DISTRIBUTION OF COLD DUST IN ORION A AND B

B. MOOKERJEA, 1 S. K. GHOSH, 1 T. N. RENGARAJAN, 1 S. N. TANDON, 2 AND R. P. VERMA 1

Received 2000 March 23; accepted 2000 July 20

ABSTRACT

Large-scale far-infrared (FIR) observations of the Orion complex at 205 and 138 μm are presented with the aim of studying the distribution of cold (<25 K) dust. The maps in these FIR bands extend over ~3600 arcmin 2 and cover regions around OMC-1, 2, and 3 in Orion A and NGC 2023 and NGC 2024 in Orion B. Some limited regions have also been mapped at 57 μm. A total of 15 sources in Orion A and 14 in Orion B (south) have been identified from our FIR maps. Dust temperature distribution in both Orion A and Orion B (south) have been determined reliably using the maps at 205 and 138 μm obtained from simultaneous observations using almost identical beams (1.6 diameter). These temperatures have been used to generate the map of τ 150, the optical depth at 150 μm, for the Orion B region. The coldest source detected is in OMC-3 and has temperature ~15 K. The diffuse FIR emission in the different subregions is found to vary between 25% and 50% of the total FIR emission from that subregion.

Key words: infrared radiation — ISM: individual (OMC-1, OMC-2, OMC-3, NGC 2023, NGC 2024)

1. INTRODUCTION

In this paper we present a large-scale high angular resolution (~1') study of the continuum emission at 205 and 138 μm from the two giant molecular clouds Orion A and Orion B (south) in the Orion complex. The mapped region of Orion A includes OMC-1, 2, and 3 and IRAS 05327—0457 (NGC 1977). In Orion B we have mapped mainly the southern portion covering NGC 2023 and NGC 2024. Limited regions including OMC-1 and OMC-2 in Orion A and NGC 2024 in Orion B have also been observed at 57 μm.

The southern part of the Orion cloud complex, also known as Orion A, contains star-forming cores that are distributed along the north-south direction (integral-shaped ridge) and named OMC-1, 2, and 3 from south to north. Observations at submillimeter–far-infrared wavelengths have shown that both warm and cold dust, each with quite different spatial distribution, contribute to the emission from the Orion molecular clouds (Thronson et al. 1986; Chini et al. 1997). Cold dust, with temperature ~20–25 K, accounts for the bulk of the mass of dust in the Orion clouds and emits significantly only at wavelengths longer than 100 μm. Earlier observations of Orion A concentrated on the emission from the hot dust, viz., mapping of OMC-1 at 50–100 μm by Werner et al. (1976) and of M43 at 37–160 μm by Smith, Harper, & Loewenstein (1987). Later observations have mostly explored the emission from the cold dust in this region. The most recent of these observations was by Johnstone & Bally (1999), covering OMC-1, 2, and 3 and extending over an area of 50' × 10' with an angular resolution of ~7:5 at 450 μm and 14' at 850 μm. Lis et al. (1998) had also mapped a region of 6' × 18' covering OMC-2 and OMC-3 at 350 μm with an angular resolution of 11'. However, the pioneering work in detecting a number of cold sources in OMC-2 and an extremely cold one (~10 K) in OMC-3 was by Chini et al. (1997), who mapped a region of ~15' × 5' with an angular resolution of ~11' at 1300 μm. Most of these condensations are considered protostellar candidates because of the associated outflow activities (Castets & Langer 1995). Observations in molecular lines such as C 18O by Castets & Langer (1995) and references therein) have revealed that the gases in OMC-2 and OMC-3 have kinetic temperatures equal to 24 and 19 K respectively, both much smaller than that in OMC-1 (70 K). These observations also identified both OMC-2 and OMC-3 as regions of high column density. C 18O observations have also detected several moderate to strongly col-limated bipolar outflows in OMC-3, which suggests recent star formation activity. The very low temperatures of sources in both OMC-2 and OMC-3, along with the evidence for star formation, indicate very early stages of the evolution of (probably) intermediate-mass stars. In this paper we have explored the distribution of dust emission and temperature of the Orion A region in a wavelength regime (205 and 138 μm in particular) for which no high angular resolution measurements exist in the literature.

The Orion B cloud contains four major sites of star formation, viz., NGC 2071 and NGC 2068 in the north and NGC 2023 and NGC 2024 in the south. We have observed only the regions around NGC 2024 and NGC 2023. The brightest emission source in the region is NGC 2024, a region of active star formation. The 1300 μm observations over a region of ~5' × 5' (with angular resolution ~30') by Mezger et al. (1988) have revealed six condensations in NGC 2024, aligned in the north-south direction. These condensations also have associated masers and H II regions. The nature of these condensations was an issue of debate and was resolved by Mezger et al. (1992). From their observations at 870 and 1300 μm they concluded that these condensations are indeed isothermal protostars. Lada, Bally, & Stark (1991a, hereafter LBS) presented a survey of the Orion B (Lynds 1630) molecular cloud in the CS(2–1) line (1/3 angular resolution) and identified the regions including NGC 2023 and NGC 2024 as bright in CS, thus indicating high density of the region. In a follow-up program Lada et al. (1991b) surveyed Orion B in the K (2.2 μm) band and
found that more than 50% of the near-infrared sources are associated with the four identified star-forming regions. In a recent high angular resolution (22°–30°) survey of Orion B (south) at 1300 μm extending over ~80° × 68°, Launhardt et al. (1996) have identified some of the dust emission peaks around NGC 2023 and NGC 2024 with the CS cores detected by LBS. Of the existing far-infrared observations of NGC 2023 and NGC 2024, the IRAS observations in the first place trace relatively warmer dust (≥30 K) and in the second place have angular resolutions varying with wavelength, so that calculating the temperature distribution from the observed flux densities is not straightforward. On the other hand, the 1300 μm observations, though of high angular resolution, trace extremely cold dust. This has motivated us to carry out simultaneous high angular resolution far-infrared observations at 205 and 138 μm with identical beams so that the density and temperature distribution of dust that is emitting significantly in this intermediate regime can be reliably quantified. The rest of the paper is organized as follows: § 2 describes the observations, and § 3 contains the results and discussion of the same.

