A DENSE MICROCLUSTER OF CLASS 0 PROTOSTARS IN NGC 2264 D-MM1

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ABSTRACT

We present sensitive and high angular resolution (~1") 1.3 mm continuum observations of the dusty core D-MM1 in the Spokes cluster in NGC 2264 using the Submillimeter Array. A dense microcluster of seven Class 0 sources was detected in a 20" × 20" region with masses between 0.4 and 1.2 M⊙ and deconvolved sizes of ~600 AU. We interpret the 1.3 mm emission as arising from the envelopes of the Class 0 protostellar sources. The mean separation of the 11 known sources (SMA Class 0 and previously known infrared sources) within D-MM1 is considerably smaller than the characteristic spacing between sources in the larger Spokes cluster and is consistent with hierarchical thermal fragmentation of the dense molecular gas in this region.

Subject headings: circumstellar matter — planetary systems: protoplanetary disks — stars: formation — techniques: interferometric

1. INTRODUCTION

NGC 2264 is a very well studied, hierarchically structured young embedded cluster (Lada & Lada 2003) associated with a giant molecular cloud in the Monoceros OB1 complex, 800 pc (± 50 pc; Sung et al. 1997; Peretto et al. 2006) away from the Sun. There is abundant evidence of ongoing star-forming activity in this cluster, such as molecular outflows (Margulis et al. 1988; Wolf-Chase et al. 2003) and Herbig-Haro objects (Reipurth et al. 2004). Margulis et al. (1989) identified luminous far-infrared sources with the Infrared Astronomical Satellite (IRAS), many of them being Class 0 and Class I objects. Submillimeter observations of these sources by Williams & Garland (2002), Wolf-Chase et al. (2003), and Peretto et al. (2006) identified several dense clumps embedded in dusty filamentary fingers of molecular material that radiated out from IRAS 12. More recent observations using the Spitzer Space Telescope revealed that many of these clumps contained bright 24 μm Class 0/I sources, and the clustering was named the Spokes cluster due to its geometrical configuration (Teixeira et al. 2006). Using nearest neighbor analysis, Teixeira et al. (2006) found that these protostars have a characteristic spacing that corresponds to the Jeans length and are very likely tracing the primordial substructure of the cluster. They interpret the regular spacing of the protostars as a fossil signature of thermal fragmentation. The most massive and densest of these submillimeter cores, D-MM1 (also known as IRAS 12 S1), has a mean density of ~10⁶ cm⁻³ (Wolf-Chase et al. 2003; Peretto et al. 2006). HCO⁺ observations of D-MM1 by Williams & Garland (2002) shows a deep redshifted absorption, indicating that it is collapsing at a speed that Peretto et al. (2006) measured to be ~0.1 km s⁻¹. Wolf-Chase et al. (2003) identified D-MM1 as a Class 0 object harboring one or more protostars. Recent near-infrared imaging using the PANIC camera at the Magellan telescope, as well as Spitzer IRAC imaging resolved D-MM1 into 11 K̵-band and eight 8 μm sources (Young et al. 2006) within the field we observed with the Submillimeter Array (SMA). These high angular resolution observations resolved D-MM1 into a dense microcluster of 7 mm compact sources associated with young Class 0 objects. We describe our observations in § 2 and present our results in § 3. Finally, we discuss our findings on the characterization of these new millimeter sources in § 4.

