IRAS 18317−0757: A CLUSTER OF EMBEDDED MASSIVE STARS AND PROTOSTARS

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ABSTRACT

We present high-resolution, multiwavelength-continuum, and molecular-line images of the massive star forming region IRAS 18317−0757. The global infrared through millimeter spectral energy distribution can be approximated by a two-temperature model (25 and 63 K) with a total luminosity of approximately log \( \frac{L}{L_{\odot}} \) = 5.2. Previous submillimeter imaging resolved this region into a cluster of five dust cores, one of which is associated with the ultracompact \( \Pi \) region G23.955+0.150, and another with a water maser. In our new 2.7 mm continuum image obtained with BIMA, only the UCH \( \Pi \) region is detected, with total flux and morphology in good agreement with the free-free emission in the VLA centimeter-wave maps. For the other four objects, the nondetections at 2.7 mm and in the MSX mid-infrared bands are consistent with cool dust emission with a temperature of 13−40 K and a luminosity of 1000−40,000 \( L_{\odot} \). By combining single-dish and interferometric data, we have identified over two dozen virialized C\(^{18}\)O cores in this region that contain \( \approx \)40% of the total molecular gas mass present. While the overall extent of the C\(^{18}\)O and dust emission is similar, the emission peaks do not correlate well in detail. At least 11 of the 123 infrared stars identified by 2MASS in this region are likely to be associated with the star-forming cluster. Two of these objects (both associated with the UCH \( \Pi \) region) were previously identified as O stars via infrared spectroscopy. Most of the rest of the reddened stars have no obvious correlation with the C\(^{18}\)O cores or the dust continuum sources. In summary, our observations indicate that considerable fragmentation of the molecular cloud has taken place during the time required for the UCH \( \Pi \) region to form and for the O stars to become detectable at infrared wavelengths. Additional star formation appears to be ongoing on the periphery of the central region, where up to four B-type (proto)stars have formed among a substantial number of C\(^{18}\)O cores.

Subject headings: infrared: stars — ISM: individual (AFGL 2194, G23.95+0.15, IRAS 18317−0757) — stars: formation

On-line material: machine-readable table

1. INTRODUCTION

The formation mechanism of massive stars is a topic of active research. Because massive star formation regions typically lie at distances of several kiloparsecs, the identification of high-mass protostars requires both good sensitivity and high angular resolution. As a consequence of their presumed youth, ultracompact \( \Pi \) regions (UCH \( \Pi \) regions) provide a good tracer of current massive star formation (Wood & Churchwell 1989) and may be expected to be accompanied by protostars in earlier evolutionary stages. Indeed, recent high-resolution millimeter-wave images of UCH \( \Pi \) regions have revealed the high-mass equivalent of Class 0 protostars. Examples include the young stellar object IRAS 23385+6053 (Molinari et al. 1998), the compact methyl cyanide core near the G31.41+0.31 UCH \( \Pi \) region (Cesaroni et al. 1994), the proto−B star G34.24+0.13MM (Hunter et al. 1998), the G9.62+0.19-F hot core (Testi et al. 2000), and the protocluster G24.78+0.08 (Furuya et al. 2002). To identify these deeply embedded objects requires an optically thin tracer in order to probe through the large extinction toward the giant molecular cloud cores that harbor them. Submillimeter continuum emission from cool dust is a good tracer of protostars because it remains optically thin at high column densities (\( N_{\text{H}} \leq 10^{25} \text{ cm}^{-2} \)) (Mezger 1994). Similarly, spectral line emission from C\(^{18}\)O is a good optically thin tracer that can reveal areas of high molecular gas column density.

Our target in this study, IRAS 18317−0757, is a luminous infrared source (log \( L_{\text{FIR}} \) = 5.2) at a kinematic distance of 4.9 kpc (\( v_{\text{LSR}} = 80 \text{ km s}^{-1} \)). Based on its IRAS colors, it has been identified as a massive protostellar candidate (Chan, Henning, & Schreyer 1996). Previous single-dish radio frequency studies of this region have revealed hydrogen recombination line emission (Kim & Koo 2001; Lockman 1989; Wink, Wilson, & Bieging 1983) and water maser emission (Genzel & Downes 1977; Churchwell, Walmsley, & Cesaroni 1990). The centimeter-wave continuum emission shows both extended components (up to 13′) (Kim & Koo 2001; Becker et al. 1994) and a UCH \( \Pi \) region (Wood & Churchwell 1989). The region has been detected in various dense gas tracers, including the NH\(_3\) (1, 1), (2, 2), and (3, 3) transitions (Churchwell et al. 1990) and CS (7−6) (Plume, Jaffe, & Evans 1992), although it was not detected in a methyl cyanide search (Pankonin et al. 2001), nor in a 6 GHz hydroxyl maser search (Baudry et al. 1997), nor in two 6.7 GHz methanol maser searches (Szymczak, Hrynek, & Kus 2000; Walsh et al. 1997). The CO (1−0) line shows a complex profile that has prevented the identification of high-velocity outflow emission in large-beam (1′) surveys (Shepherd & Churchwell 1996).

Also known as AFGL 2194, compact infrared emission was first detected from the ground in the K, L, and M bands by Moorwood & Salinari (1981) and later by Chini, Krügel, & Wargau (1987). Airborne observations of far-infrared continuum and fine-structure lines (S, O, N, and Ne) yield an electron density of 3500 cm\(^{-3}\) for the UCH \( \Pi \) region and indicate a stellar type of O9 to early B (Simpson et al. 1995). Complete infrared spectra (2.4−195 \( \mu \)m) have been recorded by the Infrared Space Observatory (ISO) SWS and LWS spectrometers.
At higher angular resolution, the region has been independently observed as part of two submillimeter continuum imaging surveys. In both cases, the emission is resolved into several components (Hunter et al. 2000; Mueller et al. 2002). Recent near-infrared imaging and spectroscopy has revealed the presence of a small cluster of stars associated with the UCH\textsuperscript{ii} region, including an O7 star (with N\textsuperscript{iii} emission and He\textsuperscript{ii} absorption) whose ionizing flux can account for all of the compact radio continuum emission (Hanson, Luhman, & Rieke 2002). These developments have prompted the higher angular resolution millimeter-wave observations that are presented in this paper in hopes of understanding this active site of massive star formation.