2. OBSERVATIONS

2.1. Maps for 205 and 138 μm

Orion molecular clouds A and B (south) were observed using a two-band far-infrared photometer system (PHT-12) at the Cassegrain focus of the Tata Institute of Fundamental Research (TIFR) 1 meter (f/8) balloon-borne telescope. The far-infrared telescope was flown from the TIFR Balloon Facility, Hyderabad, in central India (17°47N, 78°57E) in 1995 November. Details of the telescope and the observational procedure have been given by Ghosh et al. (1988). The photometer (PHT-12) consists of 12 composite silicon bolometers, each having a field of view of 1.6 and arranged in a 3 × 2 array for each band. These arrays are cooled to 0.3 K by liquid 3He. The sky was chopped at 10 Hz by wobbling the secondary mirror. The chopper throw was 4.2 along the cross-elevation axis. The same region of the sky was viewed simultaneously in two bands. The effective wavelengths for the two bands for a λ−2 emissivity law and a temperature of 35 K are 205 and 138 μm. Saturn was observed for absolute flux calibration (Ghosh et al. 1988), as well as for determination of the instrumental point-spread function, including the effect of sky chopping.

The simultaneous mapping in the two FIR bands was carried out by using raster scans in which the telescope was continuously moved along the cross-elevation axis and stepped in elevation. The chopped FIR signals were gridded in a two-dimensional sky matrix (elevation × cross-elevation) with cell size 0.3 × 0.3. The observed chopped signal matrix was deconvolved using an independently developed procedure based on the maximum entropy method (MEM), similar to that of Gull & Daniell (1978; see Ghosh et al. 1988 for details). The FWHM sizes of the deconvolved maps of the pointlike source (Saturn) are found to be 1.6 × 1.9 and 1.6 × 1.8 in the 138 and 205 μm bands, respectively. An optical photometer was used at the Cassegrain focal plane to improve the absolute positioning of the telescope during the flight. In addition, for all the observations presented here, the signal from this optical photometer measured during the far-infrared scans has been used during off-line analysis to improve the aspect information further. The absolute positional accuracy achieved in the FIR maps is ~0.5.

2.2. Map for 57 μm

Limited regions of both Orion A (OMC-1 and OMC-2) and Orion B (NGC 2024) were also observed at 57 μm in an earlier flight (1990 November) of the TIFR balloon-borne telescope, using a different photometer (PHT-2). This two-band photometer, PHT-2, was based on two liquid 4He cooled Ge(Ga) bolometers. The FIR passbands were 45–70 μm and 110–160 μm with effective wavelengths 57 and 150 μm for an input source spectrum defined by a graybody of temperature 35 K and emissivity λ−2. A 24 (diameter) region of the sky was simultaneously viewed in both the FIR bands. More details of PHT-2 can be found in Verma et al. (1994). Here, only the observations at 57 μm are presented, since the other band is very similar to the shorter wave band of PHT-12, which has better sensitivity. The PHT-2 was calibrated by observing Jupiter. Some preliminary results from observations of the Orion region have been presented by Das et al. (1993). The final results are presented here. The achieved angular resolution in the image processed maps is ~1.5, as determined from the observations of Jupiter.

2.3. HIRES-Processed IRAS Maps

To supplement our balloon-borne observations, we have used the IRAS survey data in all wave bands (12, 25, 60, and 100 μm) for the regions mapped by us in Orion B (south). These data were HIRES processed (Aumann, Fowler, & Melnyk 1990) at the Infrared Processing and Analysis Center3 (IPAC at Caltech) for improving the angular resolutions of the raw maps.

3. RESULTS AND DISCUSSION

3.1. Analysis of FIR Data

Figures 1 and 2 show the regions (indicated by the dotted boundary) in Orion B (south) and Orion A mapped at 205 and 138 μm, respectively. Regions extending over ~42° × 38° in Orion A and ~38° × 53° in Orion B (south) have been observed at both these FIR wavelengths. The 57 μm maps for both sources cover relatively smaller regions. Reliable dust temperature T(138/205) maps for selected regions have been generated using simultaneity of observation and nearly identical beams at 205 and 138 μm. The dust emissivity law has been assumed to be ϵλ ∝ λν, and the method used is briefly described in Appendix A. For most star-forming regions the emissivity exponent at longer wavelengths (>100 μm) is found to be between 1.5 and 2.5, and the calculated properties of most common types of dust grains (Draine & Lee 1984) show the same at these wavelengths. Based on these facts we have chosen β = 2 for deriving the T(138/205) distribution. Considering the uncertainties in the measured flux densities and the wavelength regime probed, the temperature computed has an uncertainty of ~(±2 K) between 14 and 50 K and of ~(±5 K) between 50 and 70 K. The intensity ratio of our FIR bands

3 IPAC is funded by NASA as part of the IRAS extended mission program under contract to the JPL.
K for numerical values of \( b \) depend on \( b \). Above 70 K the estimated temperature has an uncertainty of \( \sim (\pm 8) \) K. The morphology of the spatial distribution of \( T_d \) is insensitive to the assumed value of \( \beta \). Only the numerical values of \( T_d \) depend on \( \beta \); e.g., a temperature of 15 K for \( \beta = 2 \) corresponds to 17 K for \( \beta = 1 \), and \( T_d = 30 \) K for \( \beta = 2 \) corresponds to 50 K for \( \beta = 1 \). Distribution of \( \tau_{150} \), the optical depth at 150 \( \mu \)m for Orion B, has also been generated using these dust temperatures and \( \beta = 2 \).

