SPITZER AND HEINRICH HERTZ TELESCOPE OBSERVATIONS OF STARLESS CORES: MASSES AND ENVIRONMENTS

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Received 2009 August 27; accepted 2009 October 26; published 2009 November 18

ABSTRACT

We present Spitzer observations of a sample of 12 starless cores selected to have prominent 24 μm shadows. The Spitzer images show 8 μm and 24 μm shadows and in some cases 70 μm shadows; these spatially resolved absorption features trace the densest regions of the cores. We have carried out a 12CO (2–1) and 13CO (2–1) mapping survey of these cores with the Heinrich Hertz Telescope (HHT). We use the shadow features to derive optical depth maps. We derive molecular masses for the cores and the surrounding environment; we find that the 24 μm shadow masses are always greater than or equal to the molecular masses derived in the same region, a discrepancy likely caused by CO freezeout onto dust grains. We combine this sample with two additional cores that we studied previously to bring the total sample to 14 cores. Using a simple Jeans mass criterion, we find that ~2/3 of the cores selected to have prominent 24 μm shadows are collapsing or near collapse, a result that is supported by millimeter line observations. Of this subset at least half have indications of 70 μm shadows. All cores observed to produce absorption features at 70 μm are close to collapse. We conclude that 24 μm shadows, and even more so the 70 μm ones, are useful markers of cloud cores that are approaching collapse.

Key words: dust, extinction – ISM: clouds – ISM: globules – ISM: molecules – stars: formation

1. INTRODUCTION

Stars are born in cold cloud cores (e.g., Bergin & Tafalla 2007), where gas and dust are compressed to high enough densities to cause the core to start collapsing. One of the most critical questions in astronomy is what the physical conditions for core formation and collapse are. Therefore, observations of cores in the rare stage during, or just prior to, collapse are critical to constrain theories of the very earliest stages of star formation (e.g., Shu et al. 1987; Ballesteros-Paredes et al. 2003; Myers 2005). The initial process of collapse, or the transition from a stable core to a core with an embedded protostar, happens rapidly (Haghiashi 1966); additionally, the cores are necessarily dense and cold. These conditions pose significant observational challenges to identify cores close to collapse. Because of the temperature ranges involved, ~10 K (e.g., Lemme et al. 1996; Caselli et al. 1999; Hotzel et al. 2002), and high densities, ~10^5 cm^{-3} (e.g., Bacmann et al. 2000), cold cloud cores can best be observed at far-infrared, submillimeter, and millimeter wavelengths (e.g., Stutz et al. 2009). Such observations of dense cores show that most of them are close to equilibrium and not collapsing (e.g., Lada et al. 2008). Furthermore, if the cores are not supported by thermal and turbulent pressure alone, then a modest magnetic field can halt collapse (e.g., Kandori et al. 2005; Stutz et al. 2007; Alves et al. 2008).

Millimeter line observations are the traditional way to search for collapsing cores (e.g., Walker et al. 1986); however, there are ambiguities in the interpretation of such measurements (e.g., Walker et al. 1988; Menten et al. 1987; Mundy et al. 1990; Narayanan et al. 1998). Here we use mid-infrared shadows as an alternative observational approach to the study of starless cores, one that does not depend on the interpretation of millimeter line profiles and how these profiles relate to the underlying velocity field of the core material. Additionally, our method is sensitive to higher column densities than traditional studies of starless cores by background star extinction, usually limited to A_V <= 30 mag (e.g., Alves et al. 2001; Kandori et al. 2005).

Cores that are isolated from regions of massive star formation are very useful to understand the initial stages of collapse into stars. These cores are free from complicating factors, e.g., massive core fragmentation, feed-back from high-mass stars, and protostellar outflows (e.g., Lada & Lada 2003; de Wit et al. 2005; Fallscheer et al. 2009), to name a few, that can have large effects on a study aimed at understanding how individual low-mass stars form. We present a sample of 12 relatively isolated cores that were selected from Spitzer MIPS observations of Bok globules and other star-forming regions to have prominent 24 μm shadows, spatially resolved absorption features caused by the dense core material viewed in absorption against the interstellar radiation field. We also include two previously studied cores, CB190 (Stutz et al. 2007) and L429 (Stutz et al. 2009), for a final sample of 14 cores. Such objects with 24 μm shadows always show a counterpart 8 μm shadow, analogous to the IR absorption features produced by more distant and massive structures termed infrared dark clouds (IRDCs; e.g., Perault et al. 1996; Butler & Tan 2009; Peretto & Fuller 2009; Lee et al. 2009) and the Infrared Space Observatory (ISO) 7 μm absorption features studied by Bacmann et al. (2000; see also J. Tobin et al. 2009, in preparation). We also present Heinrich Hertz Telescope (HHT) 12CO (2–1) and 13CO (2–1) on-the-fly (OTF) maps of regions ~10' on a side surrounding each core.

Our search method is efficient at identifying cores that are near collapse. In Section 2, we describe the observations and data processing; in Section 3, we derive optical depth maps...
from the 8 μm and 24 μm images; in Section 4, we present our mass measurements and we describe the stability analysis that we apply to the sample of cores; and finally, in Section 5, we summarize our main conclusions.

2. OBSERVATIONS AND PROCESSING

2.1. Spitzer IRAC and MIPS Data

The 12 cores presented here were selected from two observing programs: Spitzer GTO program ID 53 and GO program ID 30384. Core names, MIPS and IRAC AOR numbers, and corresponding program IDs are listed in Table 1. The IRAC data consist of observations in all four channels from programs 139 (PI: N. Evans), 94 (PI: C. Lawrence), and 20386 (PI: P. Myers). The frames were processed using the Spitzer Science Center (SSC) IRAC Pipeline v14.0, and mosaics were created from the basic calibrated data (BCD) frames using a custom IDL program; see Gutermuth et al. (2008) for details. The MIPS observations at 24, 70, and 160 μm are from programs 53 (PI: G. Rieke) and 30384 (PI: T. Bourke). All observations were carried out in a scan map mode and were reduced using the Data Analysis Tool (DAT; Gordon et al. 2005). These data were processed according to steps outlined in Stutz et al. (2007); please refer to that publication for further details. The data for each core are shown in Figures 1–12.