2. OBSERVATIONS

With the Berkeley-Illinois-Maryland Association (BIMA) Millimeter Array (Welch et al. 1996), IRAS 18317–0757 was simultaneously observed in 110 GHz continuum and C\textsuperscript{18}O (1–0). The continuum bandwidth was 600 MHz. The spectral resolution for the line data was 0.2 MHz (0.53 km s\textsuperscript{-1}). The phase gain calibrator was the quasar 1741–038. The bandpass calibrator was 3C 273. The absolute flux calibration is based on 3C 273 and Uranus. A single track in the B configuration was obtained on 1998 October 10, and in the C configuration on 1999 February 5. The synthesized beam for the combined data imaged with robust weighting is 4\textquoteright\textquoteright\times 2\textquoteright\textquoteright at a position angle of $-2\degree$.

To recover the missing flux from extended structures in the interferometer spectral line data, a single-dish map of C\textsuperscript{18}O (1–0) was recorded at the NRAO\textsuperscript{1} 12 m telescope on 2000 June 16. A regular grid of 7 points \times 7 points was observed, with a spacing of 25\arcsec, providing full sampling of the telescope’s 58\arcsec beam. The system temperature was 200 K, and the on-source integration time was 2.8 minutes per point. The data were combined as zero-spacing information with the BIMA data in the MIRIAD (Multichannel Image Reconstruction, Image Analysis, and Display) software package. The resulting beam size in the final data cube (with natural weighting and UV tapering applied) is 10\arcsec\times 7\arcsec at a position angle of $-18\degree$.

\footnote{1 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.}
To complement the millimeter data, infrared images and point-source information for this region in J, H, and K bands were obtained from the Two Micron All Sky Survey (2MASS) (Cutri et al. 2003), and in the mid-infrared bands from the Midcourse Space Experiment (MSX) archives (Egan et al. 2001) and HIRES-processed IRAS data (Hunter 1997). Radio continuum images were also retrieved from the Very Large Array (VLA) Galactic plane survey of Becker et al. (1994).

3. RESULTS

3.1. Millimeter and Radio Continuum

The 2.7 mm continuum image from our BIMA observations is shown in gray scale in Figure 1, along with overlays of the 6 and 20 cm contours from the VLA Galactic plane survey images (Becker et al. 1994). At all three wavelengths, the source structure consists of a bright rim on one edge of a partially complete shell. Both the IRAS point source and the MSX point source positions lie close to the middle of the shell region. The bright, compact component was identified as an irregular/multiple-peaked UCH ii region by Wood & Churchwell (1989). At the two longest radio wavelengths, additional faint emission extends to the northwest.

3.2. Submillimeter Continuum

The 350 μm continuum image from the survey of Hunter et al. (2000) is shown in gray scale in Figure 2. For comparison, the position of the IRAS and MSX point sources are indicated, along with the single-dish water maser position. Five independent submillimeter sources can be identified, and their coordinates and flux densities are given in Table 1. The two dominant sources are SMM 1 and SMM 2. The peak of SMM 1 coincides with the UCH ii position. SMM 2 lies 22″ to the west and likely coincides with the water maser emission, whose position is uncertain to ±10″ (no interferometric observations exist). The water maser is apparently quite variable over time: 60 Jy in 1976 (Genzel & Downes 1977) to 0.7 Jy in 1989 (Churchwell et al. 1990) to undetected in 2002 (H. Beuther 2003, private communication). The three other sources have no known counterpart at other wavelengths.

3.3. Mid-Infrared Continuum

Each of the MSX images of this field show that the mid-infrared emission is dominated by the UCH ii region associated with SMM 1. Contour plots of two of the bands (8.3 and 14.7 μm) are shown in Figure 3. The positions of the five
Table 1

**Observed Emission Properties of Submillimeter Clumps**

| Source    | R.A. (J2000.0) | Decl. (J2000.0) | Flux Density | Mass | Log (N_H) | A_V | A_K |
|-----------|----------------|-----------------|--------------|------|-----------|-----|-----|
| SMM 1     | 18 34 25.4     | -07 54 49       | 63 ± 6       | 1360 ± 120 | 23.75 ± 0.04 | 140 | 15.7 |
| SMM 2     | 18 34 24.0     | -07 54 50       | 67 ± 6 <0.033 | 1400 ± 120 | 23.76 ± 0.04 | 144 | 16.1 |
| SMM 3     | 18 34 21.8     | -07 55 05       | 30 ± 6 <0.033 | 640 ± 120  | 23.42 ± 0.08 | 66  | 7.4  |
| SMM 4     | 18 34 21.7     | -07 54 44       | 27 ± 6 <0.045 | 560 ± 120  | 23.36 ± 0.09 | 57  | 6.4  |
| SMM 5     | 18 34 26.5     | -07 54 36       | 24 ± 6 <0.033 | 500 ± 120  | 23.32 ± 0.09 | 52  | 5.8  |
| Extended  |                |                 | 140 ± 20 0.25 ± 0.03 | 2900 ± 300 | ...       | ... | ...  |
| Total     |                |                 | 350 ± 60 1.72 ± 0.06 | 7400 ± 900 | ...       | ... | ...  |

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

a Within 22" aperture, as shown in Fig. 2.

b Assuming T = 25 K and grain emissivity Q = 1.0 × 10^{-4} at 350 μm (Hildebrand 1983).

c Assuming uniform emission of diameter 11" (0.25 pc).

d Extinction to a star at the center of the dust core, i.e., half the column density.

e Upper limits are 3 σ.

f Total flux including extended emission within dotted region of Fig. 2.

