

VLA and NOEMA Views of Bok Globule CB 17: The Starless Nature of a Proposed First Hydrostatic Core Candidate

Stephanie Spear¹, María José Maureira², Héctor G. Arce¹, Jaime E. Pineda², Michael Dunham^{3,4}, Paola Caselli², and

Dominique Segura-Cox²

¹ Department of Astronomy, Yale University, New Haven, CT 06511, USA; stephanie.spear@aya.yale.edu

Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse 1, D-85748 Garching, Germany

³ Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA ⁴ Department of Physics, State University of New York Fredonia, Fredonia, NY 14063, USA

Received 2021 July 1; revised 2021 October 5; accepted 2021 October 14; published 2021 December 24

Abstract

We use 3 mm continuum NOrthern Extended Millimeter Array and NH₃ Very Large Array observations toward the First Hydrostatic Core (FHSC) candidate CB 17 MMS in order to reveal the dust structure and gas properties to 600–1100 au scales and to constrain its evolutionary stage. We do not detect any compact source at the previously identified 1.3 mm point source, despite expecting a minimum signal-to-noise ratio of 9. The gas traced by NH₃ exhibits subsonic motions, with an average temperature of 10.4 K. A fit of the radial column density profile derived from the ammonia emission finds a flat inner region of radius ~1800 au and a central density of ~6 × 10⁵ cm⁻³. Virial and density structure analysis reveals the core is marginally bound ($\alpha_{vir} = 0.73$). The region is entirely consistent with that of a young starless core, hence ruling out CB 17 MMS as an FHSC candidate. Additionally, the core exhibits a velocity gradient aligned with the major axis, showing an arc-like structure in the position–velocity diagram and an off-center region with high velocity dispersion, caused by two distinct velocity peaks. These features could be due to interactions with the nearby outflow, which appears to deflect due to the dense gas near the NH₃ column density peak. We investigate the specific angular momentum profile of the starless core, finding that it aligns closely with previous studies of similar radial profiles in Class 0 sources. This similarity to more evolved objects suggests that motions at 1000 au scales are determined by large-scale dense cloud motions, and may be preserved throughout the early stages of star formation.

Unified Astronomy Thesaurus concepts: Star formation (1569); Protostars (1302); Bok globules (171); Interferometry (808); Interstellar medium (847)

1. Introduction

Low-mass star formation begins with the fragmentation and gravitational collapse of dense, unstable molecular cloud regions into cores (Larson 1969; Adams et al. 1987; Shu et al. 1987; Bergin & Tafalla 2007; Caselli et al. 2008). As these starless cores undergo gravitational collapse, the central region increases in density. Once the density of the central region reaches about 10^{-13} g cm⁻³, it is opaque enough that the heat generated by the collapse can no longer be freely radiated away. This decreases the cooling efficiency, which subsequently results in a rapid increase in the gas temperature and pressure at the center. Eventually, the temperature and pressure are sufficient to stop the collapse of the central region, forming a core in quasi-hydrostatic equilibrium known as the first hydrostatic core (FHSC; Larson 1969; Masunaga et al. 1998; Saigo & Tomisaka 2006; Tomida et al. 2010). During this short-lived stage of quasi-hydrostatic equilibrium, the core continues to accrete mass from the surrounding envelope. Once the central temperature of the core reaches around 2000 K, the core material becomes unstable and begins to collapse again, with most of the energy from this process being channeled into the dissociation of H₂. This second collapse of the smaller, internal region of the first core forms a second hydrostatic core, known as a protostar (Larson 1969).



The FHSC has thus been theorized as an intermediary stage of quasi-hydrostatic equilibrium between the prestellar and protostellar phases of low-mass star formation. Theoretical studies and numerical simulations demonstrate that FHSCs should have several defining characteristics, including: (1) a lifetime of about 10^3 to 10^4 yr; (2) a radius of $\geq 10-20$ au; (3) a small mass of 0.01–0.1 M_{\odot} ; and (4) a low internal luminosity of 10^{-4} - $10^{-1}L_{\odot}$ (Masunaga et al. 1998; Machida et al. 2008; Sakai et al. 2010; Pezzuto et al. 2012; Dunham et al. 2014; Young et al. 2019). Numerical simulations also show that a slow $(v_{out}\sim 3\text{--}5~km s^{-1})$ compact outflow may be launched at this stage. Additionally, a disk may be present during this FHSC stage, or may form directly after, out of the FHSC itself (Machida et al. 2008; Machida & Matsumoto 2011; Joos et al. 2012). It follows that the properties of the dense gas surrounding FHSCs should be between those of prestellar and protostellar cores.

While the existence of FHSCs was predicted over 40 yr ago (Larson 1969), a bona fide FHSC has yet to be observationally confirmed. Their faintness and short lifespans have been limiting in this respect, as we expect to see only one FHSC for every 18–540 protostars (Enoch et al. 2010). Studies have identified 13 FHSC candidates (Belloche et al. 2006; Chen et al. 2010; Enoch et al. 2010; Pineda et al. 2011; Chen et al. 2012; Pezzuto et al. 2012; Friesen et al. 2018; Young et al. 2018; Fujishiro et al. 2020). All of these candidates have spectral energy distributions (SEDs) consistent with the predictions for the FHSC stage. Accordingly, all of these sources have low intrinsic luminosities ($<0.1 L_{\odot}$). Additionally, clear outflows have been detected for 6

of these sources (Dunham et al. 2011; Pineda et al. 2011; Gerin et al. 2015; Busch et al. 2020; Fujishiro et al. 2020). Interferometric observations using high-density tracers have shown that some of these sources were indeed at a young evolutionary stage, either FHSC or young Class 0 protostar (Pineda et al. 2011; Chen et al. 2012; Schnee et al. 2012; Huang & Hirano 2013; Väisälä et al. 2014; José Maureira et al. 2017; Maureira et al. 2017). However, follow-up studies at higher resolutions have provided evidence for ruling out most of the candidates with outflow detections. These follow-up studies have focused on higher-resolution observations of the molecular outflows (if present) and the physical properties of the inner envelope gas and dust emission as a means of ruling out several FHSC candidates (Pineda et al. 2011; Marcelino et al. 2018; Hirano 2019; Allen et al. 2020; Busch et al. 2020; Fujishiro et al. 2020; Maureira et al. 2020). Some of these studies have shown that the detected outflows are too fast to be consistent with the theoretical predictions for FHSCs. Others have shown that the molecular line emissions and distributions of the sources are in better agreement with a slightly more advanced evolutionary stage of a young Class 0 star. Additionally, follow-up studies for two of these sources failed to detect a compact dust structure, thus demonstrating that these sources are consistent with starless condensations as opposed to FHSCs (Maureira et al. 2020).

In this paper, we present Very Large Array (VLA) molecular line observations—using the dense gas tracers NH₃(1,1) and NH₃(2,2)—as well as 3 mm NOrthern Extended Millimeter Array (NOEMA) dust continuum observations of the FHSC candidate CB 17 MMS at resolutions of ~ 4.75 (1120 au) and ~ 2.75 (625 au), respectively. This candidate is located within Bok globule CB 17 at an estimated distance of 250 ± 50 pc (Launhardt et al. 2010). This Bok globule hosts the Class I protostar CB 17 IRS, and it has been resolved into two 1.3 mm peaks (CB 17 SMM1 and SMM2) in single-dish observations with the Institut de Radioastronomie Millimétrique (IRAM) 30 m telescope, separated by 5000 au (Launhardt et al. 2010). The CB 17 SMM1 peak has also been well traced with Herschel Spectral and Photometric Imaging Receiver (SPIRE) observations, which show a rounded structure at this location.