2.2. 12CO (2–1) and 13CO (2–1) Data

These cores were mapped in the J = 2–1 transitions of 12CO (230.538 GHz) and 13CO (220.399 GHz) with the 10 m diameter HHT on Mt. Graham, AZ, USA. Observations taken in 2007 (CB27 and CB44) were obtained using a receiver that was a dual polarization superconductor–insulator–superconductor mixer system operating in double-sideband mode with a 4–6 GHz IF band. The observations taken after 2007 were obtained using a prototype 1.3 mm ALMA sideband separating receiver with a 4–6 GHz IF band. The 12CO (2–1) line was placed in the upper sideband and the 13CO (2–1) one in the lower sideband. The spectrometers were filter banks with 128 channels of 250 KHz width and separation. At the observed frequencies the spectral resolution was ~0.3 km s⁻¹, the bandwidth was ~40.0 km s⁻¹, and the angular resolution of the telescope was 32″ (FWHM). The cores were mapped with OTF scanning in R.A. at 10'' s⁻¹, with row spacing of 10'' in declination. System temperatures were calibrated by the standard ambient temperature load method (Kutner & Ulich 1981) after every other row of the map grid. Atmospheric conditions were generally clear and stable, and the system temperatures were nearly constant throughout the maps. Data for each CO isotopologues were processed with the CLASS reduction package (from the Observatoire de Grenoble Astrophysics Group), by removing a linear baseline and convolving the data to a square grid with 10'' grid spacing (equal to one-third the telescope beamwidth). The intensity scales for the two polarizations were determined from observations of standard sources made just before the OTF maps. The gridded spectral data cubes were processed with the MIRiad software package (Sault et al. 1995) for further analysis. For each sideband, the two polarizations were averaged together yielding the map RMS noise levels listed in Table 2; also listed are the map center coordinates, dates of observation, sizes, system temperatures, and velocity ranges which include significant emission. The 12CO- and 13CO-integrated intensity images, integrated over the velocity ranges listed in Table 2, are shown in Figures 13–15; these images are centered on the 24 μm shadow coordinates.

3. ANALYSIS

3.1. Optical Depth Maps

In this section, we calculate the 24 μm and 8 μm optical depths for the shadow features seen in Figures 1–12. We assume that the cores are optically thin and that there is no foreground emission originating from the surface layers. We apply an analysis analogous to that presented in Stutz et al. (2007) at 24 μm and Stutz et al. (2008b) at 8 μm; however, we update the analysis presented in that work with a more robust calculation of the unobscured background flux level (f₀ in what follows).

3.1.1. 24 μm Optical Depth Calculation

Under the above assumptions, the optical depth at 24 μm is

\[ \tau_{24} = -\ln\left(\frac{f' - f_{\text{DC}}}{f_0 - f_{\text{DC}}}\right). \]
Here $f_{DC}$ is the contribution to the image flux level of all foreground sources, such as zodiacal emission and instrumental background; $f'$ and $f'_0$ are the shadow flux and the intrinsic, unobscured flux, respectively. In what follows, $f_0$ and $f'_0$ indicate the DC-subtracted values of the shadow fluxes: $f = f' - f_{DC}$ and $f_0 = f'_0 - f_{DC}$. The contribution of $f_{DC}$ to the overall image flux level is assumed to be constant over image areas large compared to the size of the shadow, while $f_0$ is determined in the region immediately adjacent to the shadow. Further details on the determination of these two quantities are provided in the following discussion. However, before proceeding, we note that the shadow depth, or contrast, in the absence of foreground emission from the surface of the shadow itself, is the result of the depth of the absorption feature relative to the quantity $(f'_0 - f_{DC})$; a stronger background allows for robust sensitivity to larger $\tau$. Furthermore, an overestimate of $f_{DC}$ will artificially boost the shadow contrast and cause an overestimate of $\tau$ and all dependent quantities. Rather than following the procedure applied in Stutz et al. (2009), where the darkest region of the L429 shadow was used to measure $f_{DC}$, the approach implemented here takes advantage of dark regions in the Spitzer images which are not associated with any absorption features. These regions provide an independent estimate of the foreground emission; furthermore, when shadow pixels are darker than or have a lower value than the $f_{DC}$ level, we exclude them from our analysis because they are most likely not sensitive to the total column of material in that pixel, i.e., they have become saturated.

**Image DC level ($f_{DC}$) determination.** To measure $f_{DC}$, we select regions in the 24 $\mu$m image with no diffuse emission. These regions also have little to no detected emission at 70 and 160 $\mu$m. As a further check on the cleanliness of the background estimate, when possible we select the background region to overlap partially with, or be adjacent to, $^{12}$CO and $^{13}$CO map areas that are free from molecular line emission. Additionally, we avoid the areas near the edges of the images due to poor signal to noise and sparse coverage. The background region box size is 5' on a side, corresponding to $\sim$59,000 mosaic pixels, which are subsampled by $2 \times 2$ relative to the physical pixels. We set $f_{DC}$ equal to the 0.5 percentile pixel value; as discussed above, this low value is conservative because a higher value may overestimate the shadow contrast relative to $f'_0$. The error in $f_{DC}$, $\sigma_{DC}$, is determined by simulating $\sim$59,000 pixels drawn from a normal distribution with the same mean and standard deviation as the background region; the 0.5 percentile pixel value is stored and the process is repeated $10^4$ times. The standard deviation of the resulting distribution values is our estimate of $\sigma_{DC}$ (Stutz et al. 2007). The pixel error map for the background subtracted images is then calculated using the DAT (Gordon et al. 2005) pixel error map, multiplied by a factor of 2 to take into account pixel-to-pixel correlations due to the subsampling, with $\sigma_{DC}$ added in quadrature.
Figure 2. Same as Figure 1.

Figure 3. Same as Figure 1.
Figure 4. Same as Figure 1.

Figure 5. Same as Figure 1.
Figure 6. Same as Figure 1.

Figure 7. Same as Figure 1.
Figure 8. Same as Figure 1.

Figure 9. Same as Figure 1.
Figure 10. Same as Figure 1.

Figure 11. Same as Figure 1.
Unobscured flux \((f_0)\) determination. We apply iterative Gaussian fitting to the image pixel value distributions to estimate \(f_0\), the local, unobscured flux near the shadow, similar to the method developed by Stutz et al. (2008a) to reconstruct and analyze the noise properties in deep Hubble Space Telescope ACS images. In summary, we adjust the upper cutoff of the pixel value distribution so that the Gaussian fit is least affected by the non-Gaussian tail of the high pixel value distribution. This is done by finding the upper pixel value cutoff that has the narrowest Gaussian width. This fitting method is constructed to minimize the effects of sources or shadows on the estimate of \(f_0\). We proceed by constructing a pixel value histogram for all pixels within \(r_0\) of the shadow using a bin size of 0.4 µJy arcsec\(^{-2}\). We then clip the distribution by excluding all bins with values below the mean pixel value in a 30′′ radius aperture centered on the shadow. The shadow pixel value distribution in this region is indicated as a gray histogram in Figures 16–19; the mean value of the shadow flux is indicated with a solid line. Excluding these bins avoids a possible bias of the best-fit mean pixel value toward lower values. Next we fit the histogram data to an unweighted Gaussian model, using standard IDL packages, and excluding all bins with values greater than the maximum bin plus 1. We proceed by constructing a pixel value histogram for all pixels within \(r_0\) of the shadow using a bin size of 0.4 µJy arcsec\(^{-2}\). We then clip the distribution by excluding all bins with values below the mean pixel value in a 30′′ radius aperture centered on the shadow. The shadow pixel value distribution in this region is indicated as a gray histogram in Figures 16–19; the mean value of the shadow flux is indicated with a solid line. Excluding these bins avoids a possible bias of the best-fit mean pixel value toward lower values. Next we fit the histogram data to an unweighted Gaussian model, using standard IDL packages, and excluding all bins with values greater than the maximum bin plus 1. We repeat this fitting procedure as we include successively higher bin values one at a time. The resulting best-fit Gaussian width \((\sigma)\) values are shown in Figures 16–19 in the lower-left panel for each object, plotted as a function of the maximum bin value included in the fit. The solid line indicates the minimum \(\sigma\) from the distribution of Gaussian widths; the mean value of the fit corresponding to the minimum value of \(\sigma\) is the adopted value of \(f_0\). These two parameters are listed in the figure.

