TWO MASSIVE, LOW-LUMINOSITY CORES TOWARD INFRARED DARK CLOUDS

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Received 2009 April 22; accepted 2009 September 29; published 2009 October 21

ABSTRACT
This article presents high-resolution interferometric mosaics in the 850 μm wave band of two massive, quiescent infrared dark clouds. The two clouds were chosen based on their likelihood to represent environments preceding the formation of massive stars. The brightest compact sources detected in each cloud have masses \( \approx 110 M_\odot \) and \( \approx 60 M_\odot \) with radii \( <0.1 \) pc, implying mean densities of \( \langle n \rangle \approx 10^4 \) cm\(^{-3} \) and \( \langle N \rangle \approx 1 \) g cm\(^{-2} \). Supplementary data show these cores to be cold and inactive. Low upper limits to their bolometric luminosities and temperatures place them at a very early stage of evolution, while current models of massive star formation suggest they have the potential to form massive stars.

Key words: ISM: clouds – ISM: individual (MSX G030.88+00.13) – ISM: structure – stars: formation

Online-only material: color figure

1. INTRODUCTION

It is fairly well established that low-mass stars form from the gravitational collapse of dense condensations, or cores,\(^1\) within molecular clouds (Myers & Benson 1983; Beichman et al. 1986; Motte et al. 1998), and there are many examples of cores in nearby star-forming regions (\( \lesssim 300 \) pc) that appear to represent the direct progenitors of low-mass stars, at least in a statistical sense (e.g., Alves et al. 2007). However, surveys of distant regions where massive stars form suffer from poor physical resolution, blending together regions with sizes comparable to clusters of stars (e.g., Shirley et al. 2003; Evans 2008). High-resolution interferometric observations can resolve these massive clumps into substructure, more closely related to individual stars or stellar systems (e.g., Beuther et al. 2007; Pillai et al. 2006; Molinari et al. 2002). But in virtually all cases, these high-resolution studies have targeted regions with indications for young massive stars such as bright mid-infrared emission, masers, outflow, or compact H\(\alpha\).

This article presents two interferometric mosaics of infrared dark clouds (IRDCs; Simon et al. 2006a; Perault et al. 1996; Egan et al. 1998) selected to lack massive protostars yet likely to be pre-cluster clouds. Several dense cores are detected within each IRDC, but it is the most massive cores in each cloud that are the focus of this article. Following a description of our observations in Section 2, the general properties of the IRDCs are described in Section 3 using new single dish data together with published data. The interferometric mosaics are then considered in Section 4 where the physical properties of the massive cores are presented and discussed.

2. OBSERVATIONS AND DATA REDUCTION

The IRDCs MSX G030.88+00.13 and MSX G028.53−00.25 were chosen from the catalog of Simon et al. (2006b) using Spitzer Galactic plane survey data (Benjamin et al. 2003; Carey et al. 2009), and SCUBA archival data (Di Francesco et al. 2008) to be massive, dense, and lack significant 24 μm emission. These attributes were desired to maximize the probability that the clouds are in a state preceding the formation of massive stars. The observations are summarized in Table 1.

The target IRDCs were observed with the Submillimeter Array\(^2\) (SMA) in its compact configuration using the 345 GHz receivers. Mosaic observations were designed to cover the brightest SCUBA emission in each IRDC. These observations preserved the full 4 GHz bandwidth and specified both high- and low-resolution correlator chunks with 0.17 and 2.8 km s\(^{-1}\) channel widths, respectively. The data were calibrated using the MIR reduction package.\(^3\) Visibility phases were corrected using quasar observations conducted in 25 minute intervals. The bandpass was calibrated with observations of the quasar 3C279, and Uranus was used to tie down the flux scale to an accuracy of \( \sim 15\% \). The visibility data were then output into MIRIAD\(^4\) format and inverted into the image domain. The mean rms level across the mosaic maps for MSX G030.88+00.13 and MSX G028.53−00.25 are 5.4 mJy and 4.6 mJy for synthesized beam sizes of 1′′.9 × 1′′.8 and 2′0 × 1′′.1 oriented at position angles of 66° and 68°, respectively.