The FHSC candidate CB 17 MMS was identified later by Chen et al. (2012), based on the detection of a faint point source in the Submillimeter Array (SMA) 1.3 mm continuum observations at a resolution of $\sim 3''$. The location of the 1.3 mm SMA peak is offset by \sim 1500 au from the 1.3 mm peak seen in the IRAM 30 m observations (Schmalzl et al. 2014). Chen et al. (2012) show that the point source is undetected at wavelengths $\leq 70 \ \mu m$, and has a low bolometric luminosity ($\leq 0.04 \ L_{\odot}$) and low bolometric temperature of about 10 K, all of which are in agreement with it being at a very early evolutionary stage, such as that of an FHSC. CB 17 MMS was also found to drive a low velocity CO (2-1) molecular outflow (\sim 2.5 km s⁻¹ in the SMA observations; Chen et al. 2012), which is in agreement with the MHD simulations of the FHSC stage (Machida et al. 2008; Tomida et al. 2010). However, Chen et al. (2012) note that the outflow emission could come from the nearby Class I protostar instead, and that the uncertainties in factors affecting the outflow morphology and other physical properties necessitate further observations in order to determine the nature of this source definitively. This study reveals the lack of a compact emission in the new 3 mm sensitive NOEMA observations, and provides evidence from molecular line observations that the structure is consistent with that of a marginally bound starless core.

This paper is organized as follows. In Section 2, we describe the observations and the data reduction. Section 3 presents the general results prior to the spectral fitting, including the dust continuum emission and the ammonia-integrated intensity maps. In Section 4, we discuss the ammonia line-fitting procedure and the property maps produced by these fits, and offer analysis of these properties with reference to the evolutionary states of the sources. Section 5 discusses the column density and angular momentum profiles, and the interpretations of these profiles with regard to the kinematics of the core. Finally, we present our conclusions in Section 6.

2. Observations

2.1. VLA Observations

The VLA observations (Project ID 14A-362) were conducted with 27 antennas in the D configuration, which provides baselines from 0.035 to 1.03 km, resulting in a largest recoverable scale of $\sim 60''$ (15,000 au). The observations were conducted on 2014 July 8, with the total on-source integration time being 2.4 hr. Each track included the observations of a flux, bandpass, and science source phase calibrator at the beginning, the beginning or end, and intermittently throughout the track, respectively. For these observations, 0542+498 was selected for flux calibration, J0319+4130 for bandpass calibration, and J0359 +5057 for phase calibration.

Multiline observations were obtained using the K-band (central frequency ~22.3 GHz) receiver with 14 spectral windows. 8 of these windows had widths of 2 MHz, with dual polarization, 512 channels, and velocity coverages and resolutions of 25 and 0.05 km s⁻¹, respectively. For the purpose of this paper, we focus on the NH₃(1,1) and (2,2) transitions (at 23.69 and 23.72 GHz, respectively), which were each covered by two 4 MHz subbands. Each window had dual polarization, 1024 channels, and velocity coverages and resolutions of 50 and 0.05 km s⁻¹, respectively. NH₃ is a particularly good tracer of dense gas and allows observations of the central core region immediately surrounding the FHSC candidate. The CASA software (Common Astronomy Software Application; McMullin et al. 2007) was used for both calibration and imaging. The calibration of the raw visibility data was conducted using the standard VLA calibration pipeline.

We used *tclean* in CASA 5.6.2 to image the calibrated visibilities. We employed the multiscale deconvolver, using scales of 0, 7, and 21 pixels, and a pixel cell size of 0."6. These scales correspond to a point source, a beam, and three times the beam, respectively. The additional cleaning parameters that were used included a uv taper of 2."5 and natural weighting. The final beam sizes and rms of the resulting maps are given in Table 1.

2.2. NOEMA Observations

The NOEMA 3 mm single-pointing observations (project ID S20AD) were conducted using the C and D configurations, with 10 antennas, between 2020 June 14 and October 19. The combined baseline range was 24-344 m, corresponding to a maximum recoverable scale⁵ of $\sim 17''$ (4250 au). The total on-source time was 4.1 and 3.0 hr in configurations C and D, respectively. The flux and bandpass calibrators were MWC349 and 3C454.3, respectively, and the phase/amplitude calibrators were J0359+600 and 0355+508.

 $^{^5}$ Calculated as $0.6\times\lambda/B_{min}$

Table 1 Map Parameters					
Мар	Rest Frequency ^a (GHz)	Synthesized Beam	P.A.	rms ^b (mJy beam ⁻¹)	
NH ₃ (1,1) NH ₃ (2,2)	23.694495 23.722733	$5''_{0} \times 4''_{3}$ $5''_{0} \times 4''_{0}$ $2''_{0} \times 2''_{4}$	54°22 54°16	6.2 6.0	
Conunuum	82	2.9 × 2.4	51.00	0.008	

Notes.

^a Ho & Townes (1983).

 $^{\rm b}$ The rms for the molecular lines is measured using channels that are 0.05 km $\rm s^{-1}$ wide.

The observations were carried out using the wideband correlator PolyFix, resulting in two 7.7 GHz-wide sidebands, with channel spacing of 2 MHz, which were used for the continuum, after spectral line flagging. The upper sideband (USB) and lower sideband (LSB) were centered at ~90 GHz and ~74 GHz, respectively. Additionally, the setup included 27 high-resolution chunks with channel spacing of 62.5 kHz for lines within the USBs and LSBs. In this work, we focus on the continuum results only.

The data calibration was performed with the GILDAS⁶ software CLIC, using the standard procedures with the observatoryprovided pipeline (Pety 2005; Gildas Team 2013). We used the GILDAS software MAPPING for imaging, using the *multi* deconvolution algorithm, natural weighting, and a user-defined mask. We used the *uv_merge* task to combine the visibilities from the LSB and USB. With this task, a spectral index can be inputted in order to correct the flux of one of the uv tables, so that it is on the same scale as the flux of the other. We did not apply any correction, i.e., we used a spectral index of 0. The rest frequency and the half-power primary beam of the combined continuum are 82.0 GHz and 61.75, respectively. The synthesized beam and rms of the final continuum map are 2.9×2.4 (P.A. = 51°) and 8.2 μ Jy beam⁻¹, respectively.

3. Results

3.1. 3 mm Continuum

Figure 1 shows the combined USB and LSB of the 3 mm NOEMA observations, centered on the location of the 1.3 mm compact source detected in the SMA observations and proposed as FHSC candidate CB 17 MMS (Chen et al. 2012). Our observations do not detect a compact source in this location, marked with a red cross. The emission around the location of the candidate appears to be extended and, thus, resolved out by our observations. There are small-scale 1 to 2σ fluctuations over the 3σ extended emission, which can be expected for a low-brightness extended emission. The reported peak flux of the 1.3 mm unresolved compact source in Chen et al. (2012) is 3.3 mJy beam⁻¹ (6σ detection), observed with a resolution comparable to ours. The new NOEMA observations were designed to be sensitive enough to obtain a clear continuum detection of the candidate, based on the 1.3 mm SMA observations in Chen et al. (2012). Extrapolating the 1.3 mm flux using a spectral index of 3.7 (i.e., an interstellar medium (ISM)– β dust emissivity index of 1.7) provides a strict lower limit to the expected peak flux at 3 mm of 0.07 mJy.



Figure 1. The NOEMA observations of the 3 mm (82 GHz) continuum emission toward CB 17. The location of the 1.3 mm compact source CB 17 MMS, as reported in the SMA observations by Chen et al. (2012), is marked with a red cross. No compact source is detected at this location with a significance of at least 9σ (see the text). The cyan circle marks the location of the 1.3 mm IRAM 30 m peak CB 17 SMM1 (Launhardt et al. 2010). The cyan square marks the location of the NH₃ column density peak (Figure 2). The compact emission to the northwest corresponds to the Class I source CB 17 IRS. The dashed yellow contours outline the CO(2-1) outflow emission extending to the southeast of CB 17 IRS (reproduced from Chen et al. 2012). The white triangle marks the location of the high velocity dispersion observed in NH₃ (Section 4.5). Black Contours are drawn at 3σ , 4σ , and 5σ . The beam is shown in the bottom left corner.

Given the rms of the observations at 0.008 mJy/beam (Figure 1), we expected a detection with a signal-to-noise ratio (S/N) of 9. A lower spectral index, which is expected when an emission is optically thick or in the presence of larger grains, would result in an even higher expected S/N. Similar results are obtained when analyzing the USB and LSB continuum emission separately. Based on these observations, we can rule out the presence of a compact source at the location of the proposed FHSC candidate CB 17 MMS with high significance. Thus, the new continuum observations indicate that CB 17 MMS is starless.

