AN OBSERVED LACK OF SUBSTRUCTURE IN STARLESS CORES. II. SUPER-JEANS CORES

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Received 2012 May 2; accepted 2012 June 21; published 2012 August 7

ABSTRACT

We present SMA and CARMA continuum and spectral line observations of five dense cores located in the Perseus and Ophiuchus molecular clouds whose masses exceed their thermal Jeans masses. Three of these cores have previously been identified as being starless and two have been classified as being possibly protostellar. We find that one core is certainly protostellar. The other four cores, however, are starless and undetected in both C$^{18}$O and 1.3 mm continuum emission. These four starless cores have flat density profiles out to at least $\sim$0.006 pc, which is typical for starless cores in general. Density profiles predicted by some collapse models, especially in the early stages of infall, are consistent with our observations. Archival data reveal that these starless cores have significant non-thermal support against collapse, although they may still be unstable.

Key words: ISM: jets and outflows – stars: formation – stars: protostars

Online-only material: color figures

1. INTRODUCTION

Recent interferometric observations of supposedly “starless” cores in nearby molecular clouds have found several hidden protostars (e.g., Pineda et al. 2011; Dunham et al. 2011; Schnee et al. 2012; Chen et al. 2012). These observations, however, almost never reveal substructures or evidence for fragmentation in starless cores (Olmi et al. 2005; Schnee et al. 2010), with some notable exceptions, such as R CrA SMM 1A (Chen & Arce 2010) and L183 (Kirk et al. 2009). The lack of observed substructure in starless cores may imply that stellar multiplicity begins during the protostellar stage. For instance, in the disk fragmentation theory of multiple star formation, a massive accretion disk around a protostar can become unstable and fragment, creating a binary or higher-order system (Adams et al. 1989; Bonnell & Bate 1994). Alternatively, turbulence in starless cores may be forming the seeds of multiplicity (Fisher 2004; Goodwin et al. 2004, 2007), but these seeds may be below the threshold of detectability, as recently suggested by Offner et al. (2012).

In this paper, we present interferometric observations of five cores whose masses derived from dust emission at 850 $\mu$m exceed their respective thermal Jeans masses by at least a factor of two. As such, they are likely to be in the process of forming protostars and/or fragmenting. These cores, given the label “super-Jeans,” were identified by Sadavoy et al. (2010b) and thus make promising targets in the search for substructure in starless cores.

2. OBSERVATIONS

2.1. Previous Observations and Sample Definition

The cores in this study were previously observed at 850 $\mu$m with the Submillimeter Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (Di Francesco et al. 2008) and at mid- to far-infrared wavelengths with the Spitzer Space Telescope (Evans et al. 2003, 2009). Core properties such as mass and size were derived from the SCUBA maps by Sadavoy et al. (2010a), and the classification of each core (i.e., starless, protostellar, or “undetermined”) was made from 3.6 to 70 $\mu$m Spitzer maps (Sadavoy et al. 2010b). Sadavoy et al. (2010b) estimated the stability of cores by comparing the Jeans mass for a thermally supported sphere against the core mass derived from dust emission. The Jeans mass is given by

$$M_J = 1.9 \left( \frac{T_d}{10 \, K} \right) \left( \frac{R_J}{0.07 \, pc} \right) M_\odot,$$

while the dust-derived mass is given by

$$M = 0.074 \left( \frac{S_{850}}{Jyb} \right) \left( \frac{d}{100 \, pc} \right)^2 \left( \frac{\kappa_{850}}{0.01 \, cm^2 \, g^{-1}} \right)^{-1} \times \left[ \exp \left( \frac{17 \, K}{T_d} \right) - 1 \right] M_\odot.
$$

The dust temperatures ($T_d$) assumed by Sadavoy et al. (2010b) are 15 K in Ophiuchus and 11 K in Perseus, based on NH$_3$ surveys of these clouds by Friese et al. (2009) and Rosolowsky et al. (2008), respectively. The Jeans radius ($R_J$) and 850 $\mu$m flux ($S_{850}$) are estimated from the SCUBA observations, the distances assumed are shown in Table 1, and the dust opacity at 850 $\mu$m was assumed to be 0.01 cm$^2$ g$^{-1}$ by Sadavoy et al. (2010b).