The James Clerk Maxwell Telescope\(^5\) (JCMT) equipped with the HARP-B receiver array and ACSIS back end (Dent et al. 2000) was used to observe our target IRDCs over several nights. Spectral lines of CO, \(^13\)CO, C\(^{18}\)O, N\(^2\)H\(^+\), and H\(_2\)D\(^+\) were placed in spectral windows of 250 MHz width and 61 kHz resolution. Flux levels are expected to be accurate to 15% and the pointing accuracy of the final maps are estimated to be better than 3′′.5. The Starlink software suite was used to grid and output the data into FITS format, and IDL was used to perform final calibrations and co-adding. A main beam efficiency \( \eta_{MB} = 0.7 \) is used to convert corrected antenna temperatures to main beam temperatures.

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\(^1\) Following the convention presented in Williams et al. (2000), “cores” describe dense condensations of molecular gas with \( M \lesssim 100 M_\odot \), that will form individual stars or small stellar systems, while “clumps” describe dense cloud structures with mass \( \gtrsim 1000 M_\odot \) that are more likely to form clusters of stars.

\(^2\) The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics, and is funded by the Smithsonian Institution and the Academia Sinica.

\(^3\) http://www.cfa.harvard.edu/~cqf/mircook.html

\(^4\) http://bima.astro.umd.edu/miriad

\(^5\) The James Clerk Maxwell Telescope is operated by The Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the United Kingdom, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada.
The Canada–France–Hawaii Telescope\(^6\) (CFHT) was used to observe our target clouds using the WIRCam infrared detector (Puget et al. 2004). The observations were carried out in queue mode over the course of two photometric nights. The pre-processed data (de-biased, flat-fielded, and sky-subtracted by the CFHT pipeline) were downloaded and further reduced using the TERAPIX\(^7\) software suite. The images were registered, combined by weighted mean, and tied to the 2MASS\(^8\) point source catalog flux scale to an accuracy of better than 0.02 mag.

### 3. THE IRDC ENVIRONMENTS

Figures 1(a) and (b) show images from the Spitzer GLIMPSE survey in which the mid-infrared extinction features that define the clouds can be clearly seen. Contours of velocity integrated \(^{13}\)CO(3–2) overlay the images in yellow. MSX G030.88+00.13 has two velocity components along the line of sight with centroids at 95 and 107 km s\(^{-1}\) with respect to the local standard of rest. The higher velocity component shown in Figure 1(a) at \(^{13}\)CO emission levels of \((5 + 3n)\) K km s\(^{-1}\) \((n = 0, 1, 2, \ldots)\) is widespread across the region suggesting that the IRDC is part of a larger complex including the bright infrared cluster to the northwest. MSX G028.53−00.25 has a single velocity component in \(^{13}\)CO at 87 km s\(^{-1}\) shown at contour levels of \((6 + 2n)\) K km s\(^{-1}\) seen to be spatially confined to the region of mid-infrared extinction. The presence of high volume density gas in these clouds is confirmed with detections of N\(_2\)H\(^+\) \((4 − 3)\) shown as magenta contours at levels of \((1 + 0.5n)\) K km s\(^{-1}\) and \((1 + 0.4n)\) K km s\(^{-1}\) for Figures 1(a) and (b), respectively.

The velocity centroid of MSX G030.88+00.13 places it at the tangent point of Galactic rotation in this direction. Therefore, a distance of 7.2 kpc can be derived using the simple geometric relationship \(d = R_0 \cos(l) \cos(b)\), where \(R_0\) is taken to be 8.4 kpc (Ghez et al. 2008; Reid et al. 2009). The distance to MSX G028.53−00.25 is taken to be 5.4 kpc (Rathborne et al. 2006). The errors on these kinematic distances may be 15% or more due to non-circular motions in the Galaxy (e.g., Roman-Duval et al. 2009). The masses of the IRDCs are estimated to be several thousand solar masses based on CO isotopologue emission assuming 15 K gas in local thermodynamic equilibrium, SCUBA 850 \(\mu\)m continuum emission, and virial equilibrium.