To determine the effect the choice of pixel histogram radius \((r_0)\) has on our derived value of \(f_0\), we repeat this procedure over a range of \(r_0\) values from \(r_0 = 60′′\) to 300′′ in 20′′ steps; the resulting values of \(f_0\) and \(\sigma\) are shown on the right-hand side panel of Figures 16–19. In most cases, the \(f_0\) profiles flatten out by \(r_0 = 240′′\), as indicated by the dashed line. This value is used for all objects except CB42, which lies near the edge of the MIPS mosaic; since the \(f_0\) profile for CB42 appears to flatten out by 140′′, the largest value of \(r_0\) that we test for this core, we assume this value is valid. In the cases of CB26 and CB27, we do not measure as abrupt a flattening. For these cores, we still use \(r_0 = 240′′\) as a conservative estimate; larger values of \(r_0\) may overestimate \(f_0\) and the derived optical depths.

Furthermore, ideally we calculate \(f_0\) as close as possible to the shadow features; as the distance from the core is increased, other effects can bias the determination of \(f_0\), such as diffuse emission not associated with the core. We estimate the uncertainty in \(f_0\) to be \(\sigma(f_0) = 0.02 \times f_0\). The Gaussian error in the mean gives a signal-to-noise ratio \((S/N)\) for \(f_0\) of \(\gtrsim 230\) for all cores; we consider this S/N to be optimistic.

Using our calculated value of \(f_0\) and the background subtracted image, we calculate \(\tau_{24}\) in each pixel and the associated error \(\sigma(\tau_{24})\), using standard propagation of errors, including \(\sigma_{\text{DC}}\) and \(\sigma(f_0)\). The pixel-to-pixel correlations are significant, and we do not take this into account in the \(\tau\) pixel error maps; consequently, the error maps underestimate the true errors, and we do not use them in the subsequent analysis. In the cases where the values of \(\tau\) near the center of the cores are negative, causing \(\tau_{24}\) to diverge, we set the value of \(\tau_{24}\) equal to the mean \(\langle \tau_{24}\rangle\) in an aperture with radius 10″ or larger, depending on the size of the divergent region, centered on the core. For most (8/12) cores, the number of divergent pixels is less than 90, corresponding to an effective circular area with radius smaller than 6.5″; for objects CB130 and CB180 the divergent region has an effective...
radius of \( \sim 7.5 \), for CB44 the region has a radius of about 25\text{''}, and for L1552 the region’s radius is about 20\text{''}. This approach is conservative when analyzing core stability because it effectively underestimates the 24\,\mu m shadow masses. Furthermore, an alternative approach is to estimate \( f_{\text{DC}} \) as a fraction of the shadow pixel values; while this method would circumvent the divergent pixel issue, it would yield larger core masses, potentially biasing our collapse analysis. The divergent pixels found with our method are flagged and accounted for in the subsequent analysis. The 24\,\mu m \( r \) pixel maps are shown in the left column of Figures 13–15.

### 3.1.2. 8\,\mu m Optical Depth Calculation

We apply the same techniques described above for the 24\,\mu m images to the 8\,\mu m images, with the exceptions described here.\(^7\) The results are illustrated in Figures 20–23. For the \( f_{\text{DC}} \) determination, it is not possible to use the same regions as those used for the 24\,\mu m images because of the limited coverage of the 8\,\mu m images; therefore, we select new regions that are near the 24\,\mu m regions when possible. In all cases, the 8\,\mu m \( f_{\text{DC}} \) regions are selected to include the darkest regions of the image; we set \( f_{\text{DC}} \) equal to the 0.1 percentile. The background region box size is 5\text{'} on a side, corresponding to \( \sim 60,000 \) pixels at the plate scale of the IRAC images (1\text{''}22 pix\text{''}^{-1}). The 8\,\mu m error is assumed to be 2\% of the pixel flux value; the background error is estimated as described above. These two quantities added in quadrature make the background–subtracted pixel error map.

\(^7\) There is no IRAC coverage of source CB42.

The method used to determine \( f_{0} \) is identical to that described above, the only exception being that for some objects (CB23, L1544, L492, and L694-2) the maximum radius for which we can measure the pixel value distribution is limited by the size of the images. For these four objects, we chose the largest radius measurement of \( f_{0} \) for which over 50\% of the area of the annulus contains image pixels. For these cores, the maximum radius is \( r_{0} = 240\text{''} \) for CB230, and \( r_{0} = 200\text{''} \) for the rest. For cores with sufficiently large images, we observe a flattening of the \( f_{0} \) profiles at a radius of \( r_{0} = 260\text{''} \); the adopted values for \( r_{0} \) are indicated as dashed lines in the right column of Figures 20–23. In the cases of cores CB23 and CB27, we do not observe a flattening; therefore, the \( \tau_{s} \) maps for these sources may be less reliable.

As described above for the 24\,\mu m images, we use our measurements of \( f_{0} \), \( f' \), and \( f_{\text{DC}} \) measured from the 8\,\mu m images to calculate

\[
\tau_{s} = -\ln \left( \frac{f' - f_{\text{DC}}}{f_{0} - f_{\text{DC}}} \right)
\]

in each pixel; we also calculate \( \sigma_{\tau_{s}} \) with standard propagation of errors and including \( \sigma_{f_{0}} \) and \( \sigma(f_{0}) \), where \( \sigma(f_{0}) = 0.02 \times f_{0} \). Divergent pixels are assigned a value according to the procedure outlined above, are flagged, and are accounted for in subsequent analysis.

We detect 3.6\,\mu m emission above the sky level in a large fraction of our cores (TMC1-1C, CB23, CB26, CB27, L1544, L1552, and L694-2), and marginally in L492, CB130, and CB180. This emission is spatially coincident with the shadows, and similar in extent to the 160\,\mu m emission. The lack of any
significant 8 μm aromatic feature indicates that this emission is likely to be caused by the surface layer of dust grains scattering the interstellar radiation field, analogous to the near-IR emission studied by Lehtinen & Mattila (1996). Such near-IR emission has been used to study interstellar clouds (e.g., Foster & Goodman 2006; Padoan et al. 2006; Nakajima et al. 2008). Juvela et al. (2008) show that when using J, H, and K_s imaging this technique is sensitive to densities of 1 mag \( \leq A_V \leq 15 \) mag. Including the 3.6 μm emission might increase the densities accessible to this technique, as well as providing a high-spatial

\[ \text{Figure 13. } \tau_{24} \text{ maps and } ^{12}\text{CO- and } ^{13}\text{CO-integrated intensity maps, over the velocity ranges listed in Table 2. The black circle (1.5 radius) indicates the area used to calculate the 24 μm shadow masses; the white circle indicates that used to calculate the molecular masses. The } ^{13}\text{CO contours levels are 0.4, 0.6, 0.8 times the maximum value indicated in the } ^{13}\text{CO color bar.} \]
resolution shadow-independent extinction estimator. We note that for the cores L1544, CB44, and L694-2, the emission shows a limb-brightening geometry at 3.6 μm, where the center of the shadow region appears darker than the surrounding region.

