MILLIMETER MULTIPLETY IN NGC 6334 I AND I(N)
T. R. Hunter, C. L. Brogan, S. T. Megeath, K. M. Menten, H. Beuther, and S. Thorwirth

ABSTRACT
Using the Submillimeter Array (SMA), we have imaged the 1.3 mm continuum emission at the centers of the massive star-forming regions NGC 6334 I and I(N). In both regions, the SMA observations resolve the emission into multiple millimeter sources, with most of the sources clustered into areas only 10,000 AU in diameter. Toward NGC 6334 I, we find four compact sources: the two brightest (I-SMA1 and I-SMA2) are associated with previously known ammonia cores; I-SMA3 coincides with the peak of the compact H II region (NGC 6334 F), and I-SMA4 is a newly discovered object. While I-SMA3 exhibits a mixture of free-free and dust emission, the rest of the objects are dust cores. Toward NGC 6334 I(N), seven compact dust cores are found, one of which is associated with a faint centimeter source. With the exception of I-SMA3, none of the millimeter sources have infrared counterparts in Spitzer Space Telescope 3–8 μm images. Using a simple physical model for the dust continuum emission, we estimate that the mass of the interstellar material toward each of these compact objects is in the range of 3–66 M⊙. The total mass in the compact objects appears to be similar in I and I(N). The small size of these groups of sources suggest that these objects are proto-Trapezia forming in the centers of clusters of low- to intermediate-mass stars.

Subject headings: infrared: stars — ISM: individual (NGC 6334, NGC 6334 I(N)) — stars: formation — submillimeter — techniques: interferometric

Online material: color figure

1. INTRODUCTION
The formation process of massive stars continues to be a poorly understood phenomenon in astrophysics. The most fundamental clues to the origin of OB stars are their multiplicity and their common association with high column densities of molecular gas and dust. A unique feature of OB stars is that they are often found in nonhierarchically and (consequently) nonstable systems in the center of clusters (Sharpless 1954). A nearby example of this phenomenon is the Orion Trapezium, which has projected stellar separations of 4000 to 10,000 AU, and is found in the center of a rich cluster of low-mass stars. A long-standing question is whether these multiple systems are the direct result of the formation process, thus providing a clue to the process of high-mass star formation, or the result of dynamical evolution in the centers of young clusters, where the most massive stars move toward the center by ejecting lower mass stars outward (Bonnell & Davies 1998). While recent (sub)millimeter studies have identified good candidates for massive protoclusters on scales of several parsecs, the identification of proto-Trapezia is a more difficult prospect. Due to the complex nature of high-mass star-forming regions, the high extinction typically observed toward massive protostars, and their typically large distances (>1 kpc), high-resolution imaging at (sub)millimeter wavelengths is required to resolve one protostar from another. Recent space-based near-infrared (NIR) imaging has succeeded in identifying a 5600 AU diameter cluster of five proto-OB stars making up W3 IRS 5 (Megeath et al. 2005). However, because massive protostars form in the deeply embedded cores of molecular clouds, dust extinction may obscure a significant fraction of them in the infrared. In these cases, millimeter continuum emission from dust provides one of the few alternative tracers of protostars because it remains optically thin at high column densities (NHI ≤ 1025 cm−2).