There is no \(\lambda\)20 cm or \(\lambda\)6 cm emission detected toward either IRDC (Helfand et al. 2006; White et al. 2005). A total \(\lambda\)20 cm flux of 250 mJy seen toward the IR bright cluster in Figure 1(a) suggests the presence of a B0 star (Giveon et al. 2005). Two class II methanol masers are seen in the field of MSX G030.88+00.13 with velocities in rough agreement with the cloud (Pestalozzi et al. 2005). No class II masers are seen in the MSX G028.53−00.25 field. However, one water maser has been detected toward an embedded source in this cloud (Wang et al. 2006). Fits to the spectral energy distributions (SEDs) of MIPS 24 \(\mu\)m sources within the IRDCs suggest they are not massive stars (Robitaille et al. 2006, 2007). Although given the large column depths observed toward the IRDCs and their distances, it is possible that more protostars are embedded in the cloud than are detected in the Spitzer data. We estimate that less than \~100 stars are embedded within each IRDC based on extrapolations from mid-infrared emission from nearby, intermediate-mass star-forming regions (Padgett et al. 2008; Rebull et al. 2007) and a Salpeter stellar mass function with a lognormal turnover (Salpeter 1955; Chabrier 2003).

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\(^6\) The CFHT is operated by the National Research Council of Canada, the Institut National des Sciences de l’Univers of the Centre National de la Recherche Scientifique of France, and the University of Hawaii.

\(^7\) http://terapix.iap.fr

\(^8\) The Two Micron All Sky Survey is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

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**Table 1**

Summary of Observations

| Date       | Wave Band | Conditions | Target\(^9\) | Calibrators | Obs. Type |
|------------|-----------|------------|--------------|-------------|-----------|
| 2007 Jun 24 | 350.9 GHz\(^b\) | \(\tau_{225} \approx 0.08\)\(^c\) | B            | 1751+096/1743-038 | 1         |
| 2007 Jul 01 | 351.0 GHz\(^b\) | \(\tau_{225} \approx 0.08\)\(^c\) | B            | 1751+096/1743-038 | 1         |
| 2007 Jul 07 | 350.9 GHz\(^b\) | \(\tau_{225} \approx 0.08\)\(^c\) | A            | 1751+096/1743-038 | 1         |
| 2007 Oct 19 | 350.9 GHz\(^b\) | \(\tau_{225} \approx 0.08\)\(^c\) | A            | 1751+096/1743-038 | 1         |
| 2008 Jun 02 | 340.5 GHz\(^b\) | \(\tau_{225} \approx 0.15\)\(^c\) | A,B          | 1751+096/1911-201 | 1,2       |
| 2008 Jun 15 | 340.5 GHz\(^b\) | \(\tau_{225} \approx 0.11\)\(^c\) | A,B          | 1751+096/1911-201 | 1,2       |
| 2007 Jul 17 | 334.8 GHz/350.7 GHz\(^b\) | \(\tau_{225} \approx 0.10\)\(^c\) | A,B          | V437Sct/16293-2422/G45.1 | 3         |
| 2007 Jul 18 | 350.7 GHz/367.3 GHz\(^b\) | \(\tau_{225} \approx 0.06\)\(^c\) | B            | V437Sct/16293-2422/HD235858 | 3,4       |
| 2007 Jul 19 | 334.8 GHz/350.7 GHz/367.3 GHz\(^b\) | \(\tau_{225} \approx 0.06\)\(^c\) | A,B          | V437Sct/16293-2422/G34.2 | 3,4       |
| 2007 Jul 20 | 334.8 GHz/350.7 GHz/367.3 GHz\(^b\) | \(\tau_{225} \approx 0.07\)\(^c\) | A,B          | V437Sct/16293-2422/G34.2 | 3,4       |
| 2008 Aug 06 | 367.3 GHz\(^b\) | \(\tau_{225} \approx 0.05\)\(^c\) | A            | WAql          | 4         |
| 2008 Nov 12 | 367.3 GHz\(^b\) | \(\tau_{225} \approx 0.07\)\(^c\) | A            | HD179821/NMLCyg | 4         |

**Notes.** (1) Mosaic observations, (2) targeted (single pointing) observations, (3) raster scan mapping, (4) jiggle chop observations, and (5) direct imaging.