These results are similar to those for a previous FHSC candidate (L1448 IRS 2E), which was also proposed following the detection of a 6σ point source at 1.3 mm in the SMA observations (Chen et al. 2010). The point source was later undetected in both the 1.3 mm SMA and 3 mm Atacama Large Millimeter/submillimeter Array observations, which had sufficient sensitivity (Stephens et al. 2018; Maureira et al. 2020). Similar to CB 17, a nearby bright compact source was also present in the field of L1448 IRS 2E, which could have resulted in artifacts being left over from the cleaning processes in the cases of both candidates. Such artifacts, combined with the existing extended weak emission in the area and the neighboring outflow emission, may have led to their misclassification as FHSCs. Additionally, the proposals of these FHSC candidates were also based on observed CO(2-1) outflow emissions relating to the presumed compact sources. In the case of CB 17 MMS, the dashed yellow contours in Figure 1 show the location and extent of the CO(2-1) emission to the southeast of CB 17 IRS reported in the SMA observations of Chen et al. (2012). The outflow emission changes direction near the location of the presumed FHSC candidate, and is seen just above the high NH₃ column density region (Figure 2). We believe that, similar to L1448 IRS 2E,

⁶ https://www.iram.fr/IRAMFR/GILDAS



Figure 2. An integrated intensity map of $NH_3(1,1)$ (left); an NH_3 column density map (center); and an NH_3 -derived kinetic temperature map (right). The peak column density is marked by the + sign. The Class I source CB 17 IRS (*) is marked in the upper right part of each panel. The region of high NH_3 velocity dispersion, which can be seen in Figure 4, is marked by the Δ symbol. The black oval in the bottom left corner indicates the synthesized beam. Left: black contours are drawn at 10%, 30%, 50%, 70%, and 90% of the peak integrated intensity (the integrated intensity includes the satellite components). Center and right: black contours are drawn at 30%, 40%, 60%, 70%, 80%, and 90% of the peak column density. The red dashed contour indicates the 50% peak column density.



Figure 3. The NH₃(1,1) (left) and NH₃(2,2) (right) spectra at the derived column density peak. The observations are in black, while the fit results are in red. The x-axis corresponds to LSR velocities. The vertical dashed lines mark the central velocity ($v_{LSR} = -4.63 \text{ kms}^{-1}$) derived from the hyperfine fit at this position (Section 4.1).

the CO outflow emission thought to originate in the FHSC candidate outflow corresponds to the outflow emission from the nearby protostar, deflected by dense ambient material (Maureira et al. 2020).

The only clear compact source detection in the field corresponds to the Class I source CB 17 IRS toward the northwest. We fit the compact source with a Gaussian model (after applying primary beam correction) and obtained an integrated flux and a peak flux of 0.71 ± 0.03 mJy and 0.65 ± 0.02 mJy beam⁻¹, respectively.

3.2. NH₃ Integrated Intensity

Given that we do not detect a compact source in the direction of CB 17 MMS with the 3 mm NOEMA observations, we will henceforth refer to the dense starless region that we trace with NH₃ and discuss below as CB 17 SMM1. The SMM1 peak is closest to the NH₃ peak we observe with the VLA (see Figure 1), and shows a similar rounded structure in the Herschel SPIRE observations. The left panel of Figure 2 shows the NH₃(1,1) integrated intensity map of CB 17 SMM1, which includes the satellite components. The satellites refer to the NH₃(1,1) hyperfine pattern, which includes four satellite lines and a main line. This structure is demonstrated by the spectrum in Figure 3. Only pixels above 3σ were considered. The emission exhibits a roundish shape, measuring approximately $44'' \times 27''$ at the 10% peak emission contour, which corresponds to roughly 11,000 × 6700 au.

The position angle of the major axis is $135 \pm 1^{\circ}.1$ (measured east from north). The position of the presumed 1.3 mm compact source (Chen et al. 2012) lies at the edge of the contour demarcating the 90% value of the peak NH₃(1,1) integrated intensity. The nearby Class I source CB 17 IRS, located ~21" (or 5250 au) northwest of CB 17 MMS and marked with a star in Figure 2, is not being traced by the ammonia. The integrated intensity map of NH₃(2,2), showing an emission similar to but weaker than NH₃(1,1), can be found in the Appendix.

4. Molecular Line Analysis

4.1. Line Fitting

The cold-ammonia model from the python package pyspeckit (Ginsburg & Mirocha 2011) was used to derive the kinematics and physical properties toward CB 17 from the NH₃(1,1) and (2,2) emission. This package fits Gaussian profiles to the hyperfine components of the ammonia rotational transitions using a model developed in Rosolowsky et al. (2008) and Friesen et al. (2009), and relies on the theoretical framework established in Mangum & Shirley (2015). The free parameters of the fit are the fraction of NH₃ in the ortho state, the total NH₃ column density, the kinetic temperature (T_K), the excitation temperature (T_{ex}), the line-of-sight velocity (v_{LSR}), and the velocity dispersion (σ_v). In our fitting, for each pixel all parameters were left free except the fraction of NH₃ in the ortho state, which was fixed at 0.5, i.e., assuming a local thermodynamic equilibrium ortho-para ratio



Figure 4. The velocity (left), line width (center), and excitation temperature (right) maps of CB 17 MMS. The peak column density is marked by the + sign. The Class I source CB 17 IRS (\star) is marked in the upper right part of the panel. The region of high velocity dispersion is marked by the Δ symbol. The black oval in the bottom left corner indicates the synthesized beam. Black contours are drawn between 30% and 90% of the peak column density, in increments of 10%. The velocity and line width maps show the values obtained by fitting a Gaussian profile to the molecular line spectra, as discussed in Section 4.1. The cuts used to make the positionvelocity diagrams in Figure 5 are marked by the white dashed lines. The cut in the velocity map, centered on the peak NH₃ column density, corresponds to the left panel of Figure 5, while the cut in the line width map, centered on the high velocity dispersion region, corresponds to the right panel of Figure 5.

value of 1. The model assumes the same T_{ex} temperature for all hyperfines, as well as for the (1,1) and (2,2) lines. The model derives the T_K temperature from the rotational temperature by analytically solving the equations of detailed balance described in Swift et al. (2005). See Section 3.1 of Friesen et al. (2017) for a more detailed derivation of the cold-ammonia model used in pyspeckit.

Fits were attempted only for those pixels for which the $NH_3(1,1)$ S/N was above 5. After the fits were completed, we applied masking to any pixels for which the resultant error on an individual parameter was zero or the ratio between the parameter value and the error was less than 3. This was done individually for each parameter. Further, for T_K and T_{ex} we removed all pixels for which the error was ≥ 2 K, and these same pixels were removed from the final column density map. The latter resulted in the removal of sets of pixels at the edge of the integrated intensity map, which had the largest errors in these parameters. The cutoff of 2 K was chosen in order to remove the pixels for which the uncertainty was greater than the typical parameter variations seen on the map, as it would be hard to detect any real variations in temperature if the errors in the pixels were greater than the variations themselves. In the case of velocity and velocity dispersion, the errors are typically much smaller than the variations on the maps, as these parameters are more robustly constrained in the fit in comparison with T_K and T_{ex} . Hence, for the velocity and velocity dispersion maps, we did not apply any additional masking. This is why these maps are more extended than the temperature and column density maps (Figure 4). Examples of the spectra for $NH_3(1,1)$ and $NH_3(2,2)$ using the corresponding model are shown in Figure 3. The spectra correspond to those extracted at the position of the column density peak.

A summary of the values obtained from the resulting fits can be found in Table 2. The resulting maps for NH₃ column density and kinetic temperature are shown in Figure 2, while the central velocity and velocity dispersion are shown in Figure 4. The excitation temperature map is shown in the right panel of Figure 4.