The 8 μm shadow determinations provide a test of the validity of those at 24 μm. In all cases where a good comparison is possible, the agreement is satisfactory if we take the optical depths at the two wavelengths to be approximately equal, \( \tau_{24}/\tau_{8} = 1.0 \pm 0.1 \) (see also Flaherty et al. 2007; Chapman et al. 2009; Chapman & Mundy 2009). Additional details will be provided in a future publication.

### 3.2. Distance Measures

Here we make some remarks on our adopted distances, which are summarized in Table 3.

**TMC1-1C, CB23, CB26, CB27, L1544, L1552.** Kenyon et al. (1994) derive a distance to the northern portion Taurus of 140 ± 10 pc based on extinction of background stars. This distance is roughly consistent with recent determinations using trigonometric parallax with the Very Long Baseline Army (VLBA; Torres et al. 2009).

**CB42.** We find no distance estimate for this source in the literature. In the direction of CB42, the extent of the local bubble is \( \sim 100 \) pc (Lallement et al. 2003); we adopt a distance of 100 pc, a conservative lower limit.

**CB44.** Hilton & Lahulla (1995) list the Bok & McCarthy (1974) assumed distance of 400 pc. They also list the Tomita et al. (1979) estimate of 300 pc, and the Arquilla & Goldsmith (1986) distance estimate of 400–600 pc. We adopt a distance of 400 pc.
L492, CB130. Straizys et al. (2003) investigate the distance dependence of the interstellar extinction in the direction of the Aquila Rift. These authors find that the distance is 225 ± 55 pc to the front edge and that the cloud has a depth of about 80 pc. Because these cores are viewed in absorption, they are unlikely to be located behind much cloud material; therefore we adopt 225 pc as the distance to these cores.

CB180. Hilton & Lahulla (1995) list the Bok & McCarthy (1974) assumed distance of 400 pc. Bok & McCarthy (1974) do not elaborate on their adopted distances. This object is near the Scutum association. We adopt 400 pc for the distance to this core.

L694-2. Kawamura et al. (2001) derive a distance of 230 ± 30 pc using star counts.

4. DISCUSSION

4.1. Interpretation of Collapsing Cores

The stability of a cloud core is usually deduced through observations of millimeter wave molecular emission lines (e.g., Gregersen et al. 1997; Mardones et al. 1997; Gregersen & Evans 2000; Crapsi et al. 2005; Williams et al. 2006; Sohn et al. 2007), but the dynamical state of these lines can be affected by rotation, turbulence, optical depth, and other effects that
can hide or mimic the indicators for collapse. We use infrared shadows, together with millimeter wave spectroscopy, as an alternative, complementary, and reliable indicator of impending collapse (e.g., Stutz et al. 2007, 2009). These observational techniques can be used to estimate the masses and dynamical states of the cores. Conventionally, collapse is identified by fitting such observations to Bonnor–Ebert model profiles which assume spherical symmetry (e.g., Evans et al. 2001; Ballesteros-Paredes et al. 2003; Shirley et al. 2005). However, as shown in Figures 1–12, few of our objects appear symmetric on the plane of the sky, calling the applicability of this approach into question.

Instead, we have probed the collapse state of these cores on the basis of a simple Jeans mass calculation. In what follows, we determine 24 μm core masses and sizes.
starless cores), we derive a Jeans mass for each core:

$$M_J = \left( \frac{5kT}{G\mu_pm_H} \right)^{3/2} R^{3/2} M^{-1/2},$$

(2)

where $M$ is the 24 $\mu$m core mass ($M_{24}^{\text{core}}$ in Table 4), $R$ is the effective radius of the core ($R_{24}^{\text{core}}$ in Table 4), measured from the 24 $\mu$m image, and we have assumed that the mean molecular mass per free particle $\mu_p$ is equal to 2.4. The sizes of the cores are derived from the area in which we detected the 24 $\mu$m shadows (see Section 4.2.1). We note that assuming a temperature of 8 K or 12 K for these cores cause a $\sim 30\%$ change in the calculated Jeans mass. The distance dependence of the Jeans mass is $D^{3/2}$.

In the following analysis (see Tables 4 and 5), we compare shadow masses, with a distance dependence of $D^2$, to the Jeans mass. We caution that the ratio of the 24 $\mu$m masses to the Jeans mass has a steep distance dependence of $D^{3/2}$. This Jeans mass analysis avoids possible biases introduced by imposing more stringent geometrical assumptions in the core analysis. However, it only takes thermal support into account.

Under more realistic conditions, turbulence might also provide support against collapse. From Hotzel et al. (2002), the energy contributed by turbulence to the support of the cloud is

$$E_{\text{turb}} = \frac{\mu_p}{\text{AMU}} \left( \frac{\Delta V^2}{\Delta V_{\text{th}}^2} - 1 \right) E_{\text{th}},$$

(3)
where AMU is the atomic mass number of the species from which we measure the observed line width $\Delta V$, and $\Delta V_{\text{th}}$ is the expected thermal line width for that species, assuming a temperature of 10 K. To estimate possible contributions of turbulence to the support in the cores, we use previously measured $\Delta V$ values for high-density tracers from the literature when available (e.g., Lee et al. 2004; Crapsi et al. 2005; Sohn et al. 2007). When such measurements are not available, we use other line widths as estimators, noting that lower density tracers will overestimate the line width and therefore the contribution from turbulence to the support. Often, the turbulent support is much less than the thermal support and hence can be ignored in considering the stability against collapse. In the cases where turbulent support is potentially significant, we attempt to assess its contribution relative to the Jeans mass and magnetic field required for stability.

Magnetic fields may also contribute to the support. The inferred magnetic field strengths in cores range from $\lesssim 15 \mu G$ to $\sim 160 \mu G$ (Bergin & Tafalla 2007). From Stahler & Palla (2005), given a magnetic field strength $B$ and a cloud radius $R$, the mass that can be supported is

$$
M = 70 M_\odot \left( \frac{B}{10 \mu G} \right) \left( \frac{R}{1 \text{pc}} \right)^2.
$$

Using this relation, and a measurement of the core mass and size, we estimate the minimum magnetic field strength required...
to support the core. If the cores require field strengths above \( \sim 160 \, \mu \text{G} \), we consider it unlikely that the core is supported by a magnetic field. Furthermore, if the minimum magnetic field derived in this fashion is reasonable, but the core mass is significantly greater than the Jeans mass (by a factor \( \gtrsim 2 \)), we consider it unlikely that the core is stable against collapse. Our understanding of the magnetic field strengths in cores does not allow for strong constraints. However, this qualitative assessment gives a useful estimate of the possible role of the magnetic field.