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**Fig. 3.**—MSX images of IRAS 18317−0757. *Top:* 8.3 μm. *Bottom:* 14.7 μm. Contour levels are 0.005, 0.01, 0.02, 0.04, 0.08, 0.16, 0.32, and 0.64 ergs cm^{-2} s^{-1} sr^{-1}. The crosses mark the position of the submillimeter sources SMM 1−5 (Table 1). The dashed circle marks the BIMA primary beam size, for reference to Figs. 2, 7, and 11.

**Fig. 4.**—IRAS HIRES—processed images of IRAS 18317−0757. Gaussian fits to the HIRES restoring beams are denoted by dotted ellipses. The crosses mark the position of the submillimeter sources SMM 1−5 (Table 1). The contour levels are as follows: for 25 μm, 190, 381, 762, 1523, 3047, 6093, and 12,186 MJy sr^{-1}; for 60 μm, 258, 516, 1032, 2064, 4128, 8257, and 16,513 MJy sr^{-1}. 

Total flux including extended emission within dotted region of Fig. 2.
submillimeter sources are indicated in both panels. The fitted positions of a two-dimensional Gaussian model in each of the four MSX bands all agree to within 2″ and fall within the IRAS PSC error ellipse. Of the five submillimeter sources, the peak in each band lies closest to SMM 1. HIRES-processed images provide additional high-resolution information from the IRAS data (Aumann, Fowler, & Melnyk 1990). The 20-iteration contour maps at 25 and 60 μm are shown in Figure 4, again with the five submillimeter sources marked. The emission remains essentially unresolved in each band, although there is some hint that the two westernmost submillimeter sources (SMM 3 and 4) are detected in the contour extensions at 25 and 60 μm.

3.4. Spectral Energy Distributions

Using the flux density data from Table 2, the mid-infrared through radio wavelength spectral energy distribution (SED) for the entire region is shown in Figure 5. The flux density measurements at wavelengths longward of 21 μm have been fitted with a simple two-temperature modified blackbody dust model plus a free-free component, summarized in Table 3. The flux density measurement at 1.3 mm from the literature (Chini et al. 1986) should be considered a lower limit, since it was obtained with a single-element detector with a 90″ beam centered on the IRAS position, which misses most of SMM 3 and SMM 4. The temperature of the cold component of dust (25 K) agrees quite well with the kinetic temperature (25.8 K) derived from ammonia (1, 1) and (2, 2) observations with a 40″ beam centered on the UCH ii position (Churchwell et al. 1990). It is interesting to note that the warm component of dust dominates the total luminosity of the region, which is in contrast to more isolated high-mass protostellar objects (Sridharan et al. 2002) and even many other UCH ii regions. Using the grain emissivity index (β), along with the temperature and optical depth derived from the fit, one can calculate the number of cold and warm grains required to explain the observed flux density (Lonsdale-Persson & Helou 1987; Hildebrand 1983). The corresponding mass of dust can then be calculated for each clump and for the extended emission. As is typical, the cold grains dominate the mass of dust. Assuming a gas-to-dust mass ratio of 100 (Sodroski et al. 1997), the total gas mass of each clump is listed in column (6) of Table 1, and the total mass of the region is \( \approx 7400 M_\odot \). Using the individual gas masses and source diameters (from the angular diameter and distance), we compute the column density of hydrogen \( (N_{\text{H}} = N_{\text{H}_2} + 2N_{\text{H}_1}) \) toward each clump.