Using the data and equations above, Sadavoy et al. (2010b) identified 17 candidate starless cores in nearby molecular clouds whose dust-derived masses exceeded their respective Jeans masses by more than a factor of two. Based on a simple Jeans analysis, such cores would be expected either to have significant non-thermal support or else to be collapsing and possibly fragmenting. Of these 17 super-Jeans cores, we chose 5 for follow-up observations with the Submillimeter Array (SMA). We chose to observe all three of the super-Jeans cores that are 15 K in Ophiuchus and 11 K in Perseus, based on NH$_3$ surveys of these clouds by Friese et al. (2009) and Rosolowsky et al. (2008), respectively. The Jeans radius ($R_J$) and 850 $\mu$m flux ($S_{850}$) are estimated from the SCUBA observations, the distances assumed are shown in Table 1, and the dust opacity at 850 $\mu$m was assumed to be 0.01 cm$^2$ g$^{-1}$ by Sadavoy et al. (2010b).
configured four additional windows to observe the 12CO(2–1) band width of 7 GHz in the upper and lower sidebands. We also continuum with 72 windows, each 104 MHz wide, with a total (see Table 2 for details). The half-power beam width of the 6 m antennas is 54″ at 230 GHz, and all sources were observed with single pointings.

The receivers were tuned to a rest frequency of 230.538 GHz, Doppler tracked to a recessional velocity (V_{LSR} of 3.95 km s$^{-1}$ and 7.8 km s$^{-1}$ for the June and October observations, respectively). The correlator was configured to observe the 1.3 mm continuum with 72 windows, each 104 MHz wide, with a total band width of 7 GHz in the upper and lower sidebands. We also configured four additional windows to observe the 13CO(2–1) and 13CO(2–1) lines with 406 kHz (0.5 km s$^{-1}$) resolution, the 13CO line with 203 kHz (0.25 km s$^{-1}$) resolution, and the N2D+ (3–2) line with 813 kHz (1 km s$^{-1}$) resolution (see Table 3). The 13CO (2–1) and N2D+ (3–2) lines were only marginally detected toward one core (Per-8), so neither transition is discussed further in this paper. 13CO (2–1) was detected only toward Per-8.

The data were reduced using the MIR package. We flagged the data for bad channels, antennas, weather, and pointing. Radio pointing was done at 1 hr after sunset for each track. We calibrated the bandpass with a bright quasar, 3C 454.3, (Oph-1 and Per-8) by Sadavoy et al. (2010b). Per-2 and Per-8 were also observed with CARMA. Basic information on these five cores is shown in Table 1, and more information about these cores and their properties was described by Sadavoy et al. (2010a, 2010b).

2.2. SMA Calibration

Spectral line observations were taken with the eight-element SMA (Ho et al. 2004) in 2010 June and 2010 October in the compact north and compact configurations, respectively. Baselines range from 11 m to 150 m, providing sensitivity to spatial scales up to $\sim$12″ and a resolution of $\sim$3″ FWHM. The sources were grouped together by R.A. and observed together in single tracks (Oph-1 and Oph-2 in June; Per-2, Per-6, and Per-8 in October) each about 10 hr in length (see Table 2 for details). The half-power beam width of the 6 m antennas is 54″ at 230 GHz, and all sources were observed with single pointings.

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The data were reduced using the MIR package. We flagged the data for bad channels, antennas, weather, and pointing. Radio pointing was done at 1 hr after sunset for each track. We calibrated the bandpass with a bright quasar, 3C 454.3,
of the C18O (2–1) emission beginning at a value of 2 K km s$^{-1}$.