2. OBSERVATIONS

The observations were made with the Submillimeter Array (SMA) during 2005 December 25 in its “compact” configuration, and 2006 February 5 and 10 in its “extended” configuration, with eight antennas in both configurations. The frequency was centered at 230.538 GHz in the lower sideband, while the upper sideband was centered at 220.538 GHz. The primary beam size (half-power beamwidth) of the 6 m diameter antennas at 230 GHz is 54″. The phase reference centers of the field is (α, δ) = (06h41m 06.45s, +09°33’47.91” [J2000.0]). The zenith opacity (τ(half), GHz), measured with the National Radio Astronomy Observatory (NRAO) tipping radiometer located at the Caltech Submillimeter Observatory, varied between 0.03 and 0.04 in the extended configuration observation time, and in the compact configuration observation time was very stable at 0.2. The phase and amplitude calibrators were the quasars 0739+016 and 0530+135 with measured flux densities of 2.82 ± 0.1 and 0.84 ± 0.1 Jy, respectively. The uncertainty in the flux scale is estimated to be 20%, based on the SMA monitoring of quasars. Observations of Uranus provided the absolute scale for the flux density calibration. Further technical descriptions of the SMA are found in Ho et al. (2004). The data were calibrated using the Interactive Data Language (IDL) package. We weighted the (u, v) data using the ROBUST parameter of INVERT MIRIAD task set to 2, optimizing for a maximum sensitivity in the continuum image. This option is recommended to achieve the largest signal-to-noise ratio possible, although some angular resolution is sacrificed. The synthesized beam had dimensions of 1.4″ × 1.3″ with a P.A. =

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10.4". Finally, the resulting continuum image rms noise level (σ) was 3.5 mJy beam⁻¹.

3. RESULTS: NEW MILLIMETER SOURCES

We detected seven compact sources whose peak fluxes exceeded 5σ within the core D-MM1. Figure 1 shows a panel of near-infrared (NIR) and mid-infrared (MIR) images of the core with the SMA sources overlapped (contours). The $K_s$-band image (0.125 pixel⁻¹) depicts emission in the vicinity of the SMA sources; however, this NIR emission is generally not pointlike (except for the source associated with SMA 3) and may correspond to scattered light from a central protostar. The Spitzer Infrared Array Camera (IRAC) image (Teixeira et al. 2006) (1.2" pixel⁻¹) shows that SMA 1 and SMA 3 have MIR counterparts. The sources SMA 2, SMA 6, and SMA 7 are also associated with diffuse MIR emission. The pointlike sources detected in the $K_s$-band and the 8 μm images that were not detected by our SMA observations had been previously identified as Class I sources by Young et al. (2006; sources 30, 33, 35, 44, 45, 49). In Table 1 we present the physical parameters of these new objects. To measure the fluxes for the SMA sources, we used the NRAO Astronomical Image Processing System (AIPS) software. Flux densities, as well as source positions and sizes, were obtained using the AIPS IMFIT procedure, where each source was modeled with two-dimensional elliptical Gaussians. The errors cited for the flux densities correspond to statistical uncertainties and are dominated by the calibration uncertainty that is ∼20%, as previously mentioned.

To determine the mass we assume the emission arises from an optically thin, unresolved source that can be characterized by a single temperature (e.g., Mundy et al. 1995; Bally et al. 1998). The mass is calculated by $M = F(d^2/[B(T_d) \kappa_{\nu}])$, where $\nu$ is the frequency, $T_d$ is the dust temperature, $F_{\nu}$ is the integrated flux density of the source, $B$ is the Planck function, and finally, $\kappa_{\nu}$ is the dust mass opacity. We derive the latter value from Beckwith et al. [1990; $\kappa_{\nu} = 0.1(\nu/1200 \text{ GHz})^d \text{ cm}^2 \text{ g}^{-1}$] as being $\kappa_{\nu} = (0.0192)^d \text{ cm}^2 \text{ g}^{-1}$. The value of $\kappa_{\nu}$ assumes a gas-to-dust ratio of 100 (Hildebrand 1983), which may not be the most adequate to use for protostellar sources since dust settling to the midplane of the disk and erosion of the circumstellar envelope by photodissociation may decrease the gas-to-dust ratio (Williams et al. 2005; Throop & Bally 2005). In addition, the value of the emissivity index, $\beta$, is uncertain (Beckwith et al. 1990). The sizes of the sources suggest that we are observing emission from compact envelopes; hence, we adopt $\beta = 1.5$ to calculate the mass of the sources (Wolf-Chase et al. 2003; Beckwith et al. 1990).