We have adopted a well-defined extraction algorithm to identify discrete sources in these maps. This algorithm is based on identification of a local maximum followed by a critical study of the growth curve of the integrated flux densities in consecutive annular rings with the maximum at the center. The reliability of the sources detected in each map has been ensured by the following procedure: The entire observation for each region has been split into two independent data sets (by considering only the alternate scan lines in each raster) and processed (deconvolved) separately to generate two maps. The peaks detected in both these maps within a predetermined positional error have been used to quantify the dynamic range and also to validate the detected sources. The final maps presented combine all data, and positions of the confirmed sources in the composite maps have been determined. These sources have signals more than 10 times the estimated noise level of the respective maps. In this paper the method of presenting the sources is as follows: Peaks identified in any two TIFR wave bands are associated if they lie within 1'. For association with IRAS (HIRES) sources the same parameter has been taken to be 1.5. The coordinates quoted for a particular source are for the position of the peak at the longest (TIFR) wavelength at which it is detected.

### 3.2. Orion A

Figure 2 shows the 205 and 138 \( \mu \)m intensity distribution of the mapped region in Orion A. The maps include the Orion Molecular Clouds 1, 2, 3 and the source IRAS 05327—0457. Figure 3 shows the intensity map for a limited region in Orion A at 57 \( \mu \)m. Table 1 presents the coordinates and flux densities (in a circle of 3' diameter) for all the discrete sources detected in the mapped regions of Orion A at 205 and 138 \( \mu \)m. In the same table we also present the longer wavelength associations of these sources, along with the measured flux densities at 1300 \( \mu \)m (Chini et al. 1997). For the discrete sources detected at 138, 205, and 1300 \( \mu \)m the dust temperature \( T_d \) and the emissivity exponent (\( \beta \)) have been determined by fitting a single temperature graybody spectrum. \( T_d \) and \( \beta \) for A8 have been determined in a similar manner by using the flux densities measured at 450, 790, and 1100 \( \mu \)m by Goldsmith, Bergin, & Lis (1997), along with those from the present work. For all other sources with flux densities measured only at 205 and 138 \( \mu \)m, \( T_d \) has been

![Figure 1](image1.png)

**Fig. 1.—**Intensity map of Orion B (south) at 205 \( \mu \)m. The dotted boundary shows the region mapped. The peak is 2.50 kJy arcmin \(^{-2}\). The contour levels are at 90% to 30% (in steps of 20%) and 20, 10, 5, 2.5, 1.25, and 0.63 percent of the peak.

![Figure 2](image2.png)

**Fig. 2.—**Intensity maps of Orion A. The peaks are 9.00 kJy arcmin \(^{-2}\) at 205 \( \mu \)m and 29.1 kJy arcmin \(^{-2}\) at 138 \( \mu \)m. The contour levels are the same as in Fig. 1, with an additional contour at 0.31% of the peak. The lowest contour level is 3 times the measured noise.
determined assuming $\beta = 2$. For a source not detected in any of the wave bands (footnoted "c" in Table 1), we give the flux density obtained by integrating at the position of the source as detected in the other wave band(s). Table 2 presents the positions, flux densities, and associations of these sources detected at 57 $\mu$m. The source IRAS 05327 $-$ 0457 has been studied in detail in the far-infrared by Mookerjea et al. (2000); here we concentrate mainly on OMC-1, 2, and 3.

Figure 4 shows the temperature distribution as calculated from the observations at 205 and 138 $\mu$m for OMC-1 and OMC-2. The temperature in OMC-1 is as high as $\sim 70$ K close to the Orion nebula. The temperature of the OMC-1 and the bar region as calculated by Werner et al. (1976) from the ratio of 50 and 100 $\mu$m flux densities is found to be between 55 and 85 K. For the same region, the temperature calculated from our 205 and 138 $\mu$m fluxes is between 45 and 70 K. This is consistent with the fact that the longer wavelength observations presented here are tracing colder dust components as compared with those traced by the 50 and 100 $\mu$m observations. The temperature drops to an average of $\sim 25$ K in OMC-2 and is as low as 15 K in OMC-3 (not shown in the figure). The temperature map has been generated by assuming the dust to be optically thin, but explicit calculation of optical depth (at 150 $\mu$m) very close to the global intensity peak of OMC-1 shows that the regions are optically thick. In such cases, the temperatures quoted would be underestimated by as much as 5 K. However, for OMC-1, 2, and 3, the basic morphology of the isotherms remains unaltered.

Orion A is an ensemble of cores with a variety of temperatures, physical sizes, and masses. This variety in physical conditions makes it conducive to harboring stars in different stages of formation and evolution and hence makes it astrophysically interesting. The far-infrared maps presented here also support this variety by showing mor-

### Table 1

| Source | R.A. (1950) | Decl. (1950) | Association* | $F_{138}$ (kJy) | $F_{205}$ (kJy) | $F_{1100}$ (kJy) | $T_{b}$ (K) | $\beta$ |
|--------|-------------|-------------|--------------|----------------|----------------|----------------|------------|--------|
| A1     | 5 31 51.6   | $-5 06 22$  | IRAS 05318 $-$ 0506 | 1.26           | 0.58           | ...            | 29         |
| A2     | 5 32 02.0   | $-4 56 30$  | ...          | 1.24           | 0.96           | ...            | 20         |
| A3     | 5 32 04.6   | $-5 19 14$  | ...          | 0.83           | 0.39           | ...            | 28         |
| A4     | 5 32 11.6   | $-5 02 28$  | ...          | 0.56           | 0.36           | ...            | 22         |
| A5     | 5 32 32.8   | $-5 22 57$  | ...          | 2.65           | 0.68           | ...            | 80         |
| A6     | 5 32 43.7   | $-4 57 42$  | IRAS 05327 $-$ 0457 | 2.12           | 0.96           | ...            | 30         |
| A7     | 5 32 47.3   | $-4 58 33$  | ...          | 2.06           | 0.86           | ...            | 32         |
| A8     | 5 32 47.7   | $-5 24 51$  | OMC-1        | 112.50         | 35.70          | ...            | 68$^a$     | 0.5$^a$|
| A9     | 5 32 55.6   | $-5 04 00$  | OMC-3, MMS 4, 5, 6, VLA 3 | 0.42           | 0.53           | 4.77           | 15         | 2.0    |
| A10    | 5 32 59.5   | $-5 14 25$  | FIR 6a, 6b, 6c, 6d, VLA 14 | 2.22           | 1.44           | 7.45           | 25         | 1.6    |
| A11    | 5 33 01.4   | $-5 11 16$  | FIR 2, 3, 4, VLA 11, 12 | 1.88           | 1.50$^c$       | 6.94           | 20         | 1.9    |
| A12    | 5 33 01.6   | $-5 13 01$  | FIR 4, 5, 6a, 6b | 1.98$^c$       | 1.71           | 10.4           | 20         | 1.8    |
| A13    | 5 33 07.1   | $-5 01 49$  | ...          | 0.43$^c$       | 0.54           | ...            | 15         |