One sideband, with 495 MHz band width with 39 channels per band, providing a total band width of 7 GHz. One band was configured to observe C17O (2–1) in the lower sideband and CO (2–1) in the upper sideband, each with 781 kHz spectral resolution ($\sim$1 km s$^{-1}$) and 123 MHz band width (See Table 3).

The data were reduced using the MIRIAD package (Sault et al. 1995). We flagged the data for bad channels, antennas, weather, and pointing. Radio pointing was done at the beginning of each track and pointing constants were updated at least every two hours thereafter, using either radio or optical pointing routines (Corder et al. 2010). We calibrated the bandpass and gains using observations of the bright quasar 3C84, which was observed for 3 minutes out of each 21 minute source-calibrator cycle. Absolute flux calibration was done using observations of Mars and the consistency of flux measurements with the SMA data set.

Due to instrumental problems, the upper sideband of the spectral line band was lost, so our observations of CO (2–1) come from the SMA only. C17O (2–1) was detected only toward Per-8.

2.4. Imaging

We imaged the SMA and CARMA continuum and line emission from each source using MIRIAD (Sault et al. 1995), with natural weighting and an additional weighting in inverse proportion to the noise as estimated by the system temperature. Each data cube was cleaned to a cutoff of 2$\sigma$ in the residual image. The 1.3 mm continuum data for the source Per-8 came from both CARMA and the SMA, while all other maps have data from only one array. The combined CARMA+SMa 1.3 mm continuum map of Per-8 has an rms of 6 mJy beam$^{-1}$ and a beam size of 2$''$7 × 2$''$0.

3. ANALYSIS

3.1. Per-8

Continuum emission at 1.3 mm is detected from Per-8, with a peak flux of 380 mJy beam$^{-1}$ and an integrated flux of 750 mJy.

The peak of the dust emission seen with SMA and CARMA is at (J2000) 3:32:17.923 +30:49:47.869, and this is also the peak of the detected C17O (2–1) and C18O (2–1) integrated intensity.

Sadavoy et al. (2010a) initially classified Per-8 as “starless,” after rejecting a nearby compact source of mid-infrared emission detected by Spitzer in the IRAC and MIPS bands (SSTc2dJ033218.0+304947) as non protostellar. This compact source has colors similar to those of star-forming galaxies (e.g., using the prescription from Gutermuth et al. 2008) rather than the colors expected for embedded protostars (e.g., following Evans et al. 2009). Since such color analyses are not perfect and may throw out legitimate protostellar sources, Sadavoy et al. (2010b) reclassified Per-8 as “undetermined.” Indeed, Per-8 was classified as a Class 0 protostar by Hatchell & Dunham (2009), who identified an outflow from the core. Near-infrared maps of the Perseus B1 region also show shocked emission from an outflow driven by Per-8 (Walawender et al. 2009).

Given the previous observations of this source, it is not surprising that we detect a collimated CO(2–1) outflow from Per-8. The outflow is centered on the 1.3 mm continuum source, which is also coincident with the compact source detected with Spitzer. In Figure 1, we show the outflow, the 1.3 mm continuum, and a C18O (2–1) velocity map with the possible signature of a rotating disk. For the analysis of Per-8, fits to the observed spectra were made only for those profiles that had three independent velocity channels with a signal-to-noise ratio greater than 5. In Figure 2, example spectra of C18O (2–1) and C17O (2–1) at the peak of the line emission are shown. In Figure 3, we show that the 1.3 mm continuum emission presented here is spatially coincident with the IRAC source noted by Sadavoy et al. (2010b) and the peak of the SCUBA 850 $\mu$m emission.

Per-8 shows that some cores cannot be accurately classified solely from infrared continuum maps and assumed protostellar colors. For example, strong PAH emission or shocks from outflows may cause excess emission in some of the IRAC bands and skew the infrared colors (e.g., Gutermuth et al. 2008). Assumed protostellar colors are determined based on a
Figure 2. Spectra toward Per-8. Left: $^{18}$CO (2–1) spectrum taken at the peak of the $^{18}$CO (2–1) integrated intensity (J2000 3:32:17.87, +30:49:47). Right: $^{17}$CO (2–1) spectrum taken at the peak of the $^{17}$CO (2–1) integrated intensity (same location as for $^{18}$CO (2–1)). The vertical dashed line in both panels shows a velocity of 6.5 km s$^{-1}$ and is plotted to guide the eye and show that the $^{18}$CO (2–1) and $^{17}$CO (2–1) spectra peak at the same velocity.