Finally, rotation can also contribute to the support in cores. In Column 9 of Table 4, we list the rotational velocity required to fully support our sample of cores. Future high-resolution observations will determine the extent of the role of rotation in these cores. In the analysis that follows, we interpret the line widths as caused only by turbulent and thermal motions; more realistically, turbulent motions on large scales can be confused with rotation (Burkert & Bodenheimer 2000). Furthermore, irregular infall, or fragments, can mimic turbulence; inspection of Figures 1–12 reveals that a significant fraction of cores have geometries which are not regular, reminiscent of structures seen in self-gravitating two-dimensional (Burkert & Hartmann 2004) and 3D (Heitsch et al. 2008) simulations. Because of these irregular shapes, we have attempted to minimize geometrical assumptions in the analysis of our sample of cores, as discussed above; however, the stability arguments applied here inherently still assume approximate sphericity.
4.2. Mass Measurements

We describe the method used to calculate masses in the cores using the 24 μm shadows, and in the regions surrounding the cores using the 12CO and 13CO data. The results are summarized in Table 4. We also list the Jean mass for each core, assuming all the cores are at a temperature of 10 K and that the core density is described by the shadow mass \( M_{\text{core}}^{24} \) and the effective radius \( R_{\text{eff}}^{\text{core}} \); see below.

4.2.1. Core Masses: Shadow Masses

We calculate masses in the cores applying a similar method as that of Stutz et al. (2007). Core shadow masses, assumed distances, and effective areas are listed in Table 4. In these calculations, we use the 24 μm images and 8 μm dust opacities from Ossenkopf & Henning (1994): \( \kappa_8 = 1.21 \times 10^3 \) cm² gm⁻¹ for thick ice mantles at a density of \( 10^6 \) cm⁻³. This choice of dust opacity is motivated by our analysis in Section 3.1.2, where we
find that $r_{24/8} = \tau_{24}/\tau_8 = 1.0 \pm 0.1$. This choice of Ossenkopf & Henning (1994) dust model has a ratio of $\tau_{24}/\tau_8 = 1.1$, close to our measured value.

The mass in a region with an optical depth $\tau_{24}$ is

$$M_{24} = \frac{\Omega D^2}{\kappa} \alpha \times \tau_{24},$$

where $\Omega$ is the solid angle subtended by the region, $D$ is the distance, $\alpha$ ( = 100) is the assumed gas-to-dust ratio, and $\kappa$ is the assumed dust opacity. We measure the mean flux in an aperture of 1.5 radius, excluding all pixels that have $\tau_{24} \leq 0.0$ in the maps described above. Using the measurements of $f_{DC}$ and $f_0$ and the mean flux per pixel in the shadow, we then calculate the mean $\tau_{24}$ per pixel. Using Equation (2) and the number of pixels ($\Omega = N_{\text{pix}} \times \text{pixel scale}^2$) included in the mean flux calculation, we calculate a shadow mass. We use the value of $\Omega$ in subsequent analysis as a measure of the effective core sizes, where $R_{\text{core}}^{\text{eff}} = \sqrt{\Omega/\pi}$. The uncertainties in the masses measured in this fashion are of order 15%, without including distance uncertainties. We cross-check these masses by calculating core masses directly from the $\tau$-pixel maps. We find that the two sets of masses agree well; however, the mass errors are extremely low for the $\tau$-pixel map masses. We attribute this discrepancy to highly correlated errors, as discussed in Section 3.1, and disregard the small uncertainties in favor of the ~15% errors. The agreement between the two masses indicates that the method we use to estimate $f_{DC}$ (see Section 3.1.1) does not have a large effect on the calculated core masses, even accounting for divergent pixel values.

4.2.2. Envelope Masses: Molecular Masses

We use the $^{12}$CO (2–1) and $^{13}$CO (2–1) maps to derive the total column density of hydrogen, $N(\text{H})$ in the area surrounding the cores. As listed in Table 2 and shown in Figures 13–15, the CO maps cover areas that are much larger than the 24 $\mu$m shadow area. The effect of CO freezeout onto dust grains is severe
(Bacmann et al. 2002; Tafalla et al. 2002); therefore, in the area where we observe 24 μm shadows, the column densities derived from CO observations are likely to be underestimated. However, in the regions outside of the shadows, where the densities are much lower than in the cores themselves, the CO-derived N(H) column should have a much higher degree of fidelity to the true column in the observed region. Therefore, we use the CO maps to derive masses of the larger environment surrounding the cores, observed as 24 μm shadows.8

To derive masses from the CO data, we follow a similar procedure as Povich et al. (2009, see also Kang et al. 2009), and we apply the escape probability radiative transfer model for CO from Kulesa et al. (2005). The 12CO (2–1) and 13CO (2–1) data cubes are used to derive the column of CO in each 10″ × 10″ map pixel, assuming an isotope ratio of 12CO/13CO = 50. The model uses the 12CO and 13CO observations to solve for the column density of CO, N(CO), over a model grid of temperatures, densities, and column densities; given an initial guess for the density this procedure then fits simultaneously for the temperature and column density in each map pixel. The mass calculation also incorporates the van Dishoeck & Black (1988) PDR photodissociation model of CO, intended to account for the effect of the far-UV field, G0, incident on the cores. The final CO column that we calculate therefore should include the

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8 The 13CO emission sometimes appears to be bright along an edge of the shadow region (seen most clearly in L1552 and CB44) and in one case we clearly observe a deficit of emission in the region coincident with the shadow (L1544). These characteristics are likely caused by the freezeout of CO on to dust grains, as well as by a non-uniform density and temperature structure in the cores.
effect of UV dissociation; if the UV field is not strong, the application of this model can cause an overestimate of the column densities.

After calculating the total (atomic plus molecular) column \( N(H) \) in each pixel, we derive masses using the distances collected from the literature (listed in Table 3 and discussed in Section 3.2). We calculate total cloud masses by integrating the \( N(H) \) pixel distribution over a 4′ radius aperture centered on the shadow, indicated as \( M_{\text{CO,4}} \) in Table 4. The left column of Figures 24–27 show the \( ^{13}\text{CO} \)-integrated intensity maps.
In their study, this shadow is designated as TMC1-1C 3C, with a measured mass of 10 ± 0.9 M⊙. Kauffmann et al. (2008) use the MAMBO bolometer to detect CO emission; the line profiles appear to be chemically evolved. These results are consistent with our conclusion that the core is probably stable.

CB23. Our analysis shows that the 24 μm shadow mass exceeds the Jeans mass by ~25%, indicating that this core is only marginally unstable, if only thermal support is considered. The measured N2H+ line widths (see below) are narrow and indicate that the turbulent contribution to the support is only of order ~30% (Hotzel et al. 2002). A magnetic field of ~120 μG would be sufficient to support the 24 μm mass and to halt collapse (Stahler & Palla 2005). A magnetic field of this level is on the high side of the range of field strengths measured for other cores (Bergin & Tafalla 2007), but remains plausible. Park et al. (2004) observe 12CO and 13CO emission; the line profiles appear Gaussian. Lee et al. (2004) observe CS (3–2) and DCO+ (2–1); Lee et al. (1999) observe CS (2–1) and N2H+ (1–0). A blue asymmetry is observed in CS (2–1); a small amount of a blue asymmetry is seen in CS (3–2) and DCO+ (2–1), although it falls below the Lee et al. (2004) threshold to be classified as a collapse candidate. Crapsi et al. (2005) measure the N2H+ (1–0) and N2D+ (2–1) line widths to be 0.17 and 0.23 km s⁻¹, respectively, but do not classify this source as chemically or kinematically evolved. Sohn et al. (2007) observe an infall asymmetry in the HCN (1–0) line profiles of at least two of the three hyperfine components, and possibly in all three. We note that the Crapsi et al. (2005) and the Sohn et al. (2007) observations were taken at locations separated by ~60°; however, both locations are well within the shadow feature. Taken with our results, these observations indicate that this core is approaching collapse.