### Table 1: Properties of the SMA Sources

| ID  | R.A. (J2000.0) | Decl. (J2000.0) | Size* (arcsec) | P.A. (deg) | $F_{\text{230 GHz, peak}}$ (mJy beam⁻¹) | $F_{\text{230 GHz, int.}}$ (mJy) | NIR/MIRb | $R_{\text{geom}}$ (Å) | Mass (M☉) | $n$ (10¹⁶ cm⁻³) |
|-----|---------------|---------------|---------------|-----------|----------------------------------------|-------------------------------|----------|-----------------|------------|--------------|
| 1... | 06 41 05.60   | 09 34 08.0    | (1.8 ± 0.6) × 0.7" | 70 ± 13   | 21 ± 6 | 29 ± 14 | Nd, Mp | 448 | 0.4 ± 0.2 | 14.7 |
| 2... | 06 41 05.64   | 09 34 05.7    | (3.1 ± 0.7) × 0.7" | 23 ± 6    | 24 ± 6 | 56 ± 19 | Nd, Md | 592 | 0.7 ± 0.2 | 12.2 |
| 3... | 06 41 05.69   | 09 34 06.7    | (2.6 ± 0.6) × (0.9 ± 0.6) | 42 ± 13   | 27 ± 6 | 69 ± 21 | Np, Mp | 608 | 0.9 ± 0.3 | 13.8 |
| 4... | 06 41 05.87   | 09 34 11.7    | (1.8 ± 1.0) × (1.2 ± 1.2) | 96 ± 45   | 19 ± 6 | 41 ± 19 | None | 584 | 0.5 ± 0.2 | 9.2  |
| 5... | 06 41 05.98   | 09 34 09.8    | (2.6 ± 0.6) × (1.6 ± 0.5) | 59 ± 32   | 27 ± 6 | 90 ± 25 | None | 816 | 1.1 ± 0.3 | 7.5  |
| 6... | 06 41 06.09   | 09 34 08.6    | (2.5 ± 0.5) × (1.5 ± 0.4) | 87 ± 18   | 30 ± 6 | 94 ± 24 | Md  | 776 | 1.2 ± 0.3 | 9.0  |
| 7... | 06 41 06.16   | 09 34 09.5    | (2.1 ± 0.6) × (1.2 ± 0.6) | 10 ± 57   | 21 ± 6 | 51 ± 20 | Md  | 632 | 0.6 ± 0.2 | 9.1  |

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

* Deconvolved FWHM size derived from fitting a 2D elliptical Gaussian to the continuum SMA sources.

b Nd(Md): associated with diffuse $K_s$-band (8 μm) emission; Np(Mp): associated with pointlike $K_s$-band (8 μm) emission.

c The minor axis is unresolved, and we use an upper limit of beamsize/2.
Peretto et al. (2007). We use 23 K for the mass determination, as this was the temperature measured by Wolf-Chase et al. (2003) for D-MM1. Table 1 shows the masses we determined, as well as the average number density, $\bar{n}$, given by $\bar{n} = \frac{3M}{(4\pi\mu m_H R_{\text{com}}^3)}$, where $\mu$ is the mean molecular weight, 2.34, $m_H$ is the atomic H mass, and $R_{\text{com}}$ is the geometric mean radius. Due to the uncertainties referred to above, the values of the derived masses are good within a factor of 2. The values of $\bar{n}$ should be interpreted only as an estimate since the error associated with the size of the source is uncertain and reflects the particular ($u, v$) coverage of the data.