\(^9\) Target A corresponds to MSX G030.88+00.13, and target B corresponds to MSX G028.53−00.25.

\(^b\) Local oscillator frequency.

\(^c\) Atmospheric opacity at 225 GHz.
4. HIGH-RESOLUTION SUBMILLIMETER WAVE IMAGING

Figures 2(a) and (b) show the contours of the SMA mosaics overlaid on Spitzer mid-infrared composite images. The brightest sources in each mosaic dominate the compact submillimeter wave emission toward the IRDCs. These massive cores lie near the peak of the SCUBA emission and are isolated with respect to other compact sources. They are also isolated in mass with the next most massive cores in each cloud being more than a factor of 3 less massive. Table 2 displays the physical characteristics of the two compact submillimeter sources.

4.1. Two Massive, Low-luminosity Cores

The derived masses of the two cores are $\approx 110 M_\odot$ and $\approx 60 M_\odot$ with densities of $\langle n \rangle \approx 10^6$ cm$^{-3}$ and $\langle N \rangle \approx 1$ g cm$^{-2}$. Their free fall, or dynamical timescales are thus a few $10^4$ yrs implying that they are most likely short-lived structures. Both cores appear marginally resolved, but are detected in the longest baseline data suggesting that perhaps there are resolved and unresolved components.

Figure 3 shows the spectral energy distributions of the cores consisting of upper limits from 1.25 $\mu$m to 70 $\mu$m and 853 $\mu$m fluxes from Table 2. A best-fit gray body curve with $\tau = (\nu/\nu_c)^2$, and $\nu_c = 6$ THz (Ward-Thompson et al. 2002) limits the envelope temperatures, while summation under the solid curves of Figure 3 provide upper limits to the bolometric luminosities and temperatures (Myers & Ladd 1993).

High values of $M_{env}/L_{bol} \approx 2.8$ in solar units and low values for $T_{bol} \lesssim 30$ K for these cores are signs of extreme youth. Class 0 protostars, the earliest SED class, are marked by $M_{env}/L_{bol} > 0.4$ (Bontemps et al. 1996; Andre et al. 2000) and $T_{bol} \lesssim 70$ K (Chen et al. 1995). Given the large distances to these cores and the photometric sensitivity, the existence of a low-
luminosity sources deeply embedded within the cores cannot be ruled out. However, it is clear that no massive protostars exist in these cores.

Across the SMA bandpass, the cores are only detected in CO(3−2) and HCO+(4−3). The CO(3−2) is strongly filtered by the interferometer making a useful interpretation of the emission from this low density gas tracer difficult. However, no clear indication of outflow is seen toward either core in the single dish observations and the propensity for H2D+ to trace dense gas toward the two cores with the velocity scale shifted relative to the centroid of N2H+ emission for each core measured from the innermost regions of cores, it may be that this discrepancy is due in large part to beam dilution.

Figure 4 shows the composite spectra of molecular transitions tracing dense gas toward the two cores with the velocity scale blueward of its systemic velocity that may be a sign of a similar spectral feature to core 1. Also shown in Figure 4 are spectra of ortho-H2D+(11−10) and H2D+(10−9) emission in the central channels is widespread and filtered out by the interferometer. Core 2 shows a weak feature in the HCO+ self-absorption, but there is also the possibility that the blueward of the systemic velocity. This may be an indication of HCO+ emission feature that lies shifted relative to the centroid velocity of N2H+(4−3) emission for cores 1 and 2, respectively, translate to column densities of N(H2D+) ≈ 1011 cm−2 using a kinetic temperature Tk = 15 K and a critical density ncr = 106 cm−3. The fractional abundances of ortho-H2D+ are N(H2D+)/N(H2) ≈ (3−5) × 10−13. Varying Tk from 10 to 15 K and Ncr from 105 to 106 cm−3 changes these values by a factor of about 2. These numbers are significantly smaller than the values found for low-mass pre- and proto-stellar cores (Vastel et al. 2006; Caselli et al. 2008) as well as in Orion B (Harju et al. 2006). This could be due to an intrinsic dearth of H2D+. However, given the poor physical resolution of our single dish observations and the propensity for H2D+ to trace the innermost regions of cores, it may be that this discrepancy is due in large part to beam dilution.