The recent commissioning of the Submillimeter Array (SMA) on Mauna Kea, Hawaii has expanded the range of millimeter interferometry to higher frequencies and lower declinations. Now within reach is NGC 6334 (δ = −35°), a luminous and relatively nearby (1.7 kpc; Neckel 1978) molecular cloud/H II region complex containing several concentrations of massive star formation at various stages of evolution (Straw & Hyland 1989). The northeastern end appears to be the youngest and contains the radio source “F” (G351.42+0.64; Rodriguez et al. 1982), which is associated with IRAS 17175−3544. The earliest far-infrared images of this region (Emerson et al. 1973; McBreen et al. 1979) identified the emission as source “L.” An additional component “I(N)” was first detected at 1 mm (Cheung et al. 1978) and later at 400 μm (Gezari 1982). Further observations have demonstrated that although these two cores have comparable mass, NGC 6334 I dominates the combined bolometric luminosity of 2.6 × 105 L⊙ (Sandell 2000). In the NIR, an embedded cluster of stars has been detected in the central 2' of NGC 6334 I (Tapia et al. 1996). In contrast, the only NIR emission detected toward I(N) are H2 knots that are most likely associated with outflow activity (see Fig. 3 of Megeath & Tieftrunk 1999). In this paper, we present the first 1.3 mm interferometry of NGC 6334 I and I(N). Despite their strikingly different appearances in the NIR, we find that both regions contain a similar cluster of compact dust continuum cores. A detailed treatment of the millimeter line emission accompanying these objects will be the subject of a forthcoming paper (T. R. Hunter et al. 2006, in preparation).
2. OBSERVATIONS

2.1. Submillimeter Array

The Submillimeter Array (SMA)\(^6\) observations were made with six antennas in both the compact configuration (2004 May), and extended configuration (2005 May). Two pointings were observed: NGC 6334 I at 17\(^h\)20\(^m\)53\(^s\)44, \(-35\degree47\'02\"2\) and NGC 6334 I(N) at 17\(^h\)20\(^m\)54\(^s\)63, \(-35\degree45\'08\"5\). Unprojected baseline lengths ranged from 22 to 226 m. The SMA receivers are double-sideband mixers with 2 GHz bandwidth (Blundell 2004). The center frequencies were 217.6 GHz in the lower sideband (LSB) and 227.6 GHz in the upper sideband (USB). The synthesized beam is 2\(^\prime\) and the gain calibrator was NRAO 530. The synthesized beam of the 3.6 cm continuum image is 7 mJy beam\(^{-1}\). The estimated accuracy of the absolute coordinates is 0.4\(^\prime\)4. After combining the calibrated LSB and USB continuum u-v data, the 1 \(\sigma\) rms noise level achieved in the continuum images is \(7 \times 10^{-3}\) mJy beam\(^{-1}\). The resulting synthesized beam is 2\(^\prime\)71 \times 1\(^\prime\)2 and the primary beam is ~56\(^\prime\).

2.2. Very Large Array

Archival 3.6 cm data from the NRAO\(^7\) Very Large Array (VLA) were calibrated and imaged in AIPS. The observation date was 1990 May 7 (A-configuration). The flux calibrator was 3C 286, and the gain calibrator was NRAO 530. The synthesized beam of the 3.6 cm continuum image is \(0.90 \times 0.43\) at (P.A. = -18\(^\circ\)) and the rms sensitivity is 1 mJy beam\(^{-1}\).

2.3. Spitzer Space Telescope

Both SMA fields were observed with the IRAC camera (Fazio et al. 2004) on board the Spitzer Space Telescope. The total integration time was 666 s. The high dynamic range mode was used to obtain 0.4 and 10.4 s integrations. The data were reduced using the BCD data from the Spitzer Science Center version 11.4 pipeline. When constructing images, the 0.4 s data were used toward pixels where the 10.4 s data were saturated, which is only the case for some of the sources in NGC 6334 I. The pixel size for the images is 1\(^\prime\)2. Upper limits were derived from mosaics produced with the MOPEX program. To calculate the upper limits, the rms signal was found for a 5 \times 5 pixel box centered on the SMA sources. These values were converted to units of millijanskys per pixel, then multiplied by a factor of 5/2 to calculate 5 \(\sigma\) limits for detections in a 2 \times 2 pixel aperture.

3. RESULTS

3.1. NGC 6334 I

The 1.3 mm continuum emission in NGC 6334 I is shown in Figure 1. We have resolved four major continuum sources, which we denote as I-SMA1–4, in descending order of peak intensity (see Table 1). The continuum sources are all fairly compact.