CB26. Our analysis indicates that this core has a mass that exceeds the Jeans criterion by a factor of ~3. The field required to support the mass of CB26 is of order 200 μG, much larger than the upper limit of 74 μG set by Henning et al. (2001) in a nearby region of CB26. The HCN (1–0) line widths of ~0.6–0.9 km s⁻¹ measured by Turner et al. (1997) indicate that the turbulent support is of order ~2–4 times the thermal support; however, Turner et al. (1997) do not show their HCN emission (gray scale) with the calculated N(H) column density contours overlaid; we find good spatial agreement between the two. The right column of Figures 24–27 shows the 12CO and 13CO overlaid; we find good spatial agreement between the two.

### Table 4

| Source      | M^{core}_24 | M^{core}_13CO | M^{core}_CO | R^{core}_c | R^{core}_e | R^{core}_f | M^{core}_13CO |
|-------------|-------------|---------------|-------------|------------|------------|------------|---------------|
| TMC1-1C     | 1.6         | 0.9           | 7.1         | 1.4        | 0.06       | 1.8        | 2.7           |
| CB23        | 2.5         | 0.7           | 4.9         | 1.3        | 0.05       | 3.8        | 2.0           |
| CB26        | 5.0         | 0.8           | 5.0         | 1.4        | 0.06       | 6.0        | 1.6           |
| CB27        | 2.1         | 0.8           | 5.6         | 1.4        | 0.06       | 2.5        | 2.4           |
| L1544       | 1.4         | 0.8           | 6.4         | 1.4        | 0.06       | 1.7        | 2.8           |
| L1552       | 8.7         | 0.8           | 6.8         | 1.3        | 0.05       | 10.6       | 1.1           |
| CB42        | 0.3         | 0.3           | 2.9         | 1.2        | 0.04       | 1.0        | 3.0           |
| CB44        | 35.0        | 7.0           | 46.2        | 1.4        | 0.16       | 5.0        | 2.8           |
| L492        | 3.8         | 2.0           | 16.1        | 1.3        | 0.09       | 1.9        | 3.3           |
| CB130       | 3.2         | 1.5           | 15.6        | 1.2        | 0.08       | 2.1        | 3.1           |
| CB180       | 10.2        | 5.3           | 51.5        | 1.2        | 0.13       | 1.9        | 3.9           |
| L694-2       | 2.6         | 1.7           | 16.3        | 1.2        | 0.08       | 1.6        | 3.6           |

**Notes.**

a. CO mass integrated over R^{core}_e, centered on the shadow coordinates.
b. CO mass integrated over an 4′-radius aperture, centered on the shadow coordinates.

c. Effective radius of the 24 μm shadow, see Section 4.2.1.
d. Ratio of M^{core}_24 over M^{core}_CO.
e. Jeans mass assuming all cores are at 10 K, using the M^{core}_24 and R^{core}_e to calculate the mean density in each core.
f. Rotational velocity required to support a core mass of M^{core}_24 for a core size of R^{core}_e.
g. Although the quality of the 70 μm data does not allow for robust measurements, these cores show strong indications of having 70 μm shadows. The presence of a 70 μm shadow implies that the cores are optically thick at shorter wavelengths; hence M^{core}_24 should be regarded as a lower limit.
measurement, and our CO spectra show 2-velocity components, which could broaden the line widths (see Figure 24). We note that Turner et al. (1997) do not list the coordinates of these observations, and we assume that they are the same as those listed in Clemens & Barvainis (1988), which are about 1′ from the center of the shadow. Without higher density tracer line profiles from which to infer the velocity field of the material, we consider it likely that CB26 is near collapse. The young T Tauri
star associated with this source has received far more attention than the nearby starless core. This young stellar object (YSO) has been studied in detail (e.g., Launhardt et al. 1998; Henning et al. 2001; Stecklum et al. 2004; Launhardt et al. 2009; Sauter et al. 2009). It lies approximately 3.5′ to the southwest of the shadow center, and can be seen in Figure 3 as the brightest 24 μm source. Although it is not clear what evolutionary, chemical, or other, relationship the shadow and the YSO might share, it is interesting that Henning et al. (2001) measure relatively well-ordered submillimeter dust polarization in a region ~40″ on a
side toward the young star, perhaps indicating that the magnetic field in the larger region, and therefore in the shadow, might also be well behaved. The polarization vectors point roughly north–south, indicating that the magnetic field is oriented in the east–west direction, the same direction as the longer axis of the entire CB26 region.

CB27. Our analysis indicates that this source is stable, if supported only by thermal pressure. With an additional plausible level of turbulent and magnetic support, the core remains stable. This conclusion is supported by the molecular line observations, which show no evidence of asymmetry. Lee et al. (2004) measure CS (3–2) and DCO\(^+\) (2–1) line profiles that...
are indistinguishable from Gaussian. Park et al. (2004) observe $^{12}$CO and $^{13}$CO Gaussian profiles as well. Sohn et al. (2007) observe this source to have a red asymmetry in all three HCN (1–0) line profiles. Gupta et al. (2009) detect C$_6$H$^-$ emission with a line width of $\sim$0.15 km s$^{-1}$; Roberts & Millar (2007) detect N$_2$H$^+$ and N$_2$D$^+$ emission whose line profiles appear symmetric.

**L1544.** We find that our 24 $\mu$m mass is lower than the Jeans criterion for collapse; however, the 70 $\mu$m image indicates that this mass estimate is a lower limit. As can be seen in Figure 5, in the 70 $\mu$m image there is a hint of a dark region at the location of the 24 $\mu$m shadow. The quality of the 70 $\mu$m image does not allow for a robust analysis; however, Stutz et al. (2009) show that in the case of starless core L429, the 24 $\mu$m shadow mass is
Figure 28. Masses presented Table 4 are plotted here. Top panel: the CO core masses calculated over the area of the core are plotted versus the 24 μm shadow masses. Bottom panel: the total masses \( M_{\text{24}} \) are plotted vs. the 24 μm shadow masses. The arrow indicates the effect of 50% change in the assumed distance. In both panels, the black curve indicates equality between the ordinate and the abscissa.