---

Table 1: Positions, Flux Densities (in 3' Diameter), Associations, $T_{b}$, and $\beta$ of Sources Identified in Orion A at 205 and 138 $\mu$m

---

Note. — Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* IRAS: IRAS PSC; FIR & MMS: Chini et al. (1997); VLA: Reipurth et al. 1999.

$^a$ Single-temperature graybody spectrum; if flux densities at only two bands are available, emissivity $\epsilon \propto v^2$ is assumed.

$^c$ Not detected as a local peak in this wave band. Flux density is obtained by integrating in a circle of diameter 3' around the coordinates tabulated.

$^d$ Using $F_{45}$, $F_{138}$, and $F_{205}$ from this work and $F_{450} = 19.8$ kJy, $F_{790} = 2.671$ kJy, and $F_{1100} = 0.989$ kJy from Goldsmith et al. 1997.
The high temperature and low emission at longer wavelengths. In the OMC-1 region cold diffuse component of dust as well that contributes to the temperature graybody spectrum. In reality there is probably a composition over a wide range of wavelengths using a single temperature.

The dust temperature obtained by this method is 68 K and around it is similar to that observed at 60 \mu m by Smith et al. (1993). Source 3 is due to the heating of the dust in the photodissociation region around the trapezium stars. The northern tip of the emission detected at 57 \mu m is clearly displaced to the east with respect to the integral-shaped emission ridge detected in OMC-2 and OMC-3. We can discern local enhancements in the T(138/205) map close to the positions of peaks 2 and 3. These strongly indicate the existence of hotter dust toward the east.

Of the observations presented here OMC-2 and OMC-3 are detected only at the longer wavelengths (205 and 138 \mu m). In OMC-2 we detect two sources (A10 and A11) at 138 \mu m and only one source (A12) at 205 \mu m. As suggested by Table 1 the sources detected at our resolution are each associated with more than one submillimeter (1300 \mu m) source. We note that, whereas A10 and A11 are associated with two mutually exclusive groups of submillimeter sources, A12 is associated with sources from both groups. The fact that we detect A10 and A11 only at 138 \mu m and A12 only at 205 \mu m could be due to the presence of a diffuse cold component that reduces the contrast between the sources and the intermediate region. This could effectively smooth out the smaller peaks (like A10 and A11) in this region, thus resulting in only one peak (A12) at 205 \mu m. The flux densities at 1300 \mu m of the detected submillimeter sources have been calculated using the peak fluxes and sizes of the individual sources (refer to Table 1 of Chini et al. 1997). For each FIR source the contributions at 1300 \mu m from all associated sources are combined and presented in Table 1. For all sources detected in OMC-2 a single temperature graybody spectral fitting gives 20 K < T_d < 25 K and 1.6 < \beta < 2.0. Both these are consistent with the results of Chini et al. (1997).

The molecular cloud OMC-1 has long been the most extensively studied region in Orion A. OMC-2 and OMC-3 have been studied only in the recent past and have been found to be rich and interesting as a star-forming region. Our observations provide useful constraints on the intensity and temperature distribution of this region.

**Fig. 4.—Dust temperature map for the region covering OMC-1 and OMC-2, assuming a dust emissivity of \epsilon_v \propto \nu^\beta. The lowest temperature found in this region is 14 K. The numbers written on the contours refer to the temperatures: the highest contour displayed is 70 K.**

Phenomenological characteristics strongly dependent on the dust temperature. While the 205 and 138 \mu m maps tracing colder dust detect FIR emission from OMC-2 and OMC-3 very clearly, the 57 \mu m map fails to do so.

OMC-1 (A8 in Table 1 and source 1 in Table 2) is the brightest source detected at all wavelengths. As mentioned earlier, the submillimeter fluxes at 450, 790, and 1100 \mu m (Goldsmith et al.) have been used, along with the 57, 138, and 205 \mu m fluxes, to determine T_d and \beta for this source. The dust temperature obtained by this method is 68 K and the \beta is 0.5. If instead we do a similar fitting omitting the flux density at 57 \mu m, we get T_d = 30 K and \beta = 1.1. Thus the high temperature and low \beta as presented in Table 1 might be due to the effect of attempting to explain the emission over a wide range of wavelengths using a single temperature graybody spectrum. In reality there is probably a cold diffuse component of dust as well that contributes to the emission at longer wavelengths. In the OMC-1 region the maps at 205 and 138 \mu m also detect the source A5. Although the position of this source at 205 and 138 \mu m differ by \sim 1.5, we have associated the two, since there is no other nearby source of similar strength. We also note that the temperature of source A5 is \sim 80 K, even higher than the temperature of A8.

Peaks 2 and 3 detected at 57 \mu m (see Table 2) are not detected at the longer wavelengths. Source 2 is associated with the H II region M43, and the intensity distribution around it is similar to that observed at 60 \mu m by Smith et al. (1987). Source 3 is due to the heating of the dust in the photodissociation region around the trapezium stars. The northern tip of the emission detected at 57 \mu m is clearly

displaced to the east with respect to the integral-shaped emission ridge detected in OMC-2 and OMC-3. We can discern local enhancements in the T(138/205) map close to the positions of peaks 2 and 3. These strongly indicate the existence of hotter dust toward the east.