Also shown in Figure 4 are spectra of ortho-H2D+(11,0−l1,1) toward the cores. Core 1 shows an emission feature with 4.3σ significance centered at 106.6 km s−1 with a full width of 0.9 ± 0.3 km s−1. Core 2 shows a broader feature with 2.0 ± 0.7 km s−1 width at a 3.1σ significance level. This molecular species is thought to trace cold, dense, and chemically evolved gas in the deep interior of pre- or proto-stellar cores (Walmsley et al. 2004; Vastel et al. 2006; Caselli et al. 2008). Following Caselli et al. (2008), the integrated line fluxes of 0.13 K km s−1 and 0.17 K km s−1 for cores 1 and 2, respectively, translate to column densities of N(H2D+) ≈ 1011 cm−2 using a kinetic temperature Tk = 15 K and a critical density ncr = 106 cm−3. The fractional abundances of ortho-H2D+ are N(H2D+)/N(H2) ≈ (3–5) × 10−13. Varying Tk from 10 to 15 K and Ncr from 105 to 106 cm−3 changes these values by a factor of about 2. These numbers are significantly smaller than the values found for low-mass pre- and proto-stellar cores (Vastel et al. 2006; Caselli et al. 2008) as well as in Orion B (Harju et al. 2006). This could be due to an intrinsic dearth of H2D+. However, given the poor physical resolution of our single dish observations and the propensity for H2D+ to trace the innermost regions of cores, it may be that this discrepancy is due in large part to beam dilution.

### Table 2

| Name  | R.A. (J2000) | Decl. (J2000) | Fpeak (mJy/bm) | Fint (mJy) | Mass⁺ (M⊙) | n (10⁶ cm⁻³) | Tkin (K) | Tenv (K) | Tboll (K) | Lbol (L⊙) |
|-------|-------------|--------------|---------------|------------|------------|--------------|--------|--------|---------|---------|
| Core 1 | 18:47:13.7  | −01:45:03.7  | 119           | 255        | 110        | 0.082        | 0.82   | 1.1    | < 19    | < 31    | < 460   |
| Core 2 | 18:44:18.0  | −03:59:23.0  | 118           | 224        | 60         | 0.056        | 1.5    | 1.3    | < 18    | < 30    | < 170   |

**Notes.**

⁺ Masses estimated using a dust temperature of 15 K and an opacity κ = 0.019 cm² g⁻¹ derived from (Ossenkopf & Henning 1994, Table 1).

⁻ Radii are derived by deconvolving the synthesized beam from the effective radius, r = \sqrt{R_{\text{eff}}^2 - R_{\text{beam}}^2}, where R_{\text{eff}} = \sqrt{A/π} and A is the area contained within a 3σ contour.
Figure 5. \( L_{\text{bol}} - M_{\text{env}} \) diagram displaying published data for massive star-forming cores (open diamonds [Sridharan et al. 2002; Beuther et al. 2002]; filled circles and crosses [André et al. 2008]); evolutionary tracks from Molinari et al. (2008) marked in time steps of \( 10^5 \) years for the horizontal branch and \( 10^4 \) years for the vertical branch. The positions of core 1 and 2 are shown as upper limits in the diagram.

4.2. Discussion

The signposts of massive star formation toward MSX G030.88 +00.13 lend credence to the idea that there might exist regions within the cloud where massive stars will be, but have not yet, formed. The characteristics of core 1 make it a good candidate for one such region. While MSX G028.53−00.25 currently shows no signs of high-mass star formation, core 2 shares similar traits to core 1 as being a potential massive star precursor.