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1998; Norris et al. 1993). The faint continuum source with its filled circles mark 44 GHz class I CH$_3$OH masers (Kogan & Slysh 1998), the cross marks the faint 3.6 cm source (Carral et al. 2002), and the small plus sign marks a 6.7 GHz class II CH$_3$OH maser (Norris et al. 1993; Walsh et al. 1998). The triangles mark 25 GHz class I CH$_3$OH masers, and the large plus sign indicates the nature continuum emission (5, 10, 20, 40, 70, 100, 115) mJy (Fig. 2). Including the extended emission, the fraction of single-dish flux recovered in our image is 32% ± 8%. Nearly half of the total emission originates from I(N)-SMA1. Although this field lacks any strong centimeter continuum emission, two faint 3.6 cm (0.3 mJy) sources have been reported (Carral et al. 2002). One of these sources lies within 0.06 of I(N)-SMA4, which is also the source closest to a class II CH$_3$OH maser (Walsh et al. 1998; Norris et al. 1993). The faint continuum source with its (probable) associated class II CH$_3$OH maser may represent a hypercompact H II region, similar to the sources found by van der Tak & Menten (2005) in other massive star formation regions. If this interpretation is true, then this object is an important power source in the I(N) region. Class I CH$_3$OH masers have also been identified in this region at 25 GHz (Beuther et al. 2005) and at 44 GHz but with uncertain astrometry (Kogan & Slysh 1998). None of the millimeter sources have counterparts in our IRAC data (5 σ upper limits at 4.5 and 8 μm are given in Table 1). However, directly west of I(N)-SMA4 is an extended infrared source detected at 4.5 and 5.8 μm (Fig. 3). The elongated morphology suggests a jet or a reddened reflection nebulosity from an outflow cavity. In either scenario, the extended mid-IR emission would be the result of outflow activity from the embedded source in I(N)-SMA4. The unipolarity could be explained if the other lobe of the putative outflow were obscured by stronger extinction in its direction. This possible association is the only evidence, albeit indirect, for the I(N)-SMA sources at wavelengths <8 μm.

### Table 1

| Source | α (J2000.0) | δ (J2000.0) | $I_{1.3 \text{ mm}}$ (mJy beam$^{-1}$) | $F_{1.3 \text{ mm}}$ (mJy) | $F_{4.5 \mu \text{m}}$ (mJy) | $F_{8.0 \mu \text{m}}$ (mJy) |
|--------|-------------|-------------|-----------------|----------------|----------------|----------------|
| I-SMA1 | 17 20 53.44 | −35 46 57.9 | 1.77            | 3.49 ± 0.70    | <320           | ...$^a$        |
| I-SMA2 | 17 20 53.20 | −35 46 59.6 | 0.96            | 2.28 ± 0.96    | <240           | <1490         |
| I-SMA3 | 17 20 53.45 | −35 47 02.6 | 0.71            | 2.01 ± 0.40    | ...$^a$        | ...$^a$       |
| I-SMA4 | 17 20 53.12 | −35 47 03.2 | 0.52            | 1.10 ± 0.22    | <260           | <1490         |
| Total  | ...         | ...         | 10.7 ± 2.1      | ...            | ...           | ...           |
| I(N)-SMA1 | 17 20 55.21 | −35 45 04.1 | 0.82            | 2.04 ± 0.41    | <0.11          | <0.71         |
| I(N)-SMA2 | 17 20 54.90 | −35 45 06.8 | 0.35            | 0.50 ± 0.10    | <0.35          | <0.53         |
| I(N)-SMA3 | 17 20 55.00 | −35 45 07.5 | 0.27            | 0.39 ± 0.09    | <0.21          | <0.53         |
| I(N)-SMA4 | 17 20 54.69 | −35 45 08.5 | 0.17            | 0.33 ± 0.07    | <0.70          | <0.77         |
| I(N)-SMA5 | 17 20 55.08 | −35 45 02.0 | 0.27            | 0.28 ± 0.07    | <0.12          | <0.63         |
| I(N)-SMA6 | 17 20 54.59 | −35 45 17.9 | 0.27            | 0.47 ± 0.10    | <0.29          | <0.69         |
| I(N)-SMA7 | 17 20 54.96 | −35 44 57.3 | 0.07            | 0.20 ± 0.05    | <0.51          | <0.68         |
| I(N) Total | ...         | ...         | 4.6 ± 0.9$^b$   | ...            | ...           | ...           |