Of the observations presented here OMC-2 and OMC-3 are detected only at the longer wavelengths (205 and 138 \mu m). In OMC-2 we detect two sources (A10 and A11) at 138 \mu m and only one source (A12) at 205 \mu m. As suggested by Table 1 the sources detected at our resolution are each associated with more than one submillimeter (1300 \mu m) source. We note that, whereas A10 and A11 are associated with two mutually exclusive groups of submillimeter sources, A12 is associated with sources from both groups. The fact that we detect A10 and A11 only at 138 \mu m and A12 only at 205 \mu m could be due to the presence of a diffuse cold component that reduces the contrast between the sources and the intermediate region. This could effectively smooth out the smaller peaks (like A10 and A11) in this region, thus resulting in only one peak (A12) at 205 \mu m. The flux densities at 1300 \mu m of the detected submillimeter sources have been calculated using the peak fluxes and sizes of the individual sources (refer to Table 1 of Chini et al. 1997). For each FIR source the contributions at 1300 \mu m from all associated sources are combined and presented in Table 1. For all sources detected in OMC-2 a single temperature graybody spectral fitting gives 20 K < T_d < 25 K and 1.6 < \beta < 2.0. Both these are consistent with the results of Chini et al. (1997).

Recent radio observations at 3.6 cm by Reipurth, Rodriguez, & Chini (1999) have detected sources coinciding with the peaks in dust emission. These associations are also presented in Table 1. The radio emission further substantiates the conclusion that the sources detected in OMC-2 though reasonably cold are not only regions of high density but also have young stellar objects (YSOs) embedded in them.

We have detected one source (A9) in the OMC-3 region. Positionally it is coincident with the submillimeter source MMS 6 (Chini et al. 1997), the latter being the brightest of all the submillimeter sources detected in OMC-3. The flux density at 1300 \mu m for the source A9 is estimated in the same manner as above. A graybody spectrum fitted to the measured flux densities gives T_d = 15 K and \beta = 2.0. A9 is thus the coldest source in Orion A, both T_d and \beta estimated here are consistent with Chini et al. (1997) and Lis et al. (1998).

The total far-infrared luminosity has been estimated using the temperature map (Fig. 4) for the region with OMC-1 and OMC-2 and the intensity maps of the same region. The dust emissivity exponent assumed for this calculation is 2.0. From the FIR observations presented here the total luminosity detected in OMC-1 and OMC-2 is \sim 3.5 \times 10^5 L_\odot. For a similar region the luminosity based on 60 and 100 \mu m observations as given by Stacey et al. (1993) is \sim 5 \times 10^5 L_\odot. The diffuse emission at these wavelengths has been calculated by subtracting the contribution of the discrete sources and is about 25% of the total luminosity.

The molecular cloud OMC-1 has long been the most extensively studied region in Orion A. OMC-2 and OMC-3 have been studied only in the recent past and have been found to be rich and interesting as a star-forming region. Our observations provide useful constraints on the intensity and temperature distribution of this region.
3.3. Orion B (South)

3.3.1. Region around NGC 2024

Figure 5 presents intensity maps of the region around NGC 2024 at 205, 138, 100, and 57 \( \mu \text{m} \). The map at 57 \( \mu \text{m} \) is for a smaller region, but it brings out the main features of NGC 2024 at this wavelength. Table 3 presents the measured flux densities at the four IRAS and three TIFR wavelengths for the sources detected in this region. The submillimeter and IRAS Point Sources associated with these FIR sources, along with the submillimeter flux densities measured at 1300 \( \mu \text{m} \) by Launhardt et al. (1996), are presented in Table 3. In all, seven sources have been identified with sources in the IRAS Point Source Catalog (PSC), and two sources (B3 and B9) have been found to have submillimeter (1300 \( \mu \text{m} \)) counterparts. For sources not detected in one or two of the TIFR bands (footnoted “c” in Table 3) we have presented the flux densities obtained by integrating

![Intensity maps of the region around NGC 2024. Peaks are (a) 2.50 kJy arcmin\(^{-2}\) at 205\( \mu \text{m}\), (b) 7.53 kJy arcmin\(^{-2}\) at 138 \( \mu \text{m}\), (c) 3.80 kJy arcmin\(^{-2}\) at 100 \( \mu \text{m}\), and (d) 19.1 kJy arcmin\(^{-2}\) at 57 \( \mu \text{m}\). The contour levels in (a) and (b) are the same as in Fig. 1. Levels in (c) are 60\% to 10\% (in steps of 10\%) and 5, 2.5, and 1 percent of its peak. Levels in (d) are 90, 75, 60, 40, 20, 10, 7.5, 5, 3.5, 2, 1, and 0.7 percent of the peak.

**TABLE 3**

**Positions, Flux Densities (in 3’ Diameter), Associations, \( T_s \) and \( \beta \) of Sources Identified in Orion B at 205 and 138 \( \mu \text{m} \)**