4. DISCUSSION

4.1. On the Nature of the New Microcluster

Following the number counts of extragalactic objects at millimeter wavelengths from Maloney et al. (2005), we estimate that the expected number of 1.3 mm background sources, above a flux density of $S = 20$ mJy is $(N) \sim 5.76^{+0.39}_{-0.30}$ deg$^{-2}$. The probability of finding a source with flux density equal or larger than 20 mJy (see Table 1) in a 20$^\circ$ × 20$^\circ$ region is thus quite low, $\sim 10^{-4}$. We therefore conclude that all the observed SMA sources are associated with the NGC 2264 D-MM1 core. We find a very similar value using the number counts for submillimeter galaxies reported by Laurent et al. (2005). Of the seven millimeter continuum compact sources, two are associated with pointlike emission and three are associated with diffuse emission (see Fig. 1 and Table 1). Sources SMA 4 and SMA 5 do not appear to have any NIR or MIR emission, although there is NIR and MIR diffuse emission located between these sources (which could be scattered light from one or from both sources). The deconvolved sizes ($\sim 600$ AU) of these objects, as well as the high densities ($\sim 10^3$), suggest the 1.3 mm emission is arising from compact dense regions such as circumstellar envelopes. The derived masses (0.4–1.2 $M_\odot$) are comparable to those of low-mass stellar objects, indicating that a substantial amount of the total protostellar material is in the circumstellar envelopes, from which we conclude that the SMA sources are very likely protostars in the Class 0 evolutionary phase. We cannot advance more in our interpretation of the individual sources due to a lack of complementary high-resolution observations at infrared and (sub)millimeter wavelengths of this region (namely, at 850 $\mu$m). We would require such observations to build individual spectral energy distributions and model these to determine protostellar envelope and disk masses. We are, however, able to discuss the fragmentation of D-MM1 and the formation of these sources. There are 11 sources within D-MM1 (excluding one foreground star; Young et al. 2006), seven of which are the SMA sources we are reporting in this Letter. These sources are more densely packed than those in the Spokes cluster, which have a characteristic spacing similar to the Jeans length (Teixeira et al. 2006). Our interferometric observations recover $\approx 90\%$ of the flux of D-MM1 measured by Peretto et al. (2006) using their background-subtracted maps. This implies that the single dish observations correspond to the convolution of the individual fluxes emitted by the SMA sources (as suggested by Wolf-Chase et al. 2003). If we assume that each protostar has 0.5 $M_\odot$, then a rough estimate of the prefragmentation density of D-MM1 can be calculated by adding up the measured masses of the envelopes and the adopted protostellar masses, which gives us 10.9 $M_\odot$, and distributing this total mass within a region of 7870 AU radius (Peretto et al. 2006). The density we estimate in this manner is $8 \times 10^3$ cm$^{-3}$. The Jeans length, $\lambda_J = [(\pi k_B T)/(G\bar{n})]^{1/2}/(\mu m_H)$ ($k_B$ is the Boltzmann constant and $G$ is the gravitation constant) we obtain for D-MM1 is 5.9$''$ (0.023 pc or 4740 AU). Here we use a temperature $T$ of 10 K since it is logical to assume that the prefragmented starless core would be colder than the present temperature of D-MM1, 23 K. The corresponding Jeans length is very similar to the mean distance between the 11 sources, 6.9$''$ (0.026 pc or 5520 AU). However, the mean nearest neighbor separation between the sources is 2.3$''$ (0.009 pc or 1840 AU), so it is not entirely clear if the fragmentation of D-MM1 was purely thermal. It is interesting to compare our results for D-MM1 with the northern subgroup of the Serpens cluster, which consists of a rich clustering of Class 0 and Class I sources. Placing these Serpens sources at the distance of NGC 2264 and scaling the 1.4 mm fluxes measured by Hogerheijde et al. (1999) accordingly gives us fluxes comparable to what we are measuring for our SMA sources. Winston et al. (2007) found that the average separation of the Serpens protostars is about 5000 AU with some of the sources being as close as 2000 AU. They also calculate the Jeans length for the region to be 0.024 pc, which is similar (neglecting projection effects) to what we find. If this is a characteristic scale, then this could be an indication that thermal physics is the underlying engine that regulates star formation, in at least some highly clustered environments. Given that the nearest neighbor separations of the sources in D-MM1 are smaller than typical envelope sizes (5000–10000 AU), these sources may be competing between themselves for the accretion of the surrounding material of the core. Therefore, we cannot rule out the possibility that some kind of competitive accretion (Bonnell et al. 2001; Peretto et al. 2006) may be occurring in D-MM1. Additional data are required, such as the measurement of the velocity dispersion of the sources, before we are able to draw any conclusions regarding this issue. Our finding holds within it an interesting implication, specifically, that there are two scales of fragmentation in the Spokes cluster: one that formed D-MM1 and other bright members of the cluster (Teixeira et al. 2006) and a second associated with the fragmentation of the D-MM1 core itself. These two fragmentation length scales are correlated with the mean density in those regions, as would be expected if fragmentation was dominated by thermal physics. The Jeans mass for D-MM1, $M_J = 177\pi^{1/2}n^{-1/2}M_\odot$, is 0.6 $M_\odot$. Since D-MM1 would have had 10.9 $M_\odot$ in its prefragmented state, we expect the core to have fragmented into about 17 sources if thermal pressure was the dominant support against gravitational collapse. This value is within a factor of 2 of the number of sources in D-MM1, 11. A more detailed analysis is obviously required in determining the underlying stellar masses. It is, however, interesting to note that if the Class 0/I sources in D-MM1 have in fact $M \approx 0.5 M_\odot$, then their bolometric luminosities could be similar to those of IRAS 05173-0555, RNO 43 MM, CB 230, IRAS 18148-0440, or RNO 15 FIR, i.e., 7-10 $L_\odot$ (Froebrich 2005), which would yield a combined luminosity of 77–110 $L_\odot$. The bolometric luminosity of D-MM1 is 107.5 $L_\odot$ (Wolf-Chase et al. 2003).

