The Dependence of Dust Temperature on the Stellar Radiation

We made a semi-quantitative estimation for the dependence of $T_d$ on the stellar radiation. If IRS-2b has a spectral type of B0V, it would provide an ultraviolet (UV) radiation with photon flux of $N_{\text{FUV}} = 10^{48}$ s$^{-1}$ (Stahler & Palla 2005, Chapter 15 therein). If there are no strong absorbers around the star, the UV radiation at a distance $r$ can be approximated as

$$
\chi(r) = \frac{E N_{\text{FUV}}}{4\pi r^2}.
$$

We adopted $E = 9$ eV as the average photon energy for the UV radiation field. For a dust core with high opacity in optical ($A_V \gg 1$) in thermal equilibrium, the dust temperature would be

(Li et al. 2003)

$$
T_d = 12.0 \times \left[ \frac{\chi(r)}{\chi_0} \right]^{1/6} K,
$$

where $\chi_0 = 2.0 \times 10^{-4}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$ is the unit intensity for the interstellar radiation field (Draine 1978). With the two equations joined together, $T_d$ would be related to $N_{\text{FUV}}$ and $r$ in the form

$$
T_d(r) = \frac{12.0}{4\pi \chi_0} \left( \frac{E N_{\text{FUV}}}{\chi(r)} \right)^{1/6} r^{-1/3}.
$$

The modeled $T_d(r)$ function is shown in Figure 7. The $T_d(r)$ curves for B1 and O9 stars are also presented for comparison, with the range between them highlighted in yellow. The data for the FIR cores and the five positions on the ridge are presented on the diagram. Their $r$ values represent the projected distances from IRS-2b.

At the observed distances, the model predicts a range of $T_d \approx 55 – 70$ K, which reasonably agrees with the temperature on the hot ridge, but completely deviates from the core temperatures (17–22 K). The low temperatures in the FIR cores may indicate the actual distances from IRS-2b being much larger than the projected values as seen in the image. In comparison, the hot ridge should have a small uncertainty in its distance because it mainly traces the PDR near IRS-2b. The data points for the ridge suggest that the modeled $T_d(r)$ function for a B0 star can reasonably describe the dust heating in NGC 2024. Based on the model, the temperatures of FIR cores would indicate a distance of $r \approx 5$ pc. As a result, the filament should be well separated from the hot region around IRS-2b, which has a spatial extent of 0.2–0.4 pc, as shown in the MIPS 24 $\mu$m emission.

In the case that the intervening absorption between IRS-2b and the filament is not negligible, the UV radiation would be transferred to longer wavelengths. In this case the $T_d(r)$ profile can be evaluated using another dust heating model (Scoville &...
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Figure 7. (a) Dust temperature $T_d$ under the external radiation field of a central heating star as a function of the stellar distance $r$ (Li et al. 2003). The $T_d(r)$ curves corresponding to the three different stellar types are plotted with different lines for comparison. The “second model” refers to that of Scoville & Kwan (1976), with the relation expressed as Equation (11). The $(T_d, r)$ data measured for the hot ridge and the FIR cores in the filament are shown. For the data points, $r$ represents the projected distance from IRS-2b. (b) Schematic view showing the spatial layout of the hot gas/ridge and the filament.

Kwan 1976; Garay & Lizano 1999; Wang et al. 2012):

$$T_d(r) = 71 \left( \frac{0.1 \text{ pc}}{r} \right)^{2/(4+\beta)} \left( \frac{L_{\text{star}}}{10^5 L_{\odot}} \right)^{1/(4+\beta)} \left( \frac{0.1}{f} \right)^{1/(4+\beta)},$$

(11)

where the dust opacity index is adopted as the value for the hot component ($\beta = 1.6$). The luminosity is adopted as the total luminosity of the main-sequence B0 star, which is $L = 5 \times 10^5 L_{\odot}$ (Stahler & Palla 2005). $f = 0.08 \text{ cm}^{-1}$ is the dust emissivity at $\lambda = 50 \mu\text{m}$ for a condition of $\tau_{100\mu\text{m}} = 0.1$ and $n \sim 10^4 \text{ cm}^{-3}$ (Scoville & Kwan 1976). The derived $T_d(r)$ relation is plotted with a thick gray line in Figure 7. This $T_d(r)$ curve is only slightly below the UV radiation model for the B0 star and is also suggestive of a large distance for the FIR cores, i.e., 2–3 pc from IRS-2b.