The bolometric luminosity of cores versus the envelope mass, or the \( L_{\text{bol}} - M_{\text{env}} \) diagram, is a useful parameter space to visualize the evolution of cores into stars (e.g., Bontemps et al. 1996). Figure 5 shows data from several previous studies of massive star formation plotted on the \( L_{\text{bol}} - M_{\text{env}} \) diagram (see figure caption). The linear trend in log–log space is typical for such studies. Evolutionary tracks based on the turbulent core model of McKee & Tan (2003) calibrated by the data of Molinari et al. (2008) are also overlaid on the plot. The positions of core 1 and 2 from this study are seen to lie well below the trend set by previous data, another indication that they are at an early evolutionary stage. According to the Molinari et al. (2008) evolutionary tracks, core 1 is on track to evolve into a star with \( L_{\text{bol}} \approx 10^6 L_{\odot} \), or of an early B spectral type while core 2 is set to evolve into a star with \( L_{\text{bol}} \approx 2 \times 10^3 L_{\odot} \), or a mid-B spectral class.

The final stellar masses implied from the evolutionary tracks in Figure 5 may be underestimated. The star formation efficiency of dense cores is expected to be between 25% and 50% (Matzner & McKee 2000; Alves et al. 2007). Therefore, if these cores collapse monolithically they have sufficient mass to form stars with mass between \( 15 M_{\odot} \) and \( 60 M_{\odot} \). Indeed, the evolutionary models of André et al. (2008) put core 1 on track to evolve into a star of \( \approx 50 M_{\odot} \) and core 2 into a star with \( \approx 25 M_{\odot} \). However, it is not possible to tell from our data whether these cores will undergo monolithic collapse or will further fragment into smaller cores. Observations resolving the expected fragmentation length scales (\( \sim 0.03 \) pc) are needed.

The large millimeter continuum survey of the Cygnus X region has also revealed dense and massive cores at an early stage of evolution (Motte et al. 2007). However, of the most massive cores in their sample (\( M \geq 40 M_{\odot} \)), 61% have 21 \( \mu \)m Midcourse Space Experiment sources associated with them, and the remaining either contain compact H II, show 70 \( \mu \)m emission above our scaled detection limits (S. Bontemps & F. Motte 2009, private communication), or have SiO line strengths and widths that indicate protostellar activity.

Therefore it seems that the cores of this study are unique, and their existence may have implications for our understanding of massive star formation. The selection criteria and use of high resolution in the submillimeter wave band are key components to these discoveries. As the characterization of IRDCs progress (e.g., Chambers et al. 2009), further high-resolution studies of pre-cluster environments will provide statistics on the frequency and nature of these kinds of objects.

5. SUMMARY

This article presents interferometric mosaic observations in the 850 \( \mu \)m wave band toward two IRDCs chosen to be likely representations of pre-cluster environments in the Galaxy. Both clouds are massive and dense but show no sign of massive star formation. The most massive cores in each mosaic dominate the compact 850 \( \mu \)m emission and are spatially isolated near the peak of the low-resolution continuum emission. With masses of \( \approx 110 M_{\odot} \) and \( \approx 60 M_{\odot} \), and average densities of \( n \approx 10^6 \text{ cm}^{-3} \) and \( \langle N \rangle \approx 1 \text{ g cm}^{-2} \), they have the potential to form massive stars. However, upper limits to their bolometric temperatures and luminosities, no clear indication of CO outflow, and their relatively featureless spectra all indicate a very early stage of evolution. Detections of ortho-H\(_2\)D\(^+\)(1,0 − 1,1) and \( \text{N}_2\text{H}^+(4 − 3) \) support the interpretation that these cores are in a very cold and dense state. The comparison of these data with the theoretical and observational studies of massive star-forming regions suggest that these cores occupy a unique region of \( L_{\text{bol}} - M_{\text{env}} \) parameter space placing them on track to evolve into stars anywhere from mid to early B stars up to O stars.

The author is grateful for the referee’s suggestions as well as the helpful input provided by many people including Sylvain Bontemps, John Carpenter, David Jewitt, John Johnson, Émeric Le Floc’h, Steve Longmore, Frederique Motte, Thushara Pillai, Jill Rathborne, Jonathan Williams, and Qizhou Zhang.

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