4.2. X-Ray Emission Associated with SMA 1

Flaccomio et al. (2006) used the Advanced CCD Imaging Spectrometer (ACIS) on board the Chandra X-Ray Observatory (Chandra) to obtain a 97 ks long exposure of NGC 2264. We searched their X-ray catalog and found that source 237 (CXO ANC J064105.5+093407: ($\alpha, \delta$) = (06h41m05.5s, +09$^\circ$34$'$07.68$''$) [J2000.0]) is located approximately 0.6$''$ away from SMA 1. We note that the SMA has subarcsecond point-
ing accuracy and Chandra has a positional accuracy of typically 0.6′. To our present knowledge there are no other infrared or millimeter sources positioned closer to CXO ANC J064105.5+093407 so it could potentially be associated with SMA 1. The ACIS data have been recently reanalyzed and made publicly available through the AN archive of Chandra Observations of Regions of Star formation (ANCHORS). The ACIS data have been recently reanalyzed and infrared or millimeter sources positioned closer to CXO ANC J064105.5+093407 is associated with a protostellar object, very likely SMA 1. Winston et al. (2007) also reports Class 0/I sources with X-ray emission. Unfortunately, the Chandra ACIS-I camera was pointed and orientated such that D-MM1 fell precisely in the gap between the chips of the array: this may be the reason why no other X-ray source is detected in D-MM1.

5. SUMMARY

We discovered a dense microcluster of Class 0 sources within D-MM1, with envelope masses ranging from 0.4 to 1.2 $M_\odot$ and average radius of 600 AU. Five of the sources are associated with NIR/MIR emission, and one of the SMA sources, SMA 1, is associated with X-ray emission. The separations of the sources indicate that the fragmentation length scale of this core is significantly smaller than that of the Spokes cluster and comparable to the Jeans length in D-MM1. This is consistent with hierarchical thermal fragmentation: with a primary fragmentation along the lower density (10^4 cm^-3) filaments of the Spokes cluster, and a secondary fragmentation of the higher density core D-MM1 (~10^9 cm^-3).

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Facilities: SMA

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