Figure 3. Continuum data of Per-8. Gray scale shows the Spitzer/IRAC Band 4 (8 μm) emission from the region around Per-8. The 1.3 mm continuum emission detected with SMA and CARMA (thin solid contours at 100 mJy beam$^{-1}$, 150 mJy beam$^{-1}$, and 200 mJy beam$^{-1}$) are coincident with the 8 μm emission. The thick dashed contours show the 850 μm emission (at 0.5, 1.0, 1.5, and 2.0 Jy beam$^{-1}$) from Per-8 detected with SCUBA (Di Francesco et al. 2008).

best-effort basis, and only select objects most likely to be protostars. Furthermore, the photometry of Per-8 is complicated by it being a resolved source and by its location on the boundary between two c2d mosaic tiles. Occasionally misclassified cores like Per-8 should be expected and caution is necessary when using only infrared continuum maps to determine if cores are starless or protostellar.

3.2. Oph-1, Oph-2, Per-2, and Per-6

The 1.3 mm continuum emission from the remaining four cores in this survey is not detected by our SMA and CARMA observations. We calculate upper limits to the masses of point sources that could have been detected in these observations from the respective rms values reported in Table 2 and using Equation (2) scaled to 1.3 mm with an assumed emissivity spectral index of $\beta = 2$. The 3σ upper limits on the mass of a point source embedded in Oph-1, Oph-2, Per-2, and Per-6 are 0.002 $M_\odot$, 0.002 $M_\odot$, 0.01 $M_\odot$, and 0.02 $M_\odot$, respectively. Had we assumed a lower dust temperature of 5.5 K, as reported by Crapsi et al. (2007) at the center of L1544, our reported mass upper limits would be increased by a factor of four to five. In comparison, the median 3σ upper limit of the mass of compact structures in starless cores in Perseus reported by Schnee et al. (2010) is 0.2 $M_\odot$, so this survey goes a factor of 10–100 deeper than Schnee et al. (2010). The improved mass sensitivity in this paper is primarily a result of the wavelengths of observations (1.3 mm here versus 3 mm by Schnee et al. 2010) and the $\lambda^{-4}$ dependence of the dust emission. We conclude that Oph-1, Oph-2, Per-2, and Per-6 are true starless cores, based on the
non-detection of compact continuum down to a few Jupiter masses. In addition to being undetected in the 1.3 mm continuum maps, Oph-1, Oph-2, Per-2, and Per-6 show no signs of outflows in the CO and $^{13}$CO maps. The non-detection of outflows from these cores further suggests that they are indeed starless. Furthermore, these four cores are not detected in the N$_2$D$^+$, C$^{18}$O, or C$^{17}$O line maps made with the SMA and CARMA.

3.2.1. Density Profiles

To analyze further the meaning of non-detections of continuum emission from starless cores, we simulate observations of the 1.3 mm dust emission from idealized cores. We assumed a typical density distribution (Tafalla et al. 2004) of

$$n = \frac{n_0}{1 + \left(\frac{r}{r_0}\right)^{2.5}},$$  \hspace{1cm} (3)