4.2. Column Density

The column density increases toward the center, closely following the integrated intensity map (Figure 2). The mean NH₃ column density and NH₃ column density peak are 5.8×10^{14} cm^{-2} and $1.5 \times 10^{15} cm^{-2}$, respectively (the mean value is also

Table 2Map Properties					
Region	NH ₃ Column Density (1×10^{14})	Temperature (T_{kinetic})	Velocity Dispersion (σ_v)		
	cm^{-2})	(K)	$({\rm km \ s}^{-1})$		
Total Core	5.8 (2.8)	10.4 (1.1)	0.09 (0.02)		
Inner Core	10 (2.2)	10.5 (0.8)	0.1 (0.01)		
NH ₃ Column Density Peak	15 ± 1.0	8.9 ± 0.4	0.1 ± 0.003		

Note. The Total Core and Inner Core values are given as the mean (standard deviation). The median values are slightly lower (within 1σ) than the mean values. The NH₃ Column Density Peak values are given as the value and the error of the individual pixels. These properties were obtained by fitting the spectrum of each pixel (see Section 4.1). We define the "Inner Core" as the region within the 50% peak column density (see Section 5.1).

reported in Table 2). In order to explore the properties of the central area, we designate an "inner core" region within the 50% peak column density contour, which is demarcated by the red dashed contour on the map. In the following section, we consider the masses and volume densities of both the total core and the inner core. We discuss the column density profile in greater depth in Section 5.1.

4.2.1. Mass and Density from Ammonia

We estimate the mass and volume density of the core using the column density from our earlier fit (Section 4.1), considering the entire mapped structure and the inner core region. For this, we use a fractional abundance with respect to H_2 of 10^{-8} for NH₃, consistent with the mean value reported by Friesen et al. (2017) for NGC 1333 and B18 in Perseus and Taurus, respectively. However, there are a range of potential abundances that could be used. For example, Seo et al. (2015) also analyze the NH₃ masses of filaments L1495-B218 in Taurus using an abundance of 1.5×10^{-9} , which they verify by comparing the derived masses from the NH₃ column density and abundance to the masses estimated from the dust continuum and the virial masses. We verify our abundance ratio using the central H₂ column density for CB 17, as derived from lower-resolution continuum observations $(\sim 3 \times 10^{22} \text{ cm}^{-2}; \text{ Schmalzl et al. 2014})$ and our average NH₃ column density, which leads to an abundance of 1.7×10^{-8} (in

 Table 3

 Properties Derived from Ammonia

			*			
Total Mass (M_{\odot})	Inner Mass (M_{\odot})	Total Volume Density (10^6 cm^{-3})	Inner Region Size (au)	Inner Volume Density $(1 \times 10^6 \text{ cm}^{-3})$	Magnitude $(\text{km s}^{-1} \text{ pc}^{-1})$	Direction deg E of N
1.70	0.63	1.0	2950×1180	1.9	5.56 ± 0.07	-58.3 ± 0.7

Note. We assume an NH₃ fractional abundance with respect to H_2 of 10^{-8} for all estimates (Friesen et al. 2017). The Total Mass and Total Volume Density estimates are calculated for the entire column density map. The Inner Mass and Inner Volume Density estimates are calculated within 50% of the column density peak (demarcated by the red contour in Figure 2). The region size corresponds to the semimajor and semiminor axes of this Inner Region.

agreement with the assumed abundance within a factor of two). The spatial resolution of the Schmalzl et al. (2014) observations is of a similar scale to the NH₃ emission region we detect (25" or a 6250 au beam). Considering all of the pixels in the column density map, and given a mean molecular weight per hydrogen molecule of $\mu_{H_2} = 2.74$ (Tanner & Arce 2011), we obtain a total mass of 1.70 (×10⁻⁸/X[NH₃]) M_{\odot} . This method is similar to that used in Seo et al. (2015). Our estimation agrees with the $2.3 \pm 0.3 M_{\odot}$ value estimated in Schmalzl et al. (2014)—derived from dust Herschel and single-dish observations—that traced a larger structure (by a factor of four) with a radius of 18×10^3 au. It is also consistent with the masses of NH₃ leaves (structures containing individual intensity peaks) in Taurus filaments, which range from 0.05 to 4.3 M_{\odot} (Seo et al. 2015).

In order to obtain a lower limit estimate of the volume density, we consider the volume of an ellipsoid and assume that the third axis (along the line of sight) is equal to the major axis of the observed emission. The semimajor and semiminor axes of the main structure correspond to ~ 4800 and ~ 2300 au, respectively (the axis lengths are visually determined). This results in a gas volume density estimate of $\sim 1 \times 10^6$ cm⁻³ (×10⁻⁸/X[NH₃]). For the region of 50% peak column density, with semimajor and semiminor axes of 2950 and 1180 au, respectively (axis lengths are again visually estimated), we derive a mass of 0.63 M_{\odot} $(\times 10^{-8}/X[NH_3])$ and a higher corresponding gas volume density of $\sim 2 \times 10^6$ cm⁻³ ($\times 10^{-8}/X$ [NH₃]). Even considering uncertainties in the abundance of a factor of a few, the estimated central density is close to or above 10^6 cm⁻³. We later give another estimate of the volume density, based on the fit of the column density profile, that is consistent with these estimates within a factor of a few (see Table 4 and Section 5.1). This value is consistent with the detection of $N_2D^+(3-2)$ in the SMA observations (Chen et al. 2012), which has a critical density of 3×10^6 cm⁻³. In addition, the integrated intensity peak of $N_2D^+(3-2)$ closely matches the location of the NH₃ column density peak, and is unrelated to any peak in the NH_3 (2,2) emission (see the Appendix). This suggests that the NH₃ column density peak is indeed tracing the higher-density region within the core, and not a region with enhanced temperature. In comparison, Schmalzl et al. (2014) and Lippok et al. (2013) report central volume densities of only $1.3-2.3 \times 10^5$ cm⁻³, using several dust emission maps convolved to a common resolution that is a factor of five lower than the NH₃ maps presented here. The results discussed above are summarized in Table 3.

4.3. Temperature

Figure 2 includes a map of the kinetic temperature obtained through the fit of the spectra of NH_3 (1,1) and (2,2) toward each pixel, as described in Section 4.1. The map shows the average temperature along the line of sight for each pixel with significant NH_3 (1,1) and (2,2) emission in the CB 17 SMM1 core. We calculate the median temperature (and standard deviation) to be

10.4 \pm 1.1 K (see also Table 2), derived using a kernel density estimation (KDE) density distribution from all of the pixels in the temperature map (Figure 2). This value matches the dust temperature of 10.6 \pm 0.3 K found in an inner isothermal region within 4000 au (Schmalzl et al. 2014), derived from Herschel and single-dish continuum observations, and modeled considering gradients in volume density and temperature, i.e., not from line-of-sight averages. The line-of-sight averages result in a larger central dust temperature of 14.2 \pm 0.7 K (Schmalzl et al. 2014).

4.4. Central Velocity

The velocity map for the core can be found in Figure 4. The core displays a clear velocity gradient, increasing from southeast to northwest along the major axis of the structure. In order to measure the magnitude and direction of the systematic velocity gradient, we employ the methodology described in Section 2.1 of Goodman et al. (1993). We begin by fitting the function for a linear velocity gradient in a plane:

$$v_{\rm LSR} = v_0 + a\Delta\alpha + b\Delta\beta. \tag{1}$$

 $\Delta \alpha$ and $\Delta \beta$ represent the radian offsets in R.A. and decl., while *a* and *b* are the gradients per radian projection on these axes. v_0 is the core systemic velocity. Given Equation (1), the magnitude of the gradient can be shown as

$$\mathcal{G} \equiv |\nabla v_{\text{LSR}}| = (a^2 + b^2)^{1/2} / D,$$
 (2)

where D is the distance to the cloud. The gradient direction (measured east of north, in the direction of increasing velocity) is then given by

$$\theta_{\mathcal{G}} = \tan^{-1}\frac{a}{b}.\tag{3}$$

Based on this fit, we find the core systemic velocity v_0 to be -4.64 ± 0.01 km s⁻¹. The magnitude of the velocity gradient and its direction are 5.56 ± 0.07 km s⁻¹ pc⁻¹ and $-58.3 \pm 0^{\circ}$?7 east from north, respectively (Table 3).

Schmalzl et al. (2014) report a comparable gradient of $\sim 4.3 \pm 0.2$ km s⁻¹ pc⁻¹, using the N₂H⁺(1-0) line. They find an arc-like or sinusoidal pattern in the position–velocity diagram of N₂H⁺(1-0) (see their Figure 7). We find a similar arc-like pattern in the position–velocity diagram for NH₃(1,1), centered on the column density peak (see the left panel in Figure 5).