### Table 2

| Wavelength | Frequency (GHz) | Flux (Jy) | Aperture/Beam Size (arcsec) | Instrument | Reference |
|------------|----------------|----------|----------------------------|------------|-----------|
| 3.8 μm     | ...            | 0.885^a  | 15"                       | CFHT       | 1         |
| 4.6 μm     | ...            | 0.902^a  | 15"                       | CFHT       | 1         |
| 8.3 μm     | ...            | 34.4 ± 1.7 | 21"               | MSX        | This work |
| 12 μm      | ...            | 66.3 ± 6.6 | 62" × 27"       | IRAS       | 2         |
| 12.1 μm    | ...            | 61 ± 2   | 22"                      | MSX        | This work |
| 14.7 μm    | ...            | 61 ± 2   | 22"                      | MSX        | This work |
| 21.3 μm    | ...            | 245 ± 15 | 23"                      | MSX        | This work |
| 25 μm      | ...            | 395 ± 99 | 84" × 29"              | IRAS       | 2         |
| 33.5 μm    | ...            | 1400 ± 100 | 44"                     | KAO        | 3         |
| 36 μm      | ...            | 1700 ± 100 | 44"                   | KAO        | 3         |
| 51 μm      | ...            | 1900 ± 100 | 44"                    | KAO        | 3         |
| 57.3 μm    | ...            | 2100 ± 100 | 44"                    | KAO        | 3         |
| 60 μm      | ...            | 2285 ± 708 | 144" × 62"        | IRAS       | 2         |
| 88.4 μm    | ...            | 2400 ± 100 | 44"                    | KAO        | 3         |
| 100 μm     | ...            | 3339 ± 902 | 152" × 137"        | IRAS       | 2         |
| 352 μm     | 857            | 320 ± 64 | ...                     | CSO/SHARC  | 4         |
| 352 μm     | 857            | 350 ± 60 | 98" × 44"              | CSO/SHARC  | This work |
| 1.3 mm     | 230            | 4.6 ± 0.5 | 12"                     | CFHT       | 2         |
| 2.725 mm   | 110            | 1.31 ± 0.07 | 54"                 | NRAO 12 m | 5         |
| 2.735 mm   | 110            | 1.72 ± 0.04 | ...                 | BIMA       | This work |
| 3.486 mm   | 86             | 1.32 ± 0.20 | 78"                 | NRAO 11 m | 6         |
| 2.007 cm   | 14.94          | 0.536^b  | ...                     | VLA-B      | 7         |
| 2.0 cm     | 14.8           | 1.56 ± 0.08 | 60"                  | Effelsberg 100 m | 6 |
| 2.91 cm    | 10.3           | 2.11 ± 0.04 | 160"                 | NRAO 45 m | 8         |
| 3.378 cm   | 8.875          | 1.85 ± 0.09 | 84"                  | Effelsberg 100 m | 6 |
| 6.1 cm     | 4.9            | 1.290 ± 0.003 | 9" × 4"             | VLA-B      | 9         |
| 6.15 cm    | 4.875          | 2.32 ± 0.12 | 2"6                 | Effelsberg 100 m | 6 |
| 6.15 cm    | 4.875          | 2.50 ± 0.13 | 2"6                 | Effelsberg 100 m | 10 |
| 6.17 cm    | 4.860          | 0.227^b  | ...                     | VLA-A/B    | 7         |
| 19.6 cm    | 1.527          | 1.508 ± 0.005 | ...              | VLA-B      | 9         |
| 19.6 cm    | 1.527          | 1.608 ± 0.040 | 7" × 4"            | VLA-B      | 11        |
| 21.0 cm    | 1.425          | 2.13 ± 0.01 | ...                    | VLA-DnC    | 12        |

^a Aperture did not cover the UCH a position.
^b Measurements suffer from missing flux.

**References:**—(1) Chini et al. 1987; (2) Chini et al. 1986; (3) Simpson et al. 1995; (4) Mueller et al. 2002; (5) Wood, Churchwell, & Salter 1988; (6) Wink, Altenhoff, & Mezger 1982; (7) Wood & Churchwell 1989; (8) Handa et al. 1987; (9) Becker et al. 1994; (10) Altenhoff et al. 1979; (11) Garwood et al. 1988; (12) Kim & Koo 2001.
in column (7) of Table 1. Finally, we have estimated the visual and infrared (K band) extinctions toward each clump by using the conversion formula of $A_K = N_H / (2 \times 10^{21})$ derived from observations of the interstellar medium at UV (Whittet 1981; Bohlin, Savage, & Drake 1978) and X-ray wavelengths (Predehl & Schmitt 1995; Ryter 1996), followed by the relation $A_K = 0.112A_V$ from Rieke & Lebofsky (1985). The extinction values listed in columns (8) and (9) of Table 1 have been further reduced by a factor of 2 to more accurately estimate the extinction toward a young star at the center of the clump, rather than behind it.

As the SED model predicts, the free-free emission mechanism still dominates over the dust emission at frequencies as high as 110 GHz. In fact, the image at this frequency is nearly identical to the centimeter images. The 110 GHz flux densities for SMM 1–5 are listed in Table 1. Nearly all of the 110 GHz flux can be associated with SMM 1, with the rest of the emission sitting just outside the 22″ aperture used to define this object in the 350 μm map. By contrast, we have not detected any emission for SMM 2–5. Each of these upper limits is consistent with an SED proportional to $ν^α$, corresponding to dust emission with $α = 2$. For the case of SMM 3 and SMM 4, they lie sufficiently far from the main source that useful upper limits can be obtained from both the IRAS and MSX data that provide a constraint on the individual properties of these dust cores. To visualize this constraint, the SEDs of SMM 3 and SMM 4 are shown in Figure 6, along with the two most extreme models consistent with the data. The corresponding dust temperature and luminosity upper and lower limits are summarized in Table 4. Although the luminosity remains uncertain to within a factor of 30–60, the lower limits (∼1000 $L_⊙$) indicate that these objects may be powered by individual massive stars or protostars.

### 3.5. C$^{18}$O (1–0) Images

The integrated C$^{18}$O (1–0) line emission (75–85 km s$^{-1}$) is shown as gray scale in Figure 7. The dotted circles denote the positions of the submillimeter continuum clumps from Figure 2. The C$^{18}$O emission has been clipped (set to zero) at all points below 2.5 $σ$ (0.2 Jy beam$^{-1}$). There are five major peaks of emission, four of which agree roughly with the submillimeter continuum sources SMM 1–4. The strongest component peaks very close (offset: $Δα = 30^\circ, Δδ = 26^\circ$) to a small cluster of stars identified by Hanson et al. (2002) that are associated with the UCH II emission and SMM 1. Assuming optically thin line emission with $T = 25$ K, we have computed the total column density of C$^{18}$O listed in column (5) of Table 5. These values have been converted to visual extinction $A_V$ using the relationship of Hayakawa et al. (1999) for the Chamaeleon I dark cloud: $N(C^{18}O) (cm^{-2}) = 3.5 \times 10^{14} A_V - 5.7 \times 10^{14}$. Next, the values of $A_V$ have been converted to $A_K$ (see §3.4), and these are listed in column (6) of Table 5. Assuming relative abundances of $N_H : N_{CO} = 10^4$ and $N_{CO} : N_{C^{18}O} = 490$, the gas mass of each clump has been computed and listed in column (7) of Table 5. Likewise, the mass of gas associated with each of the continuum sources SMM 1–5 is listed in Table 6. The total gas mass (including the extended emission and all the clumps) is 7300 $M_⊙$. Although this value is in good agreement with the mass derived independently from the total 350 μm dust emission, the

| Component         | $T$ (K) | $β$ | $τ_{25\mu m}$ | $L$ ($L_⊙$) | $M$ ($M_⊙$) |
|-------------------|---------|-----|---------------|-------------|-------------|
| Cold dust.........| 25      | 2.0 | 0.38          | 50,000      | 7200        |
| Warm dust.........| 63      | 2.0 | 0.062         | 110,000     | 70          |
| Total dust........|         |     |               | 160,000     | 7300        |

Note.—For the free-free component, $F_ν (Jy) = 2.3ν^{0.317}$.  