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

$^a$ The extended nebula of the compact H II region precludes a meaningful infrared point source upper limit.

$^b$ The total 1.3 mm flux density includes the extended emission; the listed uncertainties include 20% calibration uncertainty.

### Figure 2

1.3 mm continuum image of NGC 6334 I(N). Contour levels are (−3, 3, 6, 9, 12, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 85, 100, 115) mJy beam$^{-1}$. Filled circles mark 44 GHz class I CH$_3$OH masers (Kogan & Slysh 1998), the small plus sign marks a 6.7 GHz class II CH$_3$OH maser (Norris et al. 1993; Walsh et al. 1998), the cross marks the faint 3.6 cm source (Carral et al. 2002), and the six-pointed stars mark infrared H$_2$ knots (Megeath & Tieftrunk 1999). The filled triangles mark 25 GHz class I CH$_3$OH masers, and the large plus sign indicates the NH$_2$ peak (Beuther et al. 2005).

### Figure 3

4.5 μm IRAC image of NGC 6334 I(N). Contours indicate the 1.3 mm continuum emission (5, 10, 20, 40, 70, 100 × 6.5 mJy beam$^{-1}$) and the dashed circle shows the primary beam of the 1.3 mm SMA observations. The newly detected infrared nebulosity happens to lie near the center of this circle, just west of I(N)-SMA4. [See the electronic edition of the Journal for a color version of this figure.]
We can estimate the mass of the individual dust sources by placing our millimeter continuum measurements in the context of a simple isothermal model of optically thin dust emission (Beltrán et al. 2006). The assumption of low optical depth is justified because the peak continuum brightness temperature of the strongest dust source (I-SMA1) is only 6.3 K. The input parameters to the model include the dust temperature, the dust mass opacity coefficient at the observed wavelength ($\kappa_{1.3\,\text{mm}}$), and the gas-to-dust mass ratio. Based on our SMA spectra (T. R. Hunter et al. 2006, in preparation), we can categorize the sources into three groups: (A) strong hot-core line emission: I-SMA1, I-SMA2 and I(N)-SMA1; (B) weak line emission: I-SMA3 and I(N)-SMA2, and (C) nearly line-free emission. Thus, from a qualitative viewpoint, the gas and dust are likely to be warmest in the group A sources, and coolest in the group C sources. By combining this information with the various gas temperature measurements from the literature, we have assigned a probable value for the dust temperature of each source, including upper and lower limits (see Table 2). For the sources in group A, the brightness temperature of the arcsecond-scale NH$_3$ (2,2) emission provides the lower limit temperature (Beuther et al. 2005). For I-SMA1 and I-SMA2, we set the “nominal” temperature equal to the dust temperature (100 K) obtained from fits to the single-dish spectral energy distribution (SED) for source I (Sandell 2000). We also use 100 K for I(N)-SMA1, for which the single-dish temperature ratio of NH$_3$ (6,6) to (3,3) indicates the presence of gas with $T > 95$ K (Küiper et al. 1995); furthermore, recent interferometric measurements have localized the bulk of the NH$_3$ (6,6) emission to the position of I(N)-SMA1 (H. Beuther et al. 2006, in preparation). For an upper limit temperature for group A, we adopt 300 K because an excitation temperature of 295 K was measured for H$_2$O in NGC 6334 I by Man gum & Wootten (1993), and 213 K was measured for CH$_3$OH by van der Tak et al. (2003).