where $n_0$ is normalized such that the total core mass within a radius of 0.05 pc is $5 M_\odot$. This density profile has a flat interior (at radii less than $r_0$) and a steep exterior (at radii greater than $r_0$). The radius $r_0$ varies from 0.002 pc to 0.02 pc in our simulations, as shown in Figure 4. We used an outer radius of 0.05 pc, as is typical of starless cores. We assumed a dust emissivity at 1.3 mm of 0.009 cm$^2$ g$^{-1}$, as given in Table 1, Column 5, of Ossenkopf & Henning (1994) for dust grains with thin ice mantles at a density of 10$^6$ cm$^{-3}$. We assumed a distance to the cores of 250 pc, appropriate for cores in the Perseus molecular cloud (Hirota et al. 2008; Lombardi et al. 2010). In one set of simulations, we assumed an isothermal dust temperature of 10 K, appropriate for starless cores in Perseus (Schnee et al. 2009). In a second set of simulations, we assumed the dust temperature profile derived for the starless core L1544 by Crapsi et al. (2007):

$$T(r) = T_{\text{out}} - \frac{T_{\text{out}} - T_{\text{in}}}{1 + (r/r_{0,T})^{1.5}},$$  \hspace{1cm} (4)

where $T_{\text{out}}$ is the temperature in the outer layer of the core and had a value of 12 K, $T_{\text{in}}$ is the temperature at the center of the core and had a value of 5.5 K, and $r_{0,T}$ had a value of 0.012 pc.
The two-dimensional flux distribution was predicted for each core, and this was used as input for the simulated observations with SMA. We used the Common Astronomy Software Applications (CASA)\(^6\) software package to simulate a 5 hr track on each core, centered on transit, with thermal noise equal to 0.5 mJy beam\(^{-1}\), which is similar to the observations described in Section 2.2.

As shown in Figure 4, simulated isothermal cores with more compact density distributions \((r_0 \leq 0.009\) pc\) would have been detected with 5σ confidence, while cores with larger central flat regions \((r_0 > 0.009\) pc\) are resolved out by the simulated SMA observations. To be consistent with the observations presented here, cores with a more realistic temperature profile and small central flat density profile \((r_0 \approx 0.006\) pc\) are ruled out, as shown in Figure 5.

Since we do not detect any of the starless cores in our sample, we estimate that their density profiles are flat on scales out to at least 0.01 pc, assuming isothermality. Allowing for an expected temperature drop toward the core center, we find that these cores must be flat out to scales larger than 0.006 pc. The density profiles that we find are in excellent agreement with previous single-dish observations. For example, Ward-Thompson et al. (1999) mapped with the IRAM 30 m telescope the 1.3 mm continuum emission from a sample of nearby starless cores and found that their flux distributions were flat out to 0.01–0.02 pc. The smoothness of the continuum emission from starless cores found in this study is also in agreement with the results of Schnee et al. (2010) and Offner et al. (2012).

### 3.2.2. Collapse Rate

Based on a simple Jeans analysis, these starless cores may be unstable and therefore in the process of collapsing. The non-detection of continuum emission from the starless cores in our sample, however, is inconsistent with collapse models that predict strongly peaked density distributions, such as those seen in expansion wave models (Silk & Suto 1988). The early stages of slow contraction, such as in models of ambipolar diffusion (e.g., Safier et al. 1997) and models of the pressure-free collapse of Bonnor–Ebert spheres (e.g., Myers 2005), have flat density distributions at small radii and are consistent with our observations. Similarly, the initial stages of uniform collapse (Silk & Suto 1988) are also consistent with our observations.

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\(^6\) http://casa.nrao.edu
The infall rate, in a free-fall approximation, for a 5 $M_\odot$ object to collapse from an initial radius of 0.1 pc to 0.05 pc (roughly the radius of the cores in this sample) is approximately 0.2 km s$^{-1}$. Collapse at this rate can be easily detected in starless cores, as the typical line width is comparable to this infall speed (Foster et al. 2009). We suggest that super-Jeans starless cores are good targets for future observations to look for infall.