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Fig. 5.—Global SED of IRAS 18317–0757. The flux density measurements are summarized in Table 2, and the components of the dust and free-free emission models are described in Table 3. Dotted line: Cold-dust component. Dashed line: Warm-dust component. Dash-dotted line: Free-free component. Solid line: Sum of all three components.

Fig. 6.—Individual SEDs of the submillimeter sources SMM 3 and SMM 4. The two longest wavelength flux density measurements are summarized in Table 1. The infrared upper limits are from the MSX and IRAS HIRES images. Solid lines: Warmest dust model consistent with the data. Dashed lines: Coolest dust model (17–41 K for SMM 3, 14–41 K for SMM 4).
fraction of mass in the extended emission (outside of SMM 1–5) is 70% in C$^{18}$O but only 40% in dust.

To study the C$^{18}$O emission in greater detail, channel maps of C$^{18}$O are shown in Figure 8. We have analyzed these maps in two ways: we first inspected the maps visually, then used an objective computer algorithm. In the visual method, we manually identified 26 cores in position-velocity space. Shown in Figure 9 is a grid of spectra constructed by integrating the emission in a 10'' aperture (0.24 pc) centered at the position of each core. The mass contained within these apertures represents about 40% of the total gas mass.

We next attempted to objectively analyze the C$^{18}$O data cube by running the clumpfind program (Williams, de Geus, & Blitz 1994). This algorithm contours the data, locates the peaks, and follows them to the low intensity limit without any constraint on the shape of the resulting clump. It was designed to operate on large-scale maps of giant molecular clouds in which the emission is well separated into distinct clumps. Our data do not fit this description, since the cores are embedded in significant extended emission. Nevertheless, we proceeded and used the recommended contour levels by setting both the starting contour and the contour interval to be twice the rms of the individual channel maps (0.6 Jy km s$^{-1}$). The program identified 17 clumps, three of which were weak and centered slightly outside the primary beam (which we reject). The largest seven clumps range in mass from 200 to 1400 $M_{\odot}$, while the smallest seven range from 18 to 94 $M_{\odot}$. The fraction of mass placed into these 14 clumps is 45% of the total emission, which is quite similar to our visual technique.

### Table 4

| Component | Infrared Limit (Jy) | $T$ (K) | $\beta^a$ | $\tau_{125\mu m}$ | $L$ ($L_{\odot}$) | $M$ ($M_{\odot}$) |
|-----------|---------------------|--------|----------|-----------------|----------------|-----------------|
| SMM 3...... | <696 (at 60 $\mu$m) | 17–41  | 2.0      | 0.30–0.049      | 1400–39000     | 270–1600        |
| SMM 4...... | <2.3 (at 21.3 $\mu$m)| 14–41  | 2.0      | 0.48–0.044      | 630–38000      | 240–2600        |

$^a$ Value fixed in fit.

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![Fig. 7.—Integrated emission from C$^{18}$O (1–0) is shown in gray scale. The dashed circle marks the BIMA primary beam at half-maximum response. The dotted circles mark the apertures defining submillimeter continuum sources SMM 1–5. The cross marks the water maser position uncertainty from Genzel & Downes (1977). The star marks the peak of the UCH II region. The ellipse is the IRAS position uncertainty, and the square contains the MSX point-source position.](image-url)
7, 8, and 10) were merged together by clumpfind into a single large clump in the late stages of the execution when the lowest contour levels were being examined. In a few other cases, two initial clumps merged into one. This merging effect of the algorithm explains the fewer number (but larger mass) of initial clumps merged into one. This merging effect of the initial clumps was more pronounced for the two clumps found. The rest of the clumps are in good general agreement with our visual identification technique.

A Gaussian line profile has been fitted to each C18O clump, and the corresponding velocity, amplitude, and line width are given in Table 5. Using the line width ($\delta v$) and aperture radius ($r$), we compute the virial mass from the formula $M = 210\, r (\text{pc}) \, \delta v^2 \, (\text{km}^2 \, \text{s}^{-2})$ (Caselli et al. 2002). In most cases, and in the overall sum, the virial masses of the clumps are quite similar to their C18O-derived masses, suggesting that the clumps are in hydrostatic equilibrium. In only three clumps does the C18O-derived mass exceed the virial mass by more than 50%. The highest excess (76%) is seen in clump 18, associated with the UCH II region. Two of these clumps (17 and 18) lie near the UCH II region and also exhibit the steepest spatial profiles, possibly suggesting an unstable condition. A cut along position angle 80° in the velocity channel centered at 80.1 km s$^{-1}$ is shown in Figure 10. The minimum in C18O emission corresponds to the presence of the free-free continuum emission along the southern portion of the shell structure seen in Figure 1; thus the steep profile may be due to interaction with the UCH II region. In any case, considering the uncertainties in the C18O mass calculations, the good agreement between the C18O mass and the virial mass is analogous to the results found in a survey of 40 lower mass C18O clumps in the Taurus complex (Onishi et al. 1996).