| Source | R.A. (1950) | Decl. (1950) | Association* | \( F_{12} \) (Jy) | \( F_{25} \) (Jy) | \( F_{57} \) (kJy) | \( F_{60} \) (kJy) | \( F_{100} \) (kJy) | \( F_{138} \) (kJy) | \( F_{205} \) (kJy) | \( F_{1300} \) (kJy) | \( T_s \)b | \( \beta \)b |
|--------|-------------|--------------|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|----------|----------|
| NGC 2024 Region: | | | | | | | | | | | | | | |
| B1 ...... 5 38 21.4 | 1 50 19 | 05383—0150 | | 60 | 65 | NMa | 0.95 | 1.40 | 0.67 | 0.29 | ... | 32 | 2.5 |
| B2 ...... 5 38 21.9 | 1 54 24 | ... | | 68 | 68 | NM | 1.17 | ... | 1.04 | 0.30 | ... | 25 | 3.8 |
| B3 ...... 5 38 43.0 | 1 49 55 | LBS 40 SM, 05387—0149 | | 80 | 133 | ... | ... | ... | 1.69 | 1.13 | 2.6 | 20 | 2.3 |
| B4 ...... 5 38 44.5 | 1 58 44 | ... | | 87 | 120 | ... | ... | 4.50c | 2.79 | 2.18 | 0.67 | ... | 21 | 3.8 |
| B5 ...... 5 38 52.6 | 1 46 10 | 05388—0147 | | 89 | ... | NM | ... | ... | 0.57d | 0.49 | ... | 20 | ... |
| B6 ...... 5 38 57.2 | 1 54 00 | ... | | 110 | ... | 5.51 | ... | ... | 1.89 | 0.90 | ... | 95 | 0.4 |
| B7 ...... 5 38 59.4 | 1 47 52 | ... | | 81 | 175 | NM | 2.83 | 3.59 | 1.25 | 0.37d | ... | 27 | 3.9 |
| B8 ...... 5 39 05.4 | 1 52 13 | 05391—0152 | | 248 | 1060 | 6.62 | 10.74 | ... | 4.24 | 1.31 | ... | 32 | 2.8 |
| B9 ...... 5 39 13.7 | 1 56 52 | LBS 33 SM, 05393—0156 | | 86 | 916 | 71.70 | ... | 85.00a | 32.30 | 12.06 | 115 | 59 | 1.0 |
| B10 ...... 5 39 21.8 | 1 45 47 | 05392—0145 | | 17 | 31 | NM | 0.32 | ... | 0.83 | 0.59 | ... | 35 | 0.5 |
| B11 ...... 5 39 21.8 | 1 49 13 | 05393—0150 | | 80 | 176 | 0.71d | 2.10 | 2.96 | 1.56 | 0.65 | ... | 32 | 2.4 |
| B12 ...... 5 39 28.5 | 2 01 36 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 80 | 0.2 |

**NGC 2023 Region:**

| B13 ...... 5 39 02.9 | 2 20 16 | LBS 36 SM | | 25 | 52 | NM | ... | 0.79d | 0.82 | 4.7 | 16 | 2.1 |
| B14 ...... 5 39 14.6 | 2 19 08 | LBS 34 SM | | 14 | ... | NM | ... | 1.93 | 1.41 | 12.5 | 25 | 1.3 |

*a LBS SM: CS cores (LBS), also detected at 1300 \( \mu \text{m} \) by Launhardt et al. (1996); IRAS PSC for all other entries.

*b Single-temperature graybody spectrum; if fluxes at only two bands are available, emissivity \( \epsilon \) \( \propto \nu^2 \) is assumed.

*c Not mapped at 57 \( \mu \text{m} \).

*d Not detected as a local peak in this wave band. Flux density is obtained by integrating in a circle of diameter 3’ around the coordinates tabulated.

*Thronson et al. 1984.
in a circle around the position of the source as detected at the other wavelength(s). We have fitted a single-temperature graybody spectrum for all sources for which measurement of flux densities at three or more wavelengths longer than 50 \( \mu m \) exist. The resulting \( T_d \) and \( \beta \) are also presented in the same table. For the remaining sources \( T_d \) is determined using \( \beta = 2 \). We find that the emissivity exponent (\( \beta \)) for some sources (B6, B10, and B12) is very small (<0.5). In addition, for B6 and B12 the fitted \( T_d \) is also very high. This indicates that for these sources possibly a two- or multi-temperature graybody spectrum is more appropriate.

Observations at 1300 \( \mu m \) by Mezger et al. (1988) have revealed six protostellar condensations within an area of 3' x 3' around NGC 2024. The far-infrared maps presented here, being of limited angular resolution, do not resolve these condensations. However the 205 \( \mu m \) and also the 100 \( \mu m \) maps show evidence of north-south extension with the northern tip having a slight westward bend (position of FIR-1, 2; Mezger et al. 1988). Positionally B9 coincides with FIR-5 (brightest condensation detected by Mezger et al. 1988) and also with LBS 33SM, a CS core detected by LBS, later detected at 1300 \( \mu m \) by Launhardt et al. (1996). The HIRES map at 100 \( \mu m \) shows signs of possible anomaly, particularly near the peak. The flux density measured (in 3' diameter) from the 100 \( \mu m \) map shows a very low value of \( \sim 18 \) kJy compared with both the IRAS PSC value (35.3 kJy) and results from the Kuiper Airborne Observatory observations by Thronson et al. (1984; 85 kJy). We have used the measurements of Thronson et al. (1984) in Table 3, as well as for determining \( T_d \) and \( \beta \) for B9.

Figure 6 shows the dust temperature distribution for this region. It has been generated using the same method as for Orion A. It shows several isolated peaks with most temperatures varying between 60 and 70 K. The source B3 is quite cold, with a maximum of 30 K and goes below 15 K toward the edges. The \( \tau_{350} \) map (Fig. 6) shows very interesting structure close to the main source B9. It distinctly shows that the region around B9 has an elongated structure with indications of at least two condensations. This structure is very similar to the structure shown by the \( NH_3 \) column density map generated by Schulz et al. (1991). This very well substantiates the fact that these are indeed protostellar condensations since they are so luminous in the infrared as well. The cold source B3 is found to be mostly optically thin (peak 0.07) at 150 \( \mu m \).

The total luminosity of the region calculated using the same method as for Orion A (§ 3.2) is \( 1.0 \times 10^5 \) \( L_\odot \). The diffuse emission contributes about 50% (at both the wavelengths) of the total luminosity. This is substantially larger than the value measured in Orion A (§ 3.2) and in other young Galactic star-forming regions (~35% in W31; Ghosh et al. 1989). The morphology of the \( [C \, II] \) (158 \( \mu m \))-emitting region in Orion B (south) as observed by Jaffe et al. (1994) agrees very well with the maps presented in this paper. The total \( [C \, II] \) luminosity detected for their assumed distance of 415 pc is 230 \( L_\odot \), while we have estimated the total far-infrared luminosity for a distance of 450 pc. Correcting for this difference in the distances assumed, we find the ratio of the \( [C \, II] \) luminosity to the total FIR luminosity to be \( 3 \times 10^{-3} \).