Generally speaking, velocity gradients at the core ($\sim 0.1 \text{ pc}$) and envelope scales (a few 1000 au) are usually interpreted as resulting from infall or rotational motions, but they could also arise from large-scale turbulence or convergent flow compression (Burkert & Bodenheimer 2000; Ballesteros-Paredes et al. 2006; Pineda et al. 2019). In the case of CB 17 SMM1, the arclike (or sinusoidal; Schmalzl et al. 2014) structure of the position–velocity diagram could be due to the interaction of the



Figure 5. Position–velocity maps of the ammonia emission in CB17 SMM1 along the P.A. of the derived velocity gradient, using only the satellite hyperfine component close to -24 km s^{-1} (see Figure 3). Left: position–velocity diagram centered on the NH₃ column density peak. The dashed line highlights the sinusoidal or arc-like feature discussed in the text. Right: position–velocity diagram centered on the high velocity dispersion region (the triangle marker in Figure 4). Black contours are drawn at 30%, 50%, 70%, and 90% of the peak emission. The directions and widths of the position–velocity diagrams are indicated by the white dashed lines in Figure 4.

dense material with the CO outflow emission originating from the nearby CB 17 IRS Class I source. Interestingly, a similar arc-like shape was recently reported by Maureira et al. (2020) toward the extremely young Class 0 protostar Cha-MMS1, using $N_2H^+(1-0)$ observations (see the bottom right panel of their Figure 10). The envelope of this protostar was also found to be interacting with a nearby outflow. In both cases, the velocity gradients of the structures are closely aligned with the nearby outflow axes. Moreover, two other starless cores (B1-NE and B1-SW in Perseus), also observed in $N_2H^+(1-0)$, show similar arc-like structures in their position-velocity diagrams (Chen et al. 2019; see their Figure 3). Similar to CB 17 SMM1 and Cha-MMS1, the velocity maxima in the position-velocity diagrams for these sources were not the locations of the higherdensity peaks, as traced by the integrated molecular emission. Chen et al. (2019) suggest that these velocity structures may be due to the convergence of two oblique gas flows. Similar convergent flow compressions could arise in the cases of CB 17 SMM1 and Cha-MMS1, from the interactions between the nearby outflows and the dense core gas traced by the dust continua and ammonia emissions (Figures 1 and 2).

4.5. Velocity Dispersion

Figure 4 shows a map of the NH₃ velocity dispersion. Except for a small region on the eastern side of the core, the velocity dispersion remains relatively constant. The median over the whole region is σ_v , med = 0.09 km s⁻¹. This corresponds to a total line width (FWHM) of $\Delta v \sim 0.21$ km s⁻¹, which is in agreement with the value obtained from only the NH₃ thermal motions at a temperature of 10.4 K (our derived mean temperature; see Section 4.2). These values and distributions are in agreement with the results presented in Schmalzl et al. (2014), using the N₂H⁺(1-0) line.

Given that the derived temperatures are mostly uniform over the mapped region (Figure 2), the high velocity dispersion region near the eastern edge of the core corresponds to the enhancement of nonthermal motions. The typical nonthermal NH₃ line width of $\Delta v = 0.33$ km s⁻¹⁷ is calculated using our derived mean temperature value of 10.4 K (Section 4.2). This value and the H₂ thermal line width at the same temperature ($\Delta v = 0.45$ km s⁻¹) lead to an H₂ nonthermal–thermal ratio of ~0.7. Thus, the entire NH₃ mapped region, including the region with the broad line widths, shows subsonic nonthermal motions. These values are entirely in agreement with the Schmalzl et al. (2014) observations of N₂H⁺(1-0), which combined both single-dish and interferometer). This good agreement also suggests that our line widths have not been greatly affected by the missing flux from large-scale structures due to the lack of single-dish observations.

The velocity dispersion map in Figure 4 exhibits a region of high velocity dispersion on the eastern side of the core, marked by the Δ symbol. In order to investigate the possible origin of this region of broad line widths, we inspect position-velocity diagrams along the velocity gradient of the core and passing through the region (Figure 5). We find that the velocity gradient around this region is not due to the central velocity of the line shifting smoothly, with its position moving from blueshifted to redshifted. Instead, there are two components of fairly constant velocity that overlap at the location where the large line widths are observed. As the spectra were fitted with a single component, the local region where the two components overlap naturally results in broad line widths. This type of velocity structure is in agreement with our previous interpretation of the interaction of converging flows near the center of the core. Both the region of the broad line widths and the 1.3 mm IRAM peak are located within the CO(2-1) outflow emission from CB 17 IRS (Figure 1). The region with the broad line widths also corresponds to a region with weak emission and thus low column densities of NH₃. Therefore, the broad line widths are likely tracing the regions where the outflow is interacting with the dense core gas. Given that we do not see a high temperature

Corresponding to $\sigma = 0.17 \text{ km s}^{-1}$ on the map.



Figure 6. The azimuthally averaged column density distribution, derived from the NH₃ column density, assuming an NH₃ fractional abundance of 10^{-8} with respect to H₂, and centered on the NH₃ column density peak. The solid red line shows the curve of the best-fit model (Table 4).

being associated with the broad line width zone, any outflow impact would be tangential rather than direct.

5. Discussion

5.1. Core Structure and Stability

In order to better understand the structure and dynamical state of the core, we perform a fit of the column density profile, presented in Figure 6. We use the same abundance ratio for NH_3 (10⁻⁸) and mean molecular weight per hydrogen molecule $(\mu_{H_2} = 2.74)$ as we did for our previous mass and volume density estimates. The column density structure, particularly in the inner regions of the core, can be an indicator of the evolutionary state of the core (Ward-Thompson et al. 1994; Bergin & Tafalla 2007; Ward-Thompson et al. 2006; Koumpia et al. 2020). In prestellar cores, the characteristic "plateau" of slowly decreasing density occurs within radii smaller than 2500–5000 au (Andre et al. 1996; Ward-Thompson et al. 1999; Bergin & Tafalla 2007). This feature is typically coupled with a power-law density decrease ($\sim r^{-2}$) at larger radii (Chandrasekhar & Wares 1949; Di Francesco et al. 2006). A number of different models are used to fit such cores, including the original dual power law of Ward-Thompson et al. (1994), the modified power laws of Tafalla et al. (2002), and the truncated isothermal Bonnor-Ebert sphere model (Ebert 1955; Bonnar 1956). For our study, we employ the analytic model of Dapp & Basu (2009), which replicates the characteristics of the Bonnor-Ebert sphere isothermal equilibria model as well as nonequilibrium models, such as that of Larson (1969).

The Dapp & Basu (2009) profile is defined as

$$\varrho(r) = \begin{cases} \varrho_c a^2 / (r^2 + a^2) & : r \leqslant R\\ 0 & : r > R. \end{cases}$$
(4)

This model is characterized by a central volume density ρ_c ; an outer radius *R*, at which point the core is truncated; and a parameter *a*, which fits the inner radius or plateau region. Integrating the volume density along the line of sight and combining this expression with Equation (4) produces a

 Table 4

 Column Density Profile Fit Parameters

Parameters	Fitted Values		
$\overline{\Sigma_c}$	$(1.3 \pm 0.1) \times 10^{23} \text{ cm}^{-2}$ $(2.7 \pm 0.5) \times 10^{-18} \text{ g cm}^{-3}$		
r ₀	$(0.6 \pm 0.1) \times 10^{6} \text{ cm}^{-3}$ 1800 ± 300 au		

Note. The outer radius r_{out} was not constrained and was set to 30,000 au in this fit (Schmalzl et al. 2014). We assume an abundance of 10^{-8} for NH₃ with respect to H₂, and a mean molecular weight μ_{H_2} of 2.74.

closed-form expression of the column density as

$$\Sigma(x) = \frac{2a^2 \varrho_c}{\sqrt{x^2 + a^2}} \arctan\left(\frac{\sqrt{R^2 - x^2}}{\sqrt{x^2 + a^2}}\right).$$
 (5)

Rewriting this in terms of the central column density Σ_c , with $\Sigma(x = 0) \equiv \Sigma_c = 2a\rho_c \arctan(c)$, leads to

$$\Sigma(x) = \frac{\Sigma_c}{\sqrt{1 + (x/a)^2}} \times \left[\arctan\left(\sqrt{\frac{c^2 - (x/a)^2}{1 + (x/a)^2}}\right) \right/ \arctan(c) \right], \quad (6)$$

where $c \equiv R/a$. See Dapp & Basu (2009) for a more detailed discussion of this derivation.