Table 5

| Source      | Near Collapse | \( M_{\text{24}}^\text{core} / M_{\text{co}}^\text{core} \) | 70 μm Shadow | \( B^a \) \( \mu \)G | \( E_{\text{thb}}/E_{\text{inb}}^b \) km s\(^{-1} \) | \( V_{\text{rot}}^c \) km s\(^{-1} \) | Chem. Evol. |
|-------------|---------------|-------------------------------------------------|--------------|-----------------|--------------------------|-----------------|-------------|
| TMC1-1C     | No            | 0.6                                             | No           | 0               | 0.4                       | No              |             |
| CB23        | Yes           | 1.3                                             | No           | 123             | 0.6                       | No              |             |
| CB26        | Yes           | 3.2                                             | No           | 214             | 0.5                       | …               |             |
| CB27        | No            | 0.9                                             | No           | 0               | 0.6                       | …               |             |
| L1544       | Yes           | > 0.5                                           | Yes          | > 66            | > 0.4                     | Yes             |             |
| L1552       | Yes           | > 8.1                                           | Yes          | > 424           | > 0.2                     | …               |             |
| CB42        | No            | 0.1                                             | No           | 0               | 1.0                       | …               |             |
| CB44        | Yes           | 12.0                                            | No           | 188             | 0.3                       | …               |             |
| L492        | Yes           | > 1.1                                           | Yes          | > 71            | 0.3                       | > 0.8           | Yes         |
| CB130       | No            | 1.0                                             | No           | 0               | 0.4                       | …               |             |
| CB180       | No            | 2.6                                             | No           | 81              | 0.4                       | …               |             |
| L694-2      | Yes           | > 0.7                                           | Yes          | > 57            | 0.4                       | > 0.4           | Yes         |
| CB190       | Yes           | 2.5                                             | No           | 78              | > 0.5                     | 0.6             | …           |
| L429        | Yes           | > 1.0                                           | Yes          | > 194           | 1                         | > 0.4           | Yes         |

Notes. See Section 4.3 for full discussion.

\(^a\) Magnetic field strength required to halt collapse.

\(^b\) Calculated from line widths collected from the literature, see Section 4.3 for references.

\(^c\) Rotational velocity required for stability.

Underestimated compared to the 70 μm shadow by a factor ~5. Taking this result, a plausible corrected 24 μm mass is ~7 \( M_\odot \), a factor of ~2.5 larger than the Jeans mass, making the core much more likely to be approaching collapse. Many authors have observed this source (e.g., Lee et al. 1999; Bacmann et al. 2000; Shirley et al. 2000; Bacmann et al. 2002; Tafalla et al. 2002; Bacmann et al. 2003; Lee et al. 2003, 2004; Williams et al. 2006; Park et al. 2004; Caselli et al. 2008; Gupta et al. 2009); the consensus is that this starless core is very evolved and likely to be collapsing. Lee et al. (2004) observe a CS (3–2) profile with a double peak with a brighter blue peak, and a DCO+ (2–1) profile with a blue asymmetry. Crapsi et al. (2005) measure the \( N_2H^+ \) (2–1) and \( N_2D^+ \) (2–1) line widths to be 0.32 and 0.29 km s\(^{-1} \), respectively; the \( N_2H^+ \) (3–2) and \( N_2D^+ \) (3–2) were 0.19 and 0.34 km s\(^{-1} \), respectively. They also find that this core has a large \( N_2D^+/N_2H^+ \) ratio equal to 0.23 and classify it as a highly evolved core, based on various observational chemical evolutionary probes. Williams et al. (2006) compare the \( N_2H^+ \) (1–0) emission from L1544 and L694-2 and conclude that both cores will form stars in ~10\(^4\) yr. Sohn et al. (2007) measure all three HCN (1–0) components to have two very strong peaks, all with the blue peak higher than the red peak. Bacmann et al. (2002) and Bacmann et al. (2003) find high degrees of CO depletion and a large deuterium abundance; Caselli et al. (2008) measure a large amount of ortho-H\(_2\)D\(^+\) \((1,0)\), \((1,1)\) emission, one of the highest in their sample, and conclude that emission from this species is correlated with CO depletion, deuterium fractionation, and an advanced chemical evolutionary stage. These results are consistent with our conclusion that this core is likely to be approaching collapse.

L1552. In this case, our analysis shows that the 24 μm shadow mass exceeds the Jeans mass by a wide margin, a factor of ~8. This source also shows a clear detection of a 70 μm shadow; applying a correction of a factor of 5 to the 24 μm mass (see L1544 discussion and Stutz et al. 2009) makes this core very unstable. Lee et al. (2004) measure a blue asymmetry in both CS (3–2) and DCO\(^+\) (2–1). The Sohn et al. (2007) HCN (1–0) profiles show a mild blue asymmetry in the line profiles and
report an N$_2$H$^+$ narrow line width of 0.22 km s$^{-1}$, indicating that turbulent support is negligible. These line measurements are consistent with our conclusion that this core is near collapse.

**CB42.** Our analysis indicates that this source is very stable against collapse, with a Jeans mass that exceeds the shadow mass by a factor of $\sim$10. Turner et al. (1997) measure an HCN line width of $\sim$0.82 km s$^{-1}$.

**CB44.** Our analysis indicates that this core has a mass that exceeds the Jeans criterion by a factor of $\sim$12. Molecular line observations of this source are sparse; however, Launhardt et al. (1998) measure a CS (2–1) line width of 1.5 km s$^{-1}$, with a profile showing some indication that it may have a red asymmetry. Observations of other (high density) tracers are needed. The magnetic field required to support the 24 $\mu$m shadow mass is of order 190 $\mu$G, large compared to observations of other cores (Bergin & Tafalla 2007). Based on this evidence and without line observations of higher density tracers, we consider it likely that CB44 is approaching collapse.

**L492.** Our mass measurement indicates that this core may be unstable to collapse. Although the 24 $\mu$m mass only marginally exceeds the Jeans mass, by $\sim$15%, this source has a 70 $\mu$m shadow, which, as discussed above, indicates that the 24 $\mu$m mass is a lower limit (Stutz et al. 2009). Kaufmann et al. (2008) report a 1.2 mm dust mass of 18.35 $\pm$ 0.17 $M_\odot$, in reasonable agreement with our CO-measured mass of 23.6 $M_\odot$, accounting for our larger CO aperture (4'). At both 8 $\mu$m and 24 $\mu$m, we observe two sub-components of this core, oriented in the east–west direction; this structure is not evident in the Kaufmann et al. (2008) MAMBO maps. Crapsi et al. (2005) measure the N$_2$H$^+$ (2–1) and N$_2$D$^+$ (2–1) line widths to be 0.26 and 0.22 km s$^{-1}$, respectively, at a position centered on the western sub-clump. The narrow line widths indicate that turbulence does not play a significant role in the support of this core. They classify this source as marginally evolved because it exhibits only three out of the eight evolutionary probes that they consider. Lee et al. (2004) measure a CS (3–2) with a blue asymmetry, DCO$^+$ (2–1) profile with a blue asymmetry and possible self-absorption; they classify this source as an infall candidate. Solf et al. (2007) measure all three HCN (1–0) components to have two strong peaks, all with the blue peak higher than the red peak, and consider this source to be an infall candidate. These results are consistent with our conclusion that this core is likely to be approaching collapse.

**CB130.** In the case of CB130, the 24 $\mu$m shadow mass is only marginally unstable. A plausible level of turbulent and/or magnetic support would halt collapse; for example, a magnetic field of $\sim$70 $\mu$G will suffice to halt collapse. There are no molecular line observations at the location of the shadow. The source CB130-3, which lies 1.5 east of the shadow center, is the closest object and was studied by Park et al. (2004) and Lee et al. (2004). Inspection of the DSS red plate reveals what appears to be a cusp, or knot, of material at the CB130-3 position. However, our 24 $\mu$m maps indicate that a denser and compact region of the CB130 complex is revealed by the 24 $\mu$m shadow which is completely enshrouded at near-IR and shorter wavelengths (see Figure 10). At the CB130-3 position, Lee et al. (2004) measure a CS (3–2) line profile with a red asymmetry. Without further molecular line observations, we conclude that this source is probably stable.