The observations presented here, being on a large scale and of good angular resolution, would be useful as guidelines in understanding the star formation scenario vis-à-vis the temperature distribution for future large-scale submillimeter continuum observations.

3.3.2. Region around NGC 2023

Figure 7 shows intensity maps of the region surrounding NGC 2023 at 205 and 138 \( \mu m \) along with HIRES maps at 100 and 60 \( \mu m \). The maps at 205 and 138 \( \mu m \) are generated by masking NGC 2024 prior to MEM deconvolution of the larger map so that details of the fainter source NGC 2023 are better visible and comparison with 100 and 60 \( \mu m \) HIRES maps is easier. The source NGC 2023 appears to have a double structure at 205 \( \mu m \). It is of interest to note that the map of fluorescent \( H_2 \) observed by Gatley et al. (1987) exhibits a shell structure with main peaks separated by an extent similar to B13 and B14. The intensity map at 138 \( \mu m \) however shows only a single source close to the brighter source (B14) at 205 \( \mu m \). Diffuse emission extending southward from the main source is clearly visible at 60, 100, and 205 \( \mu m \), while at 138 \( \mu m \) the limited dynamic range of the map restricts this emission to a seemingly isolated peak. Table 3 presents the positions, flux densities, and associated sources for the two peaks (B13 and B14) detected in this region. The coordinates of the global peaks in the 60 and 100 \( \mu m \) maps are found to be \( \sim (5^h39^m47^s, -2^\circ17'44'') \). These global peaks are separated from B14 by more than 1.5.

![Image](image-url)
Since there is no other detected source of such brightness in the neighborhood and observations at 100 and 138 \( \mu m \) trace dust of similar temperature, we have associated B14 with NGC 2023. Both sources B13 and B14 have been detected at 1300 \( \mu m \) by Launhardt et al. (1996), but there is no IRAS detection of B13. For both sources we have used the available flux densities at wavelengths longer than 60 \( \mu m \) to estimate \( T_d \) and \( \beta \) from a single-temperature gray-body spectrum (Table 3). The flatness of \( \beta \) for B14 indicates the existence of dust components of at least two temperature ranges. The source B13 is found to be reasonably cold \( (T_d = 16 K) \), thus justifying its nondetection in the IRAS wave bands.

Figure 8 shows the \( T(138/205) \) and \( \tau_{150} \) maps for the region around NGC 2023 (derived assuming \( \beta = 2.0 \)). The \( T(138/205) \) map shows a peak that does not coincide with the intensity peaks at 205 and 138 \( \mu m \). The \( T(138/205) \) peak, however, coincides with the peak positions at 60 and 100 \( \mu m \). The temperature of most of the region is around 30 K and in places goes down to values as low as \( \sim 20 K \). The \( \tau_{150} \) map more or less traces the high-intensity regions. The \( \tau_{150} \) displayed for regions that lie outside the contours of the \( T(138/205) \) map are for an assumed temperature of 10 K [not plotted in the \( T(138/205) \) map].

NGC 2023, being a well-known reflection nebula with a photodissociation region (excited by HD 37903) has been studied in various molecular and fine structure \([\text{C II}]\) lines. The continuum maps presented in Figure 7 are morphologically similar to the \( \text{C}^{18}\text{O} \) map by Wyrowski et al. (1997) and the CO \((J = 2-1)\) map by White et al. (1990). The \([\text{C II}]\) observations at 158 \( \mu m \) by Howe et al. (1991) and Jaffe et al. (1994) detect emission that is approximately 25% of the emission from NGC 2024. The rise in temperature, \( T(138/205) \), to the northwest of the main peak is explained by the presence of the exciting star HD 37903. The total luminosity measured in this region is \( 1.5 \times 10^3 L_\odot \). The diffuse emission contributes about 35% of the total emission, which is smaller than the contribution of diffuse emission around NGC 2024. The total \([\text{C II}]\) luminosity from the region as detected by Howe et al. (1991) is \( 7 L_\odot \) and is equal to \( \sim 0.5\% \) of the total FIR luminosity estimated here. This is consistent with results from most of the Galactic star-forming regions as given by Howe et al. (1991). Detection of low temperature in the region around NGC 2023, along with emission in the far-infrared, support ongoing formation of low- to intermediate-mass stars in the region. That more than 50% of the emission is in the condensations further indicates star formation in clumps in this region.

4. SUMMARY

In this paper we have presented large-scale high angular resolution (\( \sim 1' \)) far-infrared (205 and 138 \( \mu m \)) maps of the Orion A and Orion B (south) molecular clouds. For limited regions, maps at 57 \( \mu m \) have also been presented. HIRES processed IRAS images at 100 and 60 \( \mu m \) of the Orion B have been used for comparison. The regions covered include OMC-1, 2, and 3 in Orion A and NGC 2024 and NGC 2023 in Orion B (south). In all, 15 condensations in Orion A and 14 condensations in Orion B (south) have been identified. In OMC-3 the very cold source MMS 6 (Chini et al. 1997) was detected at both 205 and 138 \( \mu m \), and the temperature was determined to be \( \sim 15 \pm 2 K \). The far-infrared counterparts of the extremely dense CS cores LBS
33, 34, 36, and 40 were detected in Orion B (south) (LBS). The total far-infrared luminosity and the relative contribution of diffuse emission to the luminosity of these regions have also been quantified.

We thank B. Das for his help during the initial stages of analysis of the 57 \( \mu \text{m} \) data and S. L. D’Costa, M. V. Naik, D. M. Patkar, M. B. Naik, S. A. Chalke, G. S. Meshram, and C. B. Bakalkar for their support for the experiment. The members of the TIFR Balloon Facility (Balloon Group and Control and Instrumentation Group), Hyderabad, are thanked for their roles in conducting the balloon flights. Thanks are due to IPAC for providing HIREs processed IRAS data. We thank the anonymous referee for suggestions that have improved the quality of the paper.