We use this model to fit the azimuthally averaged H₂ column density profile of the core (Figure 6). The best-fit parameters are listed in Table 4. We find a central column density ρ_c of $0.6 \pm 0.1 \times 10^6$ cm⁻³. Based on this fit, we find an inner radius $r_0 \sim 1800$ au for the central flat region of the core, in agreement with the geometric mean of the radius containing 50% of the peak column density. This inner radius size is also consistent with the radius range of the characteristic central flattening seen in prestellar cores (Andre et al. 1996; Ward-Thompson et al. 1999; Bergin & Tafalla 2007) and with the flat inner region derived using Equation (2) in Keto & Caselli (2010). The outer radius of the core is not well constrained by the fit. The limited extent of the ammonia emission does not provide enough data at large radii for the fit to determine the steepness of the density decrease in the outer regions of the core; single-dish data (e.g., Green Bank Telescope) and mosaic observations would be needed for that. Nevertheless, the value of the outer radius does not affect our results for the inner radius or the central density. Hence, we fix this value at 3×10^4 au, which is identified as the outer radius from the fit performed by Schmalzl et al. (2014), based on Herschel and submillimeter/millimeter continuum observations.

5.1.1. Stability Assessment

We use the results from the column density fit to evaluate the stability of the core, following Dapp & Basu (2009). The inner radius a is given by

$$a = k \frac{c_s}{\sqrt{G\rho_c}},\tag{7}$$

where k is a proportionality constant, G is the gravitational constant, and the isothermal sound speed c_s is defined as $c_s = \sqrt{k_B T/\mu}$. We take the central volume density ρ_c from the fit of the central column density, where $\Sigma_c = 2a\rho_c \arctan(c)$.

Dapp & Basu (2009) demonstrate that cores considered to be in equilibrium have a $k \approx 0.4$, while cores for which k is closer to 1 are at risk of collapsing. Based on our fit, using a value of 10.4 K for the temperature, we find a k value of 0.57. This indicates that the core is straddling the boundary between equilibrium and collapse.

We also investigate the stability of CB 17 SMM1 by using the virial parameter. We obtain the virial mass using the following equation:

$$M_{\rm vir} = 5\sigma_{H_2}^2 R/G,\tag{8}$$

which assumes a uniform density profile (Bertoldi & McKee 1992). The total velocity dispersion (thermal and nonthermal) σ_{H_2} is estimated using the following:

$$\sigma_{\rm H_2}^2 = k_b T / \mu + (\sigma_{\rm obs}^2 - k_b T / m_{\rm mol}), \tag{9}$$

where σ_{obs} corresponds to the observed velocity dispersion of the molecular line, and m_{mol} is the mass of the molecule (Chen et al. 2007). Using the average observed velocity dispersion for σ_{obs} , we find a virial mass of $1.24M_{\odot}$. The virial parameter $\alpha = M_{vir}/M$ is then 0.73. For a gravitationally bound system, $\alpha \sim 1$, while in an unbound system, $\alpha \gg 1$. Based on our α value of 0.73 and the previously derived k value, we conclude that, at the scales at which we are observing the system, the core appears to be marginally bound. This is also consistent with the results from Schmalzl et al. (2014) that compare the gravitational energy with the rotational, turbulent, and thermal energies. They conclude that the core becomes marginally bound at a radius from 8000 to 18,000 au.

5.2. Central Temperature

Dense (starless) cores with a central density above 10^5 cm⁻³ are expected to exhibit drops in their dust and gas temperatures toward their centers (Keto & Field 2005). Figure 7 shows the azimuthally averaged NH₃ temperatures as a function of distance from the NH₃ column density peak, where each annulus is approximately one beam size (1200 au) in width. The errors are determined by propagating the error from the fit over each bin. The plot hints at a drop in temperature toward the center of about 1 K, starting at about 2000 au, before reaching a central temperature of 9.5 K.

Central drops in the line-of-sight-averaged temperatures derived from NH3 have been observed toward the evolved prestellar core L1544, from 6000 to 1000 au scales (Crapsi et al. 2007), and the southern prestellar core in Ophiuchus D, from 3000 to 500 au scales (Ruoskanen et al. 2011). Both of these prestellar cores exhibit central temperatures lower than what we obtain for CB 17 (~ 6 and ~ 7.5 K for L1544 and southern Ophiuchus D, respectively), close to the expected dust temperatures in cores with central densities of $\sim 10^6$ cm⁻³ (Keto & Field 2005). On the other hand, the northern prestellar core in Ophiuchus D shows a fairly constant temperature of 9 K, in better agreement with the values derived here for CB 17 SMM1 (Ruoskanen et al. 2011). As discussed in Keto & Caselli (2008), at densities below $\sim 10^5$ cm⁻³ the gas cools down primarily through molecular line radiation, which keeps the gas temperature nearly isothermal, while above this threshold it starts to cool down mainly through collisions with dust, resulting in a drop in the gas temperature toward the center. The two cores that show drops in temperature toward



Figure 7. The azimuthally averaged kinetic temperature distribution centered on the NH_3 column density peak. Each annulus is approximately one beam size (1200 au) in width. The errors, demarcated by the gray region, are determined by propagating the error in the fit for each individual pixel, and averaging them over each bin.

their central regions have higher central densities close to or above 10^6 cm⁻³, while Ophiuchus D north has a central density of the order of a few 10^5 . The hint of a temperature drop, as seen in our derived temperature profile toward CB 17, supports our results from Section 5.1 that a volume density ~ 6 × 10^5 cm⁻³ is present toward the very center of this core.

For comparison, Keto & Caselli (2010) provide theoretical density and gas temperature profiles for a starless core with a central density of 10^6 cm⁻³. Their gas temperature profile drops from 11 K at \sim 3000 au to 8 K in the center, which is consistent with our results, considering the uncertainties and that our measurement is a line-of-sight average, i.e., it does not consider a temperature gradient toward the center, which can result in an overestimation of the central temperature (Schmalzl et al. 2014). On the other hand, we can also consider the scenario that the gas temperature at the center of CB 17 remains around 9 K, even though the dust temperature is as low as 6-7 K, as expected in cores of up to 10^6 cm⁻³ (Keto & Caselli 2010). The difference between the dust and gas temperatures depends on the dust properties, such as the dust grain size a_{eff} and the cosmic ray ionization rate ζ . Assuming spherical grains, and that gas heating is due only to cosmic rays while cooling is only due to collisions with dust grains, we can provide estimates of the typical dust grain sizes required to keep the gas temperature at 9 K, while also keeping the dust temperature close to 6 K (Ivlev et al. 2019). Given a power-law distribution for sizes of dust grains, the coagulation of the grains reduces the total surface area of the dust and, hence, the coupling between the gas and the dust. This results in greater differences between the dust and gas temperatures (Ivlev et al. 2019). Using Equation (18) in Ivlev et al. (2019), with a temperature difference of 3 K, and assuming a standard value of $\zeta = 10^{-17} \text{ s}^{-1}$, we derive $a_{\text{eff}} = 6 \ \mu\text{m}$. The expression in Ivlev et al. (2019) does not consider the growth of mantles on grains, nor the fact that they are likely not perfectly spherical, both of which should increase the coupling. Because of this, grains of a few tens of μ m in size are likely to be necessary for a scenario in which the central gas temperature remains around 9 K. Another possible scenario for explaining the only marginal drop, even though the core has a central volume density close



Figure 8. The radial profile of the specific angular momentum $(j = R_{rot}V_{rot})$ of CB 17. The dashed black line shows the best-fit power-law relation from Pineda et al. (2019). The dashed red line shows the broken power-law model of the specific angular momentum from Gaudel et al. (2020).

to 10^6 , is that the dust temperature is higher toward this source due to additional heating from the nearby protostar. Future observations at a higher resolution or radiative transfer modeling could help to further constraint the density and temperature profiles of this core.