As another possibility for the low temperature, the filament can have a strong self-shielding due to its higher opacity, and thus it can also maintain a low temperature even if located close to IRS-2b. However, if the filament is near the ridge, its outer layer would also be heated to a similar temperature with the ridge and then exhibit a hot component in its SED in addition to the cold one. In fact, the FIR cores are much fainter than the ridge at $\lambda \lesssim 100 \mu\text{m}$, and their SEDs are completely dominated by the cold component. We thus conclude that the filament should indeed have a large distance from IRS-2b. The previous studies showed that the dense molecular gas should be located behind the H ii region and PDR (Roshi et al. 2014). The current data further show that the hot and cold components are actually spatially separated rather next to each other. The expected spatial layout for the filament and hot gas around IRS-2b is shown in Figure 7(b).

7. SUMMARY

We present an observational study with dust continuum and high-resolution NH$_3$ line emissions to reveal the internal structures and physical properties of the FIR cores in the NGC 2024 filament. A particular focus of this paper is the most massive core FIR-3 therein. The main results are as follows:

1. All the FIR cores in the filament are found to have low dust temperatures between 17.5 and 22 K. FIR-3 has a compact morphology, dust temperature of 17.5 K, and no significant IR sources. The physical properties are suggestive of an evolutionary stage younger than Class 0.

2. In FIR-3, the NH$_3$ line emissions exhibit a compact temperature rise feature with a peak value of $T_k = 25$ K above the surrounding level of $T_k = 15 - 19$ K. From the $T_k$ peak, the central YSO is estimated to have an accretion luminosity of $\Delta L \sim 50 L_{\odot}$. The temperature rise without an infrared counterpart suggests an ongoing or lately occurring collapse from FHSC to Class 0 protostar.

3. The FIR cores in the NGC 2024 filament have comparable or even higher luminosities than the Class 0 cores in the same mass range, but mostly due to the external heating from IRS-2b. On the mass–luminosity diagram, the FIR cores (except FIR-4) exhibit a correlation with the power-law index ($p = 1.0$) comparable to the prestellar sample. For each core, the internal stellar heating appears weak and has no significant influence on temperature or luminosity.

4. The FIR cores have much lower dust temperatures than the hot ridge (56 K). The difference in their $T_d$ suggests that the filament should be much more distant from the central heating star IRS-2b. Comparison with the dust heating models shows that the filament should be separated from the hot ridge by $D \sim 5$ pc along the line of sight. The filament and ridge also have distinct dust opacity indices of $\beta \simeq 2.7$ and 1.6, respectively.

The observed physical properties suggest an overall cold dense state in the filament. And FIR-3 could be an intermediate-mass core with a YSO possibly at a transition stage from the FHSC to Class 0. Further high-resolution observations (e.g., with ALMA) are expected to reveal its internal structures and reveal the details of the collapse and the accretion state.

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APPENDIX A
APPENDIX MATERIAL

A.1. Using Hyper to Measure the Flux Densities

The flux densities of the FIR cores are measured using Hyper (Traficante et al. 2015). In each band, the core radius is convolved with the beam size, namely, \( r_{\text{core}} = \sqrt{r_{\text{core}}^2 + r_{\text{beam}}^2} \), in order to rightly cover the observed core areas. These parameters are adopted from the 450 \( \mu \)m band ideally traces the cold dense cores. Hyper can subtract the background emission and separate the overlapped cores using multi-Gaussian fitting.

The flux errors are mainly determined by three factors: (1) flux calibration, (2) background emission subtraction, and (3) aperture size. The flux calibration has an uncertainty of 10% for PACS,\(^{11}\) 5% for SPIRE,\(^{12}\) 30% for SCUBA 450 \( \mu \)m, and 10% for SCUBA 850 \( \mu \)m (Johnstone & Bally 1999). The background fitting depends on its polynomial order. Varying the order from 0 to 3 would cause an uncertainty of \( \sim 10\% \) for the flux density. The core area depends on the sigma threshold adopted in the fitting. As it varies from 4 \( \sigma \) to 6 \( \sigma \), the core size would vary by \( \sim 30\% \), causing the flux density to vary by \( \sim 40\% \). Considering these factors, the flux error would be \( \sim 70\% \) for PACS, \( \sim 60\% \) for SPIRE, \( \sim 100\% \) for SCUBA 450 \( \mu \)m, and \( \sim 70\% \) for SCUBA 850 \( \mu \)m. The flux densities in the Herschel bands are also corrected for the photometric color-correction factors (CC).

The CC is a function of the dust temperature.\(^{13}\) The correction includes two steps, which are performed iteratively: (1) doing the SED fitting to determine the dust temperature for each core (see Section 4) and the related CC; (2) using CC to correct the flux density of each core. The temperature variation due to CC is small. The \( T_d \) values become converged within two iterations. As shown in Section 4.1, the SED fitting reveals two components with \( T_d \approx 55 \) K and \( T_d \approx 17.5 \) K. The cold component (FIR cores except FIR-5) has \( CC_{70} = 1.269, CC_{100} = 1.051, \) and \( CC_{160} = 0.964, \) and the hot component (ridge) has \( CC_{70} = 0.982, CC_{100} = 0.982, \) and \( CC_{160} = 1.010. \) The SPIRE bands only trace the cold dust emissions and have \( CC_{250} = 0.94, CC_{350} = 0.92, \) and \( CC_{500} = 0.89. \)

For each band, we also measure the random noise level from the emission-free region. The results are shown in Table 6.