For the sources in group B, we set the nominal temperature equal to the CO excitation temperature derived by Kraemer et al. (1999), which is 60 K for NGC 6334 I and 40 K for I(N). For the sources in group C, we set the nominal temperature equal to the value (33 K) derived from a large velocity gradient analysis of a single-dish submillimeter line survey (McCutcheon et al. 2000). In both I and I(N), the lower limit temperature of the group B and C sources is taken to be the temperature of the coolest dust core (20 K) in the surrounding region as measured by Sandell (2000), while the upper limit is taken to be 50 K due to the lack of direct evidence of any warmer gas at these positions. Measurements of $\kappa_{1.3\,\text{mm}}$ in NGC 6334 I and I(N) with a $30''$ beam yield values from 1.0–1.2 ± 0.6 cm$^2$ g$^{-1}$ (Schwartz et al. 1989). However, due to the large range of temperature in the compact millimeter sources, we have chosen to use tabulated values of $\kappa_{1.3\,\text{mm}}$ from Ossenkopf & Henning (1994) for a density of 10$^5$ cm$^{-3}$. For sources in group A, we use a $\kappa_{1.3\,\text{mm}} = 2$ cm$^2$ g$^{-1}$ for dust grains without mantles, which is appropriate for regions where protostellar heating has destroyed the solid ice but has not yet dispersed the dust aggregates. In the other millimeter sources that show no hot core emission and are opaque at infrared wavelengths, the grains are likely to have thick ice mantles; thus, we use $\kappa_{1.3\,\text{mm}} = 1$ cm$^2$ g$^{-1}$. Applying a gas-to-dust mass ratio ($\rho$) of 100 (Sodroski et al. 1997), these assumptions yield the masses listed in Table 2. Due to uncertainties in $\kappa_{1.3\,\text{mm}}$ and $\rho$, the uncertainties in all of the masses in Table 2 are likely to be at least a factor of 2. Subject to these uncertainties, the total mass estimates of the compact objects (in both the warm and cold temperature limits) are of similar magnitude in I and I(N), ranging from ~50 to ~150 $M_{\odot}$. In I(N), this mass is divided among a larger number of sources which are, in turn, spread over a larger angular extent.

### Table 2

| SOURCE      | COLD LIMIT T (K) | COLD LIMIT M ($M_{\odot}$) | NOMINAL T (K) | NOMINAL M ($M_{\odot}$) | WARM LIMIT T (K) | WARM LIMIT M ($M_{\odot}$) |
|-------------|------------------|-----------------------------|---------------|--------------------------|------------------|----------------------------|
| I-SMA1      | 25               | 100                         | 17            | 300                      | 5.4              |
| I-SMA2      | 27               | 15                          | 100           | 110                      | 3.5              |
| I-SMA3      | 40               | 52                          | 60            | 33                       | 19               |
| I-SMA4      | 20               | 66                          | 33            | 36                       | 22               |
| Total       | 156              | 97                          | 50            |                          |
| I(N)-SMA1   | 2                | 65                          | 100           | 100                      | 3.1              |
| I(N)-SMA2   | 1                | 20                          | 30            | 40                       | 100              |
| I(N)-SMA3   | 1                | 20                          | 23            | 33                       | 15               |
| I(N)-SMA4   | 1                | 20                          | 20            | 33                       | 11               |
| I(N)-SMA5   | 1                | 20                          | 17            | 33                       | 9                |
| I(N)-SMA6   | 1                | 20                          | 28            | 33                       | 15               |
| I(N)-SMA7   | 1                | 20                          | 12            | 33                       | 6                |
| I(N) Total  | 145              | 77                          | 39            |                          |