### 3.2.3. Stability against Collapse

The reported values of $M/M_J$ for Oph-1, Oph-2, Per-2, and Per-6 are 2.2, 2.3, 4.8, and 4.9 (Sadavoy et al. 2010b), respectively, for a Jeans mass derived from thermal support only. Although the starless cores in this paper are super-Jeans when considering only thermal support, we can estimate their stability when also accounting for their non-thermal motions. For this analysis, we looked at archival data of the published velocity dispersions for these cores. Rosolowsky et al. (2008) have published the NH$_3$ (1,1) velocity dispersions of Per-2 and Per-6, i.e., 0.31 km s$^{-1}$ and 0.46 km s$^{-1}$, respectively. The N$_2$H$^+$ (1–0) velocity dispersions of Per-2 and Per-6, 0.33 km s$^{-1}$ and 0.32 km s$^{-1}$, are similar to the ammonia line dispersions (Johnstone et al. 2010). The typical velocity dispersion measured in NH$_3$ spectra of starless cores in Perseus is <0.2 km s$^{-1}$ (Foster et al. 2009), so Per-2 and Per-6 have especially large non-thermal motions. The velocity dispersion due to thermal motions NH$_3$ at 10 K is ~0.07 km s$^{-1}$, or about four to six times smaller than the observed dispersions measured from ammonia spectra of Per-2 and Per-6. Friesen et al. (2009) and Roueff et al. (2005) have published the NH$_3$ and ND$_3$ velocity dispersions for regions near Oph-1 and Oph-2, which have values of 0.16 km s$^{-1}$ and 0.18 km s$^{-1}$, about two times larger than the thermal velocity dispersion.

To determine the stability of the starless cores in our sample, including the non-thermal motions, we calculate a “typical” virial mass for a uniform density core, following Bertoldi & McKee (1992):

$$M_{\text{vir}} = \frac{5 R \sigma^2}{G}. \quad (5)$$

Taking values typical of the starless cores in this sample ($\sigma = 0.4$ km s$^{-1}$ and $R = 0.05$ pc), we find that a typical virial mass is ~$9 M_\odot$ (or roughly $4.5 M_\odot$ for a density distribution of a critically stable Bonnor–Ebert sphere). Given that the actual masses of the cores are approximately equal to the Bonnor–Ebert virial mass, we cannot be completely confident that the cores are bound or gravitationally unstable. The uncertainties in the core masses and non-thermal support, however, are significant. Indeed, the large line widths seen in these cores could be interpreted as coming from a structured velocity field (from infall itself, for example), and may not be an indication of turbulent support at all. We note also that the manner in which the observed non-thermal motions might supply pressure support without significant dissipation is still unclear. High angular resolution observations of the velocity fields around these cores can distinguish between these possibilities.

### 4. SUMMARY

In this paper, we presented new SMA and CARMA observations of five super-Jeans cores that have been previously classified as being candidate “starless” or “undetermined” by Sadavoy et al. (2010b). We find, in agreement with previous observations, that the core Per-8 is actually protostellar and is the origin of a collimated bipolar outflow. The cores Oph-1, Oph-2, Per-2, and Per-6 are truly starless, however, with non-detections in the 1.3 mm continuum corresponding to 3$\sigma$ upper limits to the mass of any embedded point source of $\leq 0.02 M_\odot$. Our simulations suggest that these four cores have flat density profiles out to radii of at least ~0.006–0.01 pc, in agreement with previous single-dish and interferometric observations of starless cores. Although Oph-1, Oph-2, Per-2, and Per-6 are super-Jeans when considering only their thermal support, when non-thermal support is considered their stability against collapse is much more uncertain.

We thank Robert Gutermuth for helpful discussion on the nature of Per-8. We thank our anonymous referee for suggestions that improved this paper. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. J.D.F. acknowledges support by the National Research Council of Canada and the National Sciences and Engineering Council of Canada (via a Discovery Grant). D.J. is supported by a Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant. 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. Support for CARMA construction was derived from the Gordon and Betty Moore Foundation, the Kenneth T. and Eileen L. Norris Foundation, the James S. McDonnell Foundation, the Associates of the California Institute of Technology, the University of Chicago, the states of California, Illinois, and Maryland, and the National Science Foundation. Ongoing CARMA development and operations are supported by the National Science Foundation under a cooperative agreement, and by the CARMA partner universities.

### Facilities: SMA, CARMA

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