APPENDIX A

ESTIMATION OF DUST TEMPERATURE DISTRIBUTION USING THE TWO-BAND FIR OBSERVATIONS

As mentioned in § 2.1 the spatial intensity distribution in each band is gridded with pixels of size 0.3 \( \times \) 0.3. Only those pixels that have signals exceeding 5 times the noise level of the corresponding map are considered to be valid for the purpose of finding the dust temperature distribution. Each intensity map is first smoothed by taking a running average over 3 \( \times \) 3 valid pixels. This is done to be extremely conservative about the derived spatial structures in the temperature maps. Since the two intensity maps refer to identical portions of the sky and the beams are also almost identical, a pixel-by-pixel ratio between the two maps gives reliable dust temperatures.

For optically thin emission the observed flux density at any wavelength can be written as

\[
F_{\nu} = \Omega B_{\nu}(T_d)\tau_{\nu},
\]

where \( \Omega \) is the solid angle of the region under consideration. We assume \( \tau_{\nu} \approx \nu^\beta \). Since the pixel sizes are identical the ratio of flux densities for any two wavelengths is

\[
\frac{F_{\nu_1}}{F_{\nu_2}} = \left( \frac{\nu_1}{\nu_2} \right)^{3+\beta} \exp \left( \frac{\nu_2}{kT_d} \right) \exp \left( \frac{\nu_1}{kT_d} \right)^{-1}.
\]

Thus for an assumed emissivity exponent (\( \beta \)) the ratio of the flux densities at any two wavelengths is a function of the dust temperature only. The temperature is computed using a look-up table containing the calculated ratios of flux densities for various temperatures and an assumed \( \beta \). This process is repeated for all pixels to generate the dust temperature distribution map.

REFERENCES

Aumann, H. H., Fowler, J. W., & Melnyk, M. 1990, AJ, 99, 1674
Castets, A., & Langer, W. D. 1995, A&A, 294, 835
Chini, R., Reipurth, B., Ward-Thompson, D., Bally, J., Nyman, L.-A., Sievers, A., & Bilsawala, Y. 1997, ApJ, 474, L135
Das, B., Ghosh, S. K., Rengarajan, T. N., Verma, R. P., Iyengar, K. V. K., & Tandon, S. N. 1993, Bull. Astron. Soc. India, 21, 587
Draine, B. T., & Lee, H. M. 1984, ApJ, 285, 89
Gatley, I., et al. 1987, ApJ, 318, L73
Ghosh, S. K., Iyengar, K. V. K., Rengarajan, T. N., Verma, R. P., & Daniel, R. R. 1988, ApJ, 330, 928
Ghosh, S. K., Iyengar, K. V. K., Rengarajan, T. N., Tandon, S. N., Verma, R. P., & Daniel, R. R. 1988, ApJ, 330, 928
Goldsmith, P. F., Bergin, E. A., & Lis, D. C. 1997, ApJ, 491, 615
Gull, S. F., & Daniell, G. J. 1978, Nature, 272, 686
Howe, J. E., Jaffe, D. T., Genzel, R., & Stacey, G. J. 1991, ApJ, 373, 158
Ja¢e, D. T., Zhou, S., Howe, J. E., Herrmann, F., Madden, S. C., Poglitsch, A., van der Werf, P. P., & Stacey, G. J. 1994, ApJ, 436, 203
Johnstone, D., & Bally, J. 1999, ApJ, 510, L49
Lada, E. A., Bally, J., & Stark, A. A. 1991a, ApJ, 368, 432 (LBS)
Lada, E. A., DePoy, D. L., Evans, N. J., & Gatley, I. 1991b, ApJ, 371, 171
Launhardt, R., Mezger, P. G., Haslam, C. G. T., Kreyss, E., Lemke, R., Sievers, A., & Zylka, R. 1996, A&A, 312, 569
Lis, D. C., Serabyn, E., Keene, J., Dowell, C. D., Benford, D. J., Phillips, T. G., Hunter, T. R., & Wang, N. 1998, ApJ, 509, 299

Mezger, P. G., Chini, R., Kreyss, E., Wink, J. E., & Salter, C. J. 1988, A&A, 191, 44
Mezger, P. G., Sievers, A. W., Haslam, C. G. T., Kreyss, E., Lemke, R., Mauersberger, R., & Wilson, T. L. 1992, A&A, 256, 631
Mookerjea, B., Ghosh, S. K., Rengarajan, T. N., Tandon, S. N., & Verma, R. P. 2000, ApJ, 539, 775
Reipurth, B., Rodriguez, L. F., & Chini, R. 1999, AJ, 118, 983
Schulz, A., Gusten, A., Zylka, R., & Serabyn, E. 1991, A&A, 246, 570
Smith, J., Harper, D. A., & Loewenstein, R. F. 1987, ApJ, 314, 76
Stacey, G. J., Jaffe, D. T., Geis, N., Genzel, R., Harris, A. I., Poglitsch, A., Stutzki, J., & Townes, C. H. 1993, ApJ, 404, 219
Thronson, H. A., et al. 1986, AJ, 91, 1350
Thronson, H. A., Lada, C. J., Schwartz, P. R., Smith, H. A., Smith, J., Glaccum, W., Harper, D. A., & Loewenstein, R. F. 1984, ApJ, 280, 154
Verma, R. P., Baht, R. S., Ghosh, S. K., Iyengar, K. V. K., Rengarajan, T. N., & Tandon, S. N. 1994, A&A, 284, 936
Werner, M. W., Gatley, I., Harper, D. A., Becklin, E. E., Loewenstein, R. F., Telesto, C. M., & Thronson, H. A. 1976, ApJ, 204, 420
White, G. J., Sanderson, C., Monteiro, T. S., Richardson, K. J., & Hayashi, S. S. 1990, A&A, 227, 200
WyROWSKI, F., WALMSLEY, C. M., Natta, A., & TIELENS, A. G. G. M. 1997, A&A, 324, 1135