5.3. A Starless Core Angular Momentum Profile

The specific angular momentum radial profile may be indicative of the evolutionary state of a core (Pineda et al. 2019). Assuming symmetry around an axis, the specific angular momentum at distance *r* is described as $j(r) = R_{rot}V_{rot}$ where R_{rot} is the rotation radius or impact parameter and V_{rot} is the rotational velocity around the axis of symmetry ($V_{rot} = V_{obs} - V_c$, where V_c is the velocity at the NH₃ integrated intensity peak). Following the methodology of Pineda et al. (2019), we derive the specific angular momentum as a function of radius for CB 17 SMM1.⁸ Figure 8 shows the resultant specific angular momentum profile for CB 17 and a comparison with the profiles derived for Class 0 sources in Pineda et al. (2019) and Gaudel et al. (2020).

Pineda et al. (2019) studied two Class 0 and one FHSC candidate (L1451-mm). They found that the radial profiles of their three sources were consistent with the power law $j(r) \propto r^{1.80\pm0.04}$ to 1000 au. Gaudel et al. (2020) found that the specific angular momentum profiles of young Class 0 objects can be fit by a broken power law of $j(r) \propto r^{0.3\pm0.3}$, inward of 1600 au, and $j(r) \propto r^{1.6\pm0.2}$ otherwise.

The power law for the larger radii in Gaudel et al. (2020) has a similar exponent to the power law in Pineda et al. (2019). Both studies conclude that the observed specific angular momentum at these scales is not likely to be the result of purely rotational motion, suggesting that gravitationally-driven turbulence from large-scale collapse motions or turbulent cascades from large-scale molecular clouds could be the source of this outer envelope angular momentum.

We find that the specific angular momentum radial profile of CB 17 is in good agreement with the power-law relation from Fineda et al. (2019) and the power-law relation from Gaudel et al. (2020) at r > 1600 au (see Figure 8). It is also in good agreement with that of the star-forming filament LBS23, where $j(r) \propto r^{1.83\pm0.01}$ (Hsieh et al. 2021).

The close alignment between the CB 17 specific angular momentum profile and the power-law relations from Pineda et al. (2019) and Gaudel et al. (2020) is interesting, given that all of the sources used in fitting the power laws in these published studies have already formed a compact object in their center, and thus are more evolved than CB 17 SMM1. This implies that the average motions at 1000 au scales are not greatly affected by the presence of a central object, and may instead originate from larger-scale turbulent cascades or colliding turbulent flows (Chen et al. 2019), as we suggested in Section 4.4. The former would be in agreement with the measurements in Hsieh et al. (2021), supporting the suggestion that the same mechanism producing the velocity gradients in prestellar cores and Class 0 protostars is also present at filamentary scales. Furthermore, our results show clear agreement between the magnitudes of the specific angular momentum profiles of our starless core and the Class 0 sources. This may suggest that these motions are preserved throughout the prestellar stage, and then later inherited by the more evolved (protostellar) cores. Future measurements of the specific angular momentum profile as a function of radius for a sample of isolated prestellar cores-such as L1544 (Crapsi et al. 2007)-would help to elucidate whether neighboring protostars, as is the case for CB 17 IRS, have any influence in the core motions at $\sim 10^3$ au scales.

6. Summary and Conclusion

The primary goal of this study was to determine the evolutionary state of the first core candidate CB 17 MMS, and to assess whether or not this source is a bona fide first core. We revealed the continuum emission using NOEMA 3 mm observations, with a resolution of ~625 au, and the gas properties with VLA observations of NH₃(1,1) and NH₃(2,2), with a resolution of 1120 au. Our conclusions can be summarized as follows:

- 1. The NOEMA 3 mm observations toward the FHSC candidate CB 17 MMS do not detect any compact source at the location of the 1.3 mm compact source reported in Chen et al. (2012), with a significance of at least 9σ . We argue that the CO outflow emission originally thought to originate in the FHSC candidate outflow actually corresponds to the outflow emission from a nearby protostar, which is deflected by the dense ambient material.
- 2. We detect a compact NH₃ emission showing a peak column density of 1.5×10^{15} cm⁻², an average temperature of 10.4 K, and subsonic motions. The line-of-sight temperature profile shows a slight drop of 1 K in the inner 2000 au.
- 3. The core exhibits a velocity gradient aligned with the neighboring outflow axis, showing an arc-like structure in the position–velocity diagram and an off-center region with high velocity dispersion, caused by two distinct velocity peaks. We believe these features indicate that CB 17 SMM1 has two overlapping velocity components that are compressed near the center of the core, due to the interactions with the CO outflow from the nearby protostar.

⁸ Using the "velocity tools" package: https://github.com/jpinedaf/velocity_tools.

- 4. We fit the radial column density profile and found that the profile exhibits a flat inner region to $r_0 = 1800$ au and a central density of 6×10^5 cm⁻³. An analysis of the density profile and virial mass of the core reveal it to be close to being gravitationally bound. This is consistent with our understanding of this starless source as being in an early evolutionary stage, potentially triggered by the compression causing the outflow.
- 5. The specific angular momentum radial profile of the CB 17 starless core aligns closely with the profiles observed by others for more evolved Class 0 sources. The similarity between sources at very different evolutionary stages suggests that the dominant outer envelope motions for these sources are the remnants of large-scale dense cloud motions that are preserved throughout the early stages of star formation.

The results of our study lead to the conclusion that CB 17 SMM1 is fully consistent with a marginally bound starless core, allowing us to definitively rule out CB 17 MMS as a bona fide FHSC. A follow-up study using the 3 mm molecular lines observed with NOEMA (including deuterated and nondeuterated species) will help us to shed light on the inner physical and chemical properties of this newly confirmed starless core.

Finally, we note that of the early list of eight proposed FHSC candidates based on SEDs, compact emission, and/or outflow detection-Cha-MM1, Per-bolo 58, L1448 IRS 2E, L1451mm, CB 17 MMS, B1b-N, B1b-S, and Per-bolo 45 (Belloche et al. 2006; Chen et al. 2010; Enoch et al. 2010; Pineda et al. 2011; Chen et al. 2012; Pezzuto et al. 2012; Schnee et al. 2012) -about half have now been confirmed as starless cores, while the other half are most likely very young Class 0 protostars. Only one, L1451-mm, remains a promising FHSC candidate (Pineda et al. 2011; Maureira et al. 2020).

M.J.M. thanks Jan-Martin Winters for assistance and support with the NOEMA data calibration. The authors thank Munan Gong and Kedron Silsbee for useful discussions that helped to improve the discussion of the results. This work is based on observations carried out under project number S20AD [081-20] with the IRAM NOEMA Interferometer [30 m telescope]. IRAM is supported by INSU/CNRS (France), MPG (Germany), and IGN (Spain). S.H.S. thanks the Science, Technology, and Research Scholars (STARS) II Program for its support. This work was partially funded by National Science Foundation award AST-1714710, awarded to HGA.

Software: CASA (McMullin et al. 2007), GILDAS (Pety 2005; Gildas Team 2013), pyspeckit (Ginsburg & Mirocha 2011).

Appendix **Additional Figure**

In Figure 9 we show the integrated intensity map of the NH₃(2,2) emission toward CB17 MMS.



Figure 9. The integrated intensity map of $NH_3(2,2)$. Black contours are drawn at 10%, 30%, 50%, 70%, and 90% of the peak NH₃(2,2) integrated intensity. The peak NH₃ column density (as seen in Figure 2) is marked by the white plus sign. The $N_2D+(3-2)$ peak emission from the SMA observations reported by Chen et al. (2012) is indicated by the fuchsia circle. As we note in Section 4.2.1, this emission peak is closely aligned with the NH₃ column density peak, but is not coincident with any NH₃(2,2) emission peaks. The position of the Class I source CB 17 IRS is marked with a star symbol in the upper right part of the panel. The region of high velocity dispersion, which can be seen in Figure 4, is marked by the Δ symbol. The black oval in the bottom left corner indicates the synthesized beam.