### Table 5

| Number | R.A. (J2000.0) | Decl. (J2000.0) | Emission (Jy km s$^{-1}$) | log ($[\text{C}^{18}\text{O}]$) (cm$^{-2}$) | $A_v$ (mag) | $M_\text{vir}$ (M$_\odot$) | $M_\text{tot}$ (M$_\odot$) | $v_{\text{peak}}$ (Jy beam$^{-1}$) | Line Width (km s$^{-1}$) | $F_{\text{peak}}$ (Jy) |
|--------|----------------|----------------|---------------------------|------------------------------------------|-------------|-----------------|-----------------|---------------------------|-------------------|------------------|
| 1      | 18 34 21.183   | -07 55 13.78  | 14.3                      | 16.39                                    | 8.1         | 119             | 80.3 ± 0.1      | 6.9 ± 0.2       | 2.1 ± 0.2        | 110               |
| 2      | 18 34 21.583   | -07 54 53.17  | 16.7                      | 16.46                                    | 9.5         | 139             | 80.0 ± 0.1      | 6.3 ± 0.6       | 2.3 ± 0.2        | 120               |
| 3      | 18 34 21.602   | -07 55 23.45  | 14.3                      | 16.39                                    | 8.1         | 120             | 80.4 ± 0.2      | 6.2 ± 0.6       | 2.1 ± 0.2        | 110               |
| 4      | 18 34 21.689   | -07 55 05.58  | 17.9                      | 16.49                                    | 10.2        | 150             | 80.1 ± 0.1      | 7.8 ± 0.2       | 2.2 ± 0.2        | 115               |
| 5      | 18 34 21.760   | -07 54 42.88  | 14.8                      | 16.40                                    | 8.3         | 123             | 80.0 ± 0.1      | 5.5 ± 0.5       | 2.6 ± 0.3        | 136               |
| 6      | 18 34 22.090   | -07 54 32.96  | 11.3                      | 16.29                                    | 6.5         | 94              | 79.9 ± 0.2      | 3.9 ± 0.5       | 2.8 ± 0.4        | 147               |
| 7      | 18 34 22.097   | -07 55 13.66  | 18.9                      | 16.51                                    | 10.6        | 158             | 80.2 ± 0.1      | 8.6 ± 0.3       | 2.3 ± 0.2        | 120               |
| 8      | 18 34 24.321   | -07 54 52.93  | 14.7                      | 16.40                                    | 8.3         | 123             | 79.5 ± 0.1      | 6.1 ± 0.6       | 2.2 ± 0.2        | 115               |
| 9      | 18 34 22.470   | -07 54 09.96  | 3.8                       | 15.82                                    | 2.3         | 32              | 78.7 ± 1.0      | 4.4 ± 0.9       | 0.8 ± 0.2        | 42                |
| 10     | 18 34 22.539   | -07 55 04.57  | 17.3                      | 16.48                                    | 9.9         | 145             | 79.7 ± 0.1      | 7.1 ± 0.6       | 2.3 ± 0.2        | 120               |
| 11     | 18 34 23.098   | -07 55 55.95  | 22.1                      | 16.58                                    | 12.5        | 185             | 80.0 ± 0.1      | 6.6 ± 0.5       | 3.2 ± 0.2        | 168               |
| 12     | 18 34 23.381   | -07 55 16.93  | 10.7                      | 16.27                                    | 6.2         | 90              | 78.8 ± 0.3      | 3.1 ± 0.5       | 3.4 ± 0.5        | 154               |
| 13     | 18 34 23.457   | -07 53 59.41  | 10.3                      | 16.25                                    | 5.9         | 86              | 78.8 ± 0.3      | 3.0 ± 0.5       | 3.2 ± 0.2        | 168               |
| 14     | 18 34 23.558   | -07 54 43.66  | 11.3                      | 16.29                                    | 6.5         | 94              | 79.7 ± 0.2      | 3.9 ± 0.5       | 2.7 ± 0.4        | 122               |

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

$A_v$ computed from $N$(C18O) using formula from Hayakawa et al. 1999 and converted to $A_v$ using Rieke & Lebofsky 1985.

$M_\text{tot}$ computed using formula from Scoville et al. 1986, assuming optically thin gas at 25 K, $[12\text{CO}/\text{C}^{18}\text{O}] = 490$, and $[\text{H}_2/\text{CO}] = 10^4$, yielding a conversion factor of 8.35 M$_\odot$ (Jy km s$^{-1}$).
all three bands. The K-band image is shown in Figure 11, with the position of the C$^{18}$O clumps indicated by dotted circles. In general, the noncoincidence between the two phenomena is striking. As listed in column (6) of Table 5, the extinction at K band through the C$^{18}$O clumps ranges from 2.3 to 12.5 magnitudes, with a median value of 8.1. The faintest star detected has K magnitude 14.44, while the brightest upper limit has magnitude 10.11. Thus, even the brightest K-band star observed in the field (star 112 with $M_K = 7.35$) would be undetected if placed behind the typical clump. This fact may account for the lack of stars seen toward the C$^{18}$O clumps.