A.2. The SED Fitting

The SED fitting is based on the least-squares fit of the observed flux densities, that is, to look for the minimum of

\[
\chi^2 = \sum_{\lambda} \left( \log S_\lambda(T_d) - \log S_{\lambda,\text{obs}} \right)^2 .
\]

\( S_\lambda(T_d) \) is defined in Equation (1), and the free parameters to fit are \( T_d, \beta, \) and \( M_{\text{core}}. \) The fitting is implemented using the NonLinearLSQFitter in the Astropy package.\(^{14}\) The errors in \( \beta, T_d, \) and \( M_{\text{core}} \) are estimated by varying the data points within the uncertainty range for the fitting. The estimated uncertainty levels are \( \delta T_d \approx \pm 1 \) K, \( \delta \beta \approx \pm 0.3, \) and 50%–60% for \( M_{\text{core}}. \) In the case that the SED contains two temperature components with comparable intensities, the wavelength range of \( \lambda = 160–850 \mu \)m is found to be still dominated by the cold component, while the range of \( \lambda = 20–70 \mu \)m is dominated by the hot component. In fact, the two components are only blended around FIR-5. The other cores are dominated by the cold dust, while the emission out of the filament is dominated by the hot dust.

A.3. The Fitting of the NH\(_3\) Hyperfine Structures

In modeling the \( \text{NH}_3 \) spectra, we first calculate the \( \text{NH}_3 \) optical depth over the spectral frequency range

\[
\tau(\nu) = \tau_0 \sum_{j=1}^{N} a_j \exp \left[ -4 \ln 2 \left( \frac{\nu - \nu_j - \nu_f}{\Delta \nu} \right)^2 \right],
\]

where \( \nu_j \) and \( a_j \) are the rest frequency and relative intensity for each hyperfine component, respectively. \( N \) is the total number of the hyperfine transitions, and \( \Delta \nu \) is the FWHM line width. The values of \( a_j \) and \( N \) for (1, 1) and (2, 2) lines can be obtained from Kukolich (1967). \( \tau_0 \) is the integrated optical depth of all the components. For a given \( (J, K) \) inversion transition, the modeled brightness temperature \( T_b \) is (Friesen et al. 2009)

\[
T_b(J, K) = \Phi \eta_j [T_{\text{ex}}(J) - T_{\text{bg}}] [1 - \exp(-\tau_0)],
\]

where \( \Phi \) is the beam filling factor for the emission region, which is adopted as \( \Phi = 1. \) \( \eta \) is the mean-beam efficiency, which is also adopted to be 1.0 if there is a flux calibrator. \( T_{\text{ex}} \) is the line excitation temperature. \( T_{\text{bg}} = 2.73 \) K is the temperature of the cosmic microwave background, and \( J(T) = (h\nu/k)[\exp(h\nu/kT) - 1]^{-1} \) is the Planck-corrected brightness temperature. Frequency \( \nu \) is related to the radial velocity \( v \) as \( (\nu - \nu_0)/v = (v - v_{\text{sys}})/c. \) The free parameters for the fitting are \( T_{\text{ex}}, \nu_0, \Delta \nu, \) and \( \tau_0. \) The best-fit spectrum is obtained also using NonLinearLSQFitter.

The column density of the \( (J, K) \) level is calculated following Equation (13) in Rosolowsky et al. (2008):

\[
N(J, K) = \frac{8\pi \nu_0^2 g_1}{c^2} \frac{1}{g_2 A(J, K)} \times \frac{1 + \exp(-h\nu_0/kT_{\text{ex}})}{1 - \exp(-h\nu_0/kT_{\text{ex}})} \int \tau(\nu) d\nu,
\]

\(^{11}\) See PACS observer’s manual: [http://herschel.esac.esa.int/Docs/PACS/html/pacs.om.html](http://herschel.esac.esa.int/Docs/PACS/html/pacs.om.html).

\(^{12}\) See SPIRE observer’s manual: [http://herschel.esac.esa.int/twiki/bin/view/Public/SpireCalibrationWeb](http://herschel.esac.esa.int/twiki/bin/view/Public/SpireCalibrationWeb).

\(^{13}\) For PACS, see Müller, Okumura, & Klaas, PACS Photometer—Color Corrections, [http://herschel.esac.esa.int/twiki/pub/Public/PacsCalibrationWeb/cc_report_v1.pdf](http://herschel.esac.esa.int/twiki/pub/Public/PacsCalibrationWeb/cc_report_v1.pdf). For SPIRE, see SPIRE hand book, [http://herschel.esac.esa.int/Docs/SPIRE/html/spire.om.html](http://herschel.esac.esa.int/Docs/SPIRE/html/spire.om.html).