ORCID iDs

María José Maureira https://orcid.org/0000-0002-7026-8163

Héctor G. Arce https://orcid.org/0000-0001-5653-7817 Jaime E. Pineda https://orcid.org/0000-0002-3972-1978 Michael Dunham https://orcid.org/0000-0003-0749-9505 Paola Caselli https://orcid.org/0000-0003-1481-7911 Dominique Segura-Cox https://orcid.org/0000-0003-3172-6763

References

- Adams, F. C., Lada, C. J., & Shu, F. H. 1987, ApJ, 312, 788
- Allen, V., Cordiner, M. A., Adande, G., et al. 2020, arXiv:2010.01151
- Andre, P., Ward-Thompson, D., & Motte, F. 1996, A&A, 314, 625
- Ballesteros-Paredes, J., Klessen, R. S., Mac Low, M. M., & Vazquez-Semadeni, E. 2006, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 63
- Belloche, A., Parise, B., van der Tak, F. F. S., et al. 2006, A&A, 454, L51
- Bergin, E. A., & Tafalla, M. 2007, ARA&A, 45, 339
- Bertoldi, F., & McKee, C. F. 1992, ApJ, 395, 140
- Bonnar, W. B. 1956, MNRAS, 116, 351
- Burkert, A., & Bodenheimer, P. 2000, ApJ, 543, 822
- Busch, L. A., Belloche, A., Cabrit, S., Hennebelle, P., & Commerçon, B. 2020, A, 633, A126
- Caselli, P., Vastel, C., Ceccarelli, C., et al. 2008, A&A, 492, 703
- Chandrasekhar, S., & Wares, G. W. 1949, ApJ, 109, 551
- Chen, C.-Y., Storm, S., Li, Z.-Y., et al. 2019, MNRAS, 490, 527
- Chen, X., Arce, H. G., Dunham, M. M., et al. 2012, ApJ, 751, 89
- Chen, X., Arce, H. G., Zhang, Q., et al. 2010, ApJ, 715, 1344
- Chen, X., Launhardt, R., & Henning, T. 2007, ApJ, 669, 1058
- Crapsi, A., Caselli, P., Walmsley, M. C., & Tafalla, M. 2007, A&A, 470, 221
- Dapp, W. B., & Basu, S. 2009, MNRAS, 395, 1092

- Di Francesco, J., Evans, N. J., Caselli, P., et al. 2006, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 17
- Dunham, M. M., Chen, X., Arce, H. G., et al. 2011, ApJ, 742, 1
- Dunham, M. M., Stutz, A. M., Allen, L. E., et al. 2014, in Protostars and Planets VI, ed. H. Beuther et al. (Tucson, AZ: Univ. Arizona Press), 195 Ebert, R. 1955, ZA, 37, 217
- Enoch, M. L., Lee, J. E., Harvey, P., Dunham, M. M., & Schnee, S. 2010, ApJ, 722, L33
- Friesen, R. K., Di Francesco, J., Shirley, Y. L., & Myers, P. C. 2009, ApJ, 697, 145'
- Friesen, R. K., Pineda, J. E., Rosolowsky, E., et al. 2017, ApJ, 843, 63
- Friesen, R. K., Pon, A., Bourke, T. L., et al. 2018, ApJ, 869, 158
- Fujishiro, K., Tokuda, K., Tachihara, K., et al. 2020, ApJL, 899, L10
- Gaudel, M., Maury, A. J., Belloche, A., et al. 2020, A&A, 637, A92
- Gerin, M., Pety, J., Fuente, A., et al. 2015, A&A, 577, L2
- Gildas Team 2013, GILDAS: Grenoble Image and Line Data Analysis Software, Astrophysics Source Code Library, ascl:1305.010
- Ginsburg, A., & Mirocha, J. 2011, PySpecKit: Python Spectroscopic Toolkit, Astrophysics Source Code Library, ascl:1109.001
- Goodman, A. A., Benson, P. J., Fuller, G. A., & Myers, P. C. 1993, ApJ, 406, 528
- Hirano, N. 2019, ALMA2019: Science Results and CrossFacility Synergies, 90
- Ho, P. T. P., & Townes, C. H. 1983, ARA&A, 21, 239
- Hsieh, C.-H., Arce, H. G., Mardones, D., Kong, S., & Plunkett, A. 2021, ApJ, 908, 92
- Huang, Y.-H., & Hirano, N. 2013, ApJ, 766, 131
- Ivlev, A. V., Silsbee, K., Sipilä, O., & Caselli, P. 2019, ApJ, 884, 176
- Joos, M., Hennebelle, P., & Ciardi, A. 2012, A&A, 543, A128
- José Maureira, M., Arce, H. G., Offner, S. S. R., et al. 2017, ApJ, 849, 89
- Keto, E., & Caselli, P. 2008, ApJ, 683, 238
- Keto, E., & Caselli, P. 2010, MNRAS, 402, 1625
- Keto, E., & Field, G. 2005, ApJ, 635, 1151
- Koumpia, E., Evans, L., Di Francesco, J., van der Tak, F. F. S., & Oudmaijer, R. D. 2020, A&A, 643, A61
- Larson, R. B. 1969, MNRAS, 145, 271
- Launhardt, R., Nutter, D., Ward-Thompson, D., et al. 2010, ApJ, 188, 139
- Lippok, N., Launhardt, R., Semenov, D., et al. 2013, A&A, 560, A41
- Machida, M. N., Inutsuka, S., & Matsumoto, T. 2008, ApJ, 676, 1088
- Machida, M. N., & Matsumoto, T. 2011, MNRAS, 413, 2767

- Mangum, J. G., & Shirley, Y. L. 2015, PASP, 127, 266
- Marcelino, N., Gerin, M., Cernicharo, J., et al. 2018, A&A, 620, A80
- Masunaga, H., Miyama, S. M., & Inutsuka, S. 1998, ApJ, 495, 346
- Maureira, M. J., Arce, H. G., Dunham, M. M., et al. 2017, ApJ, 838, 60
- Maureira, M. J., Arce, H. G., Dunham, M. M., et al. 2020, MNRAS, 499, 4394
- McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, ASP Conf., 376, Astronomical Data Analysis Software and Systems XVI, ed. R. A. Shaw, F. Hill, & D. J. Bell, (San Francisco, CA: ASP), 127
- Pety, J. 2005, in Proc. of Annual Meeting of the French Society of Astronomy and Astrophysics, ed. F. Casoli (Les Ulis: EDP Sciences), 721
- Pezzuto, S., Elia, D., Schisano, E., et al. 2012, A&A, 547, A54
- Pineda, J. E., Arce, H. G., Schnee, S., et al. 2011, ApJ, 743, 201
- Pineda, J. E., Zhao, B., Schmiedeke, A., et al. 2019, ApJ, 882, 103
- Rosolowsky, E. W., Pineda, J. E., Foster, J. B., et al. 2008, ApJS, 175, 509
- Ruoskanen, J., Harju, J., Juvela, M., et al. 2011, A&A, 534, A122
- Saigo, K., & Tomisaka, K. 2006, ApJ, 645, 381
- Sakai, N., Sakai, T., Hirota, T., & Yamamoto, S. 2010, ApJ, 722, 1633
- Schmalzl, M., Launhardt, R., Stutz, A. M., et al. 2014, A&A, 569, A7
- Schnee, S., Di Francesco, J., Enoch, M., et al. 2012, ApJ, 745, 18
- Seo, Y. M., Shirley, Y. L., Goldsmith, P., et al. 2015, ApJ, 805, 185
- Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23
- Stephens, I. W., Dunham, M. M., Myers, P. C., et al. 2018, ApJS, 237, 22
- Swift, J. J., Welch, W. J., & Di Francesco, J. 2005, ApJ, 620, 823
- Tafalla, M., Myers, P. C., Caselli, P., Walmsley, C. M., & Comito, C. 2002, ApJ, 569, 815
- Tanner, J. D., & Arce, H. G. 2011, ApJ, 726, 40
- Tomida, K., Tomisaka, K., Matsumoto, T., et al. 2010, ApJ, 714, L58
- Väisälä, M. S., Harju, J., Mantere, M. J., et al. 2014, A&A, 564, A99
- Ward-Thompson, D., Andre, P., Crutcher, R., et al. 2006, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 33
- Ward-Thompson, D., Motte, F., & Andre, P. 1999, MNRAS, 305, 143
- Ward-Thompson, D., Scott, P. F., Hills, R. E., & Andre, P. 1994, MNRAS, 268, 276
- Young, A. K., Bate, M. R., Harries, T. J., & Acreman, D. M. 2019, MNRAS, 487, 2853
- Young, A. K., Bate, M. R., Mowat, C. F., Hatchell, J., & Harries, T. J. 2018, MNRAS, 474, 800