A J–H versus H–K color-color diagram of the 2MASS stars is shown in Figure 12. The solid line marks the locus of main-sequence stars, and the dashed lines denote the reddening vector, which is annotated in magnitudes of visual extinction. We see that 19 of the stars exhibit more than 10 magnitudes of visual extinction. Eleven of these 19 are located within the lowest C$^{18}$O contours (see Fig. 13) and are likely to be associated with the star-forming material of the cluster. For example, associated with the UCH II region is a small cluster of five stars. Of these five stars, star 92 is the object identified as an O8.5 star on the basis of its infrared spectrum (with weak He i emission) (Hanson et al. 2002). It lies near the peak of the millimeter continuum map and is one of the few stars that reside within any of the C$^{18}$O clumps. The next closest star, number 86, lies close to the center of the shell structure seen in the millimeter continuum. Because of the presence of N m emission, it is classified as an O7 star. The ratio of He i to Brγ confirms the level of ionizing flux expected from such a star. To within a factor of 2, it can account for all the Lyman continuum flux from the centimeter emission and probably explains the shell-like symmetry. Besides stars 86 and 92, three additional stars (4, 47, and 106) exhibit excess near-infrared emission (i.e., they lie to the right of the reddening vector in Fig. 12), which may indicate the presence of circumstellar disks. Star 106 lies only 4″ from the center of SMM 5, while star 47 lies at the edge of C$^{18}$O clump 12. Star 4 sits just outside the BIMA primary beam, where very little C$^{18}$O has been detected.

The brightest star in the field, number 112, has J magnitude 8.7 and the colors of an M2 star consistent with about 3 magnitudes of visual extinction. It could be a foreground giant at 1.8 kpc. There is no reference to it in the SIMBAD database.

4. DISCUSSION

4.1. A Protocluster of Massive Stars?

With the exception of the two O stars associated with SMM 1, and star 106 possibly associated with SMM 5, none of the near-infrared stars are associated with the other submillimeter continuum or C$^{18}$O cores. The “starless” continuum objects SMM 2–4 may harbor embedded zero-age
main-sequence (ZAMS) stars or protostars that are not yet visible in the near-infrared, while the C$^{18}$O cores have not yet formed protostars. If so, they may resemble the lower mass prestellar cores detected by ISO (Bacmann et al. 2000). To examine this hypothesis, we can compare the limiting K-band magnitude of the 2MASS image with the expected brightness of an embedded ZAMS star with total luminosity equal to the dust luminosity of each core. It is difficult to estimate the individual luminosities of these cores because of the limited, coarse-resolution imaging data available on the mid-infrared side of their SEDs. However, using upper limits obtained from the MSX and IRAS images (as listed in Table 4), the luminosities of SMM 3 and 4 are constrained to be in the range $10^3$–$10^4$ L$_{\odot}$, depending on the dust temperature. Assuming the temperature of 25 K derived for the region as a whole yields a typical luminosity of $2 \times 10^4$ L$_{\odot}$, consistent with a B0 star. A B0 star has absolute visual magnitude $M_V = -4.1$ (Allen 1976) and $V-K = -0.85$ (Koornneef

Fig. 9.—Spectra from each C$^{18}$O (1–0) clump position listed in Table 5, integrated over a 10" diameter aperture. A Gaussian fit to each spectrum is overlaid in dotted lines. The fit parameters and the corresponding virial masses are listed in Table 5.

Fig. 10.—Solid line: Spatial profile of C$^{18}$O along the position angle +80° passing through clump 18 in the channel map for velocity 80.1 km s$^{-1}$. Dotted line: Same profile for the 2.7 mm continuum image. The axis of this strip is indicated in Figs. 13 and 1. The vertical scale on the left side describes the line data, while the right side describes the continuum.

| Stars Detected in All Three 2MASS Bands |
|-----------------------------------------|
| Number | 2MASS PSC |
|--------|------------|
| 1...... | 18342011–0755050 |
| 4a..... | 18342057–0755207 |
| 5....... | 18342064–0754497 |
| 6....... | 18342066–0754341 |
| 7....... | 18342067–0754593 |

Note.—Table 7 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

* Stars with $A_V > 10$, according to the color-color diagram shown in Fig. 12.
1983), yielding $M_K = -3.25$. At a distance of 4.9 kpc, this would be reduced to an apparent $K$ magnitude of 8.65. If such a star were placed at the center of the SMM 4 dust cloud, a $K$ extinction of 6.4 magnitudes (see Table 1) would result, yielding a final $K$ magnitude of $\sim$15. By comparison, the faintest star detected in the 2MASS image has a $K$ magnitude of 14.44. Thus we cannot rule out the possibility that each submillimeter source (SMM 2–5) may contain a ZAMS or main-sequence star rather than a protostar. Deeper imaging in $K$, $L$, or $M$ band would improve the constraints. At present, our best reasonable conclusion is that SMM 2–5 contain some number of young stellar objects or main-sequence stars with luminosities equivalent to at least a B-type star.

With the exception of SMM 5, as one moves from east to west across the region, the general trend is for objects in the cluster to exhibit fewer signs of compact, energetic phenomena. SMM 1 is associated with the well-developed UCH II region. The dust core (SMM 2) associated with the water maser probably traces an intermediate stage indicative of outflow or disk activity from the protostar. The next two dust cores (SMM 3 and SMM 4) exhibit no maser activity or ionized gas. We note that the dust-derived masses for these two objects exceed but remain in reasonable agreement with the $^{18}$O-derived masses (within 27% and 45%, respectively). In contrast, the dust-derived mass of the faintest submillimeter source (SMM 5) is a factor of 3 larger than the $^{18}$O-derived mass. Unfortunately, the uncertainties in the mass estimates are too large for us to interpret this difference in physical terms (such as a depletion of CO, which has been seen in objects such as B68 by Bergin et al. 2002). The other molecular cores not seen in continuum may be the youngest features in the region on their way to forming stars. Or they could simply be colder, inactive objects for which the accompanying dust emission is below the detection threshold. Deeper and higher resolution submillimeter observations are needed to explore these possibilities.