\(^{14}\) Astropy is a community Python package for astronomy (Bray 2014).
\[ A(J, K) \] is the Einstein A-coefficient. Using the partition function \( Z \) 
\[
Z = \sum_J (2J + 1) S(J) \exp \left( -\frac{h[J(J + 1) + (C - B)J^2]}{kT_{\text{rot}}(K)} \right),
\]
the total NH\(_3\) column density is \( N(1, 1) \times Z/Z(1, 1) \), where \( B = 298117 \) MHz and \( C = 1867260 \) MHz are the rotational constants. The function \( S(J) \) accounts for the extra statistical weight of the ortho- over para-NH\(_3\) states, with \( S(J) = 2 \) for \( J = 3, 6, 9, \ldots \) and \( S(J) = 1 \) for all other \( J \) values. The previous studies (e.g., Tafalla et al. 2004) presented an empirical formula for \( T_k \) as a function of \( T_{\text{rot}} \). But this relation might be inaccurate at high temperatures \((T_k > 20 \text{ K})\) and densities. To accurately determine \( T_k \), we calculated the energy-level distributions using the non-LTE radiative transfer model RADEX (van der Tak et al. 2007). The input parameters include \( T_k, \nu_{\text{rot}}, N(\text{NH}_3), \) and \( \Delta V \). We considered the \( T_k \) range from 15 to 30 K. The other parameters are set to be the values measured in Cd-2. With the input parameters, RADEX will estimate energy level population, and the theoretical \( T_{\text{rot}} \) is determined by the ratio of \( N(2, 2)/N(1, 1) \) assuming a Boltzmann distribution:
\[
\frac{N(2, 2)}{N(1, 1)} = \frac{g(2, 2)}{g(1, 1)} \exp \left( -\frac{\Delta E}{T_{\text{rot}}(K)} \right),
\]
The \( T_{\text{rot}} - T_k \) relation can then be numerically sampled for a series of \( T_k \) values in our range. The result is shown in Figure 8. It shows that the derived relation for FIR-3 is very close to \( T_{\text{rot}} = T_k \). This is within our expectation, since at such high densities \((10^7 \text{ cm}^{-3})\) the level population would be nearly thermalized.

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**Table 6**

| Image Data | rms Noise (mJy pix\(^{-1}\)) | Absolute Flux Error | Resolution (arcsec) | Pixel Size (arcsec) | Peak Intensity\(^a\) (mJy arcsec\(^{-2}\)) | Average Intensity\(^a\) (mJy arcsec\(^{-2}\)) |
|-----------|-------------------------------|---------------------|---------------------|---------------------|------------------------------------------|------------------------------------------|
| IRAC 8 \(\mu\)m | 0.2 | 3% | 2.0 | 0.6 | 489 | 150 |
| MSX 12 \(\mu\)m | 0.5 | 3% | 20 | 6 | 82 | 40 |
| MSX 16.5 \(\mu\)m | 0.4 | 5% | 20 | 6 | 87 | 52 |
| MSX 21 \(\mu\)m | 3.0 | 5% | 20 | 6 | 87 | 52 |
| PACS 70 \(\mu\)m | 5 | 10% | 9 | 2 | \(12 \times 10^3\) | \(5.3 \times 10^3\) |
| PACS 100 \(\mu\)m | 5 | 10% | 6.7 | 1.6 | \(11 \times 10^3\) | \(2.0 \times 10^3\) |
| PACS 160 \(\mu\)m | 6 | 10% | 11 | 3 | \(6 \times 10^3\) | \(1.5 \times 10^3\) |
| SPIRE 250 \(\mu\)m | 10 | 5% | 18 | 6 | \(5 \times 10^3\) | \(0.8 \times 10^3\) |
| SPIRE 350 \(\mu\)m | 10 | 5% | 25 | 10 | \(1 \times 10^3\) | \(0.3 \times 10^3\) |
| SPIRE 500 \(\mu\)m | 5 | 5% | 36 | 14 | \(0.1 \times 10^3\) | \(0.2 \times 10^3\) |
| SCUBA 450 \(\mu\)m | 0.1 | 30% | 9 | 2 | 810 | 400 |
| SCUBA 850 \(\mu\)m | 0.1 | 10% | 14 | 1 | 50 | 20 |

\(\mu\)Jy arcsec\(^{-2}\), in order to provide a fair comparison for all the bands. The images are kept in original appearance and not smoothed, regridded, or performed with any other computation. The peak and average intensities represent the values estimated within the observed region as shown in Figure 1.