### 4. DISCUSSION

The observed multiplicity and strength of the millimeter continuum emission is quite similar between NGC 6334 I and I(N), in contrast to their strikingly different appearance in the NIR (Megeath & Tieffrunk 1999) and in thermal lines of NH$_3$ and CH$_3$OH (Beuther et al. 2005). Although previous maser and NH$_3$ observations of NGC 6334 I had suggested the presence of multiple sources, our millimeter image provides a direct and unambiguous picture of a massive protocluster. The estimated mass of interstellar material toward each source is sufficient to form a massive star and is significantly greater than typical objects detected in the single-dish surveys of low-mass star-forming regions such as Perseus, where an average core mass of 2.3 $M_{\odot}$ has been found with a beam size of ~8000 AU (Enoch et al. 2006). In addition, it is likely that a compact protostellar object may already be present at the center of each source, heating the surrounding gas and dust and leading to our strong millimeter detections. This scenario is particularly likely for the strong hot-core sources I-SMA1 and I-SMA2. It is important to note that the masses in Table 2 do not include the total stellar mass that may be present in addition to the interstellar material.

In the case of NGC 6334 I(N), the presence of outflows, masers, warm gas emission, and a faint centimeter continuum source also indicate the presence of embedded sources. This cluster of sources may be in an earlier evolutionary phase than source I, as suggested by the lack of a NLR cluster, H ii region, or bright mid-IR source, and by the significantly higher gas column density inferred from N$_2$H$^+$ observations (Pirogov et al. 2003). However, if the millimeter sources contain central protostars, then the lack of mid-IR detections toward all seven sources is especially curious, because, in contrast to source I, there is no confusion from bright, extended nebulosity in this region. If we consider the I(N) bolometric luminosity of $1.9 \times 10^5 L_{\odot}$ (Sandell 2000), the earliest zero-age main sequence (ZAMS) star that could be present is type B2 V (Hanson et al. 1997). Our lowest 4.5 $\mu$m upper limit of 0.11 mJy (from Table 1) corresponds to an apparent magnitude of $m_{4.5\,\mu m} > 15.5$. This limit is consistent with the nondetection of an embedded B2 V ZAMS star as long as the extinction at 4.5 $\mu$m is $>4.9$ mag, assuming an absolute stellar magnitude.
have identified examples of young massive protostars in the center of an established infrared cluster containing low- to intermediate-mass stars. In source I(N), we see evidence of massive protostars without a surrounding NIR cluster, which challenges the common picture of high-mass stars forming after the first generation of low-mass stars (e.g., Herbig 1962; Kumar et al. 2006). More sensitive infrared imaging is needed to probe deeper through the extinction for signs of lower mass protostars in this field. However, until such evidence is found, the question of the relative age of I and I(N) hinges on three main facts: (1) the ratio of bolometric luminosity between I and I(N) is large (≈140; Sandell 2000); (2) the I(N) region exhibits significantly less hot-core line emission than NGC 6334 I (Thorwirth et al. 2003; T. R. Hunter et al. 2006, in preparation); and (3) a cluster of compact dust continuum sources exists in I and I(N) with a comparable amount of mass (this paper). These observations suggest that either NGC 6334 I is a more evolved cluster than I(N), or I(N) is forming a cluster with a larger number of stars but of lower mass. In either case, our millimeter data provide strong evidence that NGC 6334 I(N) is forming a cluster of stars, even though an associated NIR cluster has not been identified and may be still in the process of forming. Finally, we note that the virial masses derived from single-dish molecular line spectra (including $N_2H^+$ by Pirogov et al. [2003] and $HC_3N$ by Sollins & Megeath [2004]) for both NGC 6334 I and I(N) are several times higher than the total estimated mass contained in the compact millimeter sources. This fact illustrates the wealth of star-forming material in both regions that has either not assembled into compact protostars or exists in a wider distribution of smaller cores below our sensitivity limit. It is this gas which may be forming the cluster surrounding the SMA sources in NGC 6334 I(N) and which may further increase the population of the cluster in NGC 6334 I.

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