4.2. Fragmented Structure

The $^{18}$O emission of IRAS 18317–0757 is distributed in clumps aligned roughly along an east-west ridge. Evidence of periodic density structure has been previously observed in $^{18}$O in giant molecular clouds, specifically Orion A (Dutrey et al. 1991). The typical spatial wavelength found by Dutrey et al. (1991) is 1 parsec, and the fragment masses range from 70 to 100 $M_\odot$. More recently, fragmentation has been seen to extend to even smaller spatial scales in Orion from VLA observations of NH$_3$ (Wiseman & Ho 1998). Similarly, new observations of the mini-starburst W43 in submillimeter dust continuum reveal about 50 fragments with a typical size of 0.25 pc and mass of 300 $M_\odot$ (Motte, Schilke, & Lis 2003). In comparison, $^{18}$O maps of the Taurus complex reveal 40 dense cores of a typical size similar to those in W43 (0.23 pc) but with a smaller typical mass of 23 $M_\odot$ (Onishi et al. 1996). In IRAS 18317–0757 the typical spacing that we find between

![Fig. 11.—Near-infrared K-band image of IRAS 18317–0757 from the 2MASS database. The dotted circles represent the position of the 26 $^{18}$O (1–0) clumps identified in Table 5 and plotted in Fig. 8. The line indicates the axis used to produce the emission profiles in Fig. 10.](image-url)
the major C$^{18}$O cores is roughly 24" (0.5 pc), i.e., intermediate between Orion and W43, while our fragment masses range from 35 to 187 $M_\odot$, i.e., intermediate between W43 and Taurus. The fraction of total mass that resides in C$^{18}$O cores is 40%, which is somewhat larger than the value of 20% seen in NH$_3$ cores in W3(OH) (Tieftrunk et al. 1998) and the 19% seen in CS cores in Orion B (Lada, Bally, & Stark 1991). In any case, it is becoming clear that high-mass star formation regions, like their low-mass counterparts, contain a wealth of accreting material, including two O stars powering the UCH II region and exhibits an infrared spectrum consistent with a spectral type of O8.5, while star 86 is classified as O7 (Hanson et al. 2002).

4.3. Future Work

High-resolution mid- and far-infrared imaging is needed to accurately determine the temperature and size of the individual dust cores presently identified and to search for lower mass objects. Deeper imaging in the near-infrared is needed to search for additional ZAMS stars at high extinction levels within the dust and C$^{18}$O cores. Also, narrowband imaging in H$_2$ lines and (sub)millimeter interferometric imaging of SiO transitions may help distinguish which of the cores show jets and outflows. Submillimeter interferometry with higher spectral resolution in other optically thin tracers less affected by depletion would be useful to search for evidence of active infall toward the C$^{18}$O cores identified in this work. Finally, interferometric observations of the 22 GHz or submillimeter water maser transitions would be quite useful to better localize the maser activity to SMM 2 or one of the C$^{18}$O cores.  

5. CONCLUSIONS

Our high angular resolution observations of the luminous [$\log (L/L_\odot) = 5.2$], massive star forming region IRAS 18317−0757 have revealed a complex field of objects likely to be in various stages of star formation. Of the five submillimeter dust cores, one is associated with the UCH II region G23.955+0.150, and another with a water maser. The 2.7 mm continuum is completely dominated by free-free emission from the UCH II region, with total flux and morphology in agreement with VLA centimeter-wave maps. For the other four objects, the upper limits found at 2.7 mm and in the MSX mid-infrared band are consistent with pure optically thin dust emission at temperatures of 13–40 K and a dust grain emissivity index $\beta = 2$. Three out of four of these objects have no associated 2MASS star, and they are each likely to contain at least one (proto)star of luminosity 1000–40,000 $L_\odot$. In addition, we have identified two dozen C$^{18}$O cores in this region that contain $\approx$40% of the total molecular gas mass (7300 $M_\odot$) present. Their typical size and line width are 0.25 pc and 2–3 km s$^{-1}$, respectively. While the overall extent of the C$^{18}$O and dust emission is similar, most of the emission peaks do not correlate well in detail. Compared to the dust emission, a greater fraction of the C$^{18}$O emission exists in extended features. At least 11 of the 123 infrared stars identified by 2MASS in this region are likely to be embedded in the star-forming material, including two O stars powering the UCH II emission. Most of the rest of the reddened stars anticorrelate with the position of the dust and C$^{18}$O cores and are likely visible simply due to the relatively lower extinction. In summary, our observations indicate that considerable fragmentation of the molecular cloud has taken place during the time required for the UCH II region to form and for the O stars to become detectable at infrared wavelengths. Additional star formation appears to be ongoing throughout the region, with evidence for up to four B-type (proto)stars scattered among more than two dozen molecular gas cores.

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This page contains a color figure, Fig. 12, which depicts a color-color diagram ($J-H$ vs. $H-K$) for the stars detected in all three bands of the 2MASS PSC (numbers correspond to Table 7). The solid line marks the main sequence (Koornneef 1983). The dashed lines mark the reddening band (Rieke & Lebofsky 1985), with visual extinction levels marked (for an O7–O9 star). The circled numbers are the two stars associated with the peak centimeter through submillimeter continuum emission. Of these, star 92 is most closely associated with the UCH II region and exhibits an infrared spectrum consistent with a spectral type of O8.5, while star 86 is classified as O7 (Hanson et al. 2002).
Fig. 13.—Integrated emission from $^{13}$CO (1–0) is shown in gray scale and contours. The dashed circle marks the BIMA primary beam at half-maximum response. Point sources from the 2MASS catalog (detected in all three bands) are indicated by their number from Table 7 (with font size proportional to $K$-band brightness). The cross marks the water maser position uncertainty from Genzel & Downes (1977). The line indicates the axis used to produce the emission profiles in Fig. 10. Contour levels are 20%–90% of the peak emission (15.8 Jy beam$^{-1}$).

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