**CB180.** Our analysis indicates that this source is unstable, with a 24 $\mu$m line width that exceeds the Jeans mass by a factor of $\sim$2.6. Caselli et al. (2002) measure an N$_2$H$^+$ line width of 0.9 km s$^{-1}$ but do not show the spectrum of this object; this width indicates that the contribution of turbulence is about 4 times that of the thermal support (Hotzel et al. 2002). Given the 24 $\mu$m shadow mass, a magnetic field of order $\sim$70 $\mu$G would suffice to halt collapse. Based on these pieces of evidence, and without kinematical information from detailed line profiles, we consider it likely that CB180 is close to collapse.

**L694-2.** Our 24 $\mu$m mass indicates that this core is stable; however, as with L1544, L1552, and L492, this source has a 70 $\mu$m shadow. Correcting our 24 $\mu$m mass by a factor of 5, as discussed above, yields a core mass that exceeds the Jeans mass by a factor of $\sim$4. Like L1544, this source has been studied in some detail (e.g., Lee et al. 1999; Harvey et al. 2003a, 2003b; Lee et al. 2004; Crapsi et al. 2005; Williams et al. 2006; Lee et al. 2007; Sohn et al. 2007; Caselli et al. 2008). Crapsi et al. (2005) measure the N$_2$H$^+$(2–1) and N$_2$D$^+$(2–1) line widths to be 0.27 and 0.24 km s$^{-1}$, respectively; the N$_2$H$^+$(3–2) and N$_2$D$^+$(3–2) were 0.31 and 0.24 km s$^{-1}$, respectively. They also find that this core has a large N$_2$D$^+/N_2$H$^+$ ratio equal to 0.26. Similar to L1544, this core is classified by Crapsi et al. (2005) as highly evolved, both chemically and kinematically. Sohn et al. (2007) measure HCO$^+$(1–0) double-peaked line profiles with a blue asymmetry. Caselli et al. (2008) measure a large amount of ortho-H$_2$D$^+$(11$_{1,0}$–11$_{1,1}$) emission, one of the highest in their sample, along with L1544 (and L429). The line widths indicate that the turbulent support is negligible, contributing of order $\sim$0.4$\times$ the thermal support. These results are consistent with our conclusion that this core is approaching collapse.

Here we summarize results from two previous studies of cores CB190 (Stutz et al. 2007) and L429 (Stutz et al. 2009) which use similar techniques applied to 24 $\mu$m and 70 $\mu$m shadows, respectively:

**CB190.** Stutz et al. (2007) carry out a detailed study of this core. The 24 $\mu$m shadows analysis indicates that the mass of the core is twice the Jeans mass; however, the magnetic field required to support the core material is about 90 $\mu$G, a plausible field strength for starless cores. If the magnetic field is in fact present in CB190, it will leak out of the core in $\sim$3 Myr, an ambipolar diffusion timescale (Stahler & Palla 2005). Turbulent pressure does not provide sufficient support against collapse. Millimeter line emission from various species is too faint to constrain the kinematics in the core. Without more line profile information, we conclude that CB190 is near collapse.

**L429.** Stutz et al. (2009) study the 70 $\mu$m shadow cast by this core and conclude that a plausible level of magnetic support will not halt collapse. Additionally, the molecular line widths are narrow, indicating that the turbulent support is of order the thermal support in this core. Stutz et al. (2009) conclude that L429 is in a near collapse state. Lee et al. (2004) observe a blue asymmetry in the CS (3–2) line, while Crapsi et al. (2005) and Lee et al. (1999) measure symmetrical double-peaked N$_2$H$^+$ (1–0) and CS (2–1) lines, respectively. Sohn et al. (2007) measure HCN (1–0) double-peaked lines but note that this source is one of two out of 85 cores in their study with anomalous hyperfine line ratios. More high-resolution line observations are needed to clarify these results. Caselli et al. (2008) measure a large amount of ortho-H$_2$D$^+$(11$_{0,0}$–11$_{1,1}$) emission for this source, and find that this emission is correlated with a large degree of central concentration, and a large amount of CO depletion and deuteration, indicating that this source is evolved. Taken together, these pieces of evidence indicate that L429 is close to collapse.

In this paper, we emphasize how the 24 $\mu$m shadow observations can reveal structure not evident in previous studies. We highlight the 24 $\mu$m observations of CB130 and L492. In the
case of L492, we observe what appear to be two sub-clumps in the shadow feature (Figure 9), oriented in a roughly east–west direction separated by about 40°, reported here for the first time. Molecular line observations are centered on the western component (e.g., Crapsi et al. 2005) and indicate that this core is likely to be collapsing. The two components may be an example of core fragmentation; high spatial resolution observations of this core should be able to confirm if both sub-clumps are collapsing, and to measure the relative radial velocity between them. In the case of CB130, we have discovered a 24 μm shadow which is ~1.5 west of the region previously selected for millimeter line studies (e.g., Lee et al. 2004; Park et al. 2004); further observations taken at the location of the 24 μm shadow will confirm if this core is near collapse.

In the top panel of Figure 28, we compare the 24 μm shadow masses ($M_{24}^{\text{core}}$ in Table 4) to the CO-derived core masses ($M_{CO}^{\text{core}}$ in Table 4). In all cases, $F_{\text{core}} = M_{24}^{\text{core}} / M_{CO}^{\text{core}} \geq 1.0$; this discrepancy is likely due to the effect of freezeout of CO in dense regions (e.g., Bachmann et al. 2002; Tafalla et al. 2002); the effect will be stronger than illustrated for cores with 70 μm shadows (L1544, L1552, L492, and L694-2, see above discussion) because the 24 μm mass is likely to be underestimated. In the lower panel of Figure 28, we show the 24 μm masses as a function of the total molecular CO-derived masses (integrated over a 4° radius). Cores with 70 μm shadows are marked with gray arrows, indicating a plausible mass correction of a factor of 5 (Stutz et al. 2009). We tentatively detect a rough trend in core mass with increasing envelope mass. We caution that this trend may be driven by distance uncertainties, small sample size, and incomplete mass census. Observations from upcoming facilities, e.g., SCUBA2, which can image the submillimeter dust continuum emission, and *Herschel*, which can image the 70 μm shadows with a high degree of spatial resolution (~6") will provide further constraints on the evolution of starless cores.

5. CONCLUSIONS

We study the 8 μm, 24 μm, and 70 μm shadows cast by a sample of 14 starless cores. We derive 24 μm core masses and sizes; we apply a Jeans mass criterion, and attempt to account for turbulent and magnetic support in the cores, in order to estimate and especially at 70 μm masses as a factor of 5 (Stutz et al. 2009). We tentatively detect a rough trend in core mass with increasing envelope mass. We caution that this trend may be driven by distance uncertainties, small sample size, and incomplete mass census. Observations from upcoming facilities, e.g., SCUBA2, which can image the submillimeter dust continuum emission, and *Herschel*, which can image the 70 μm shadows with a high degree of spatial resolution (~6") will provide further constraints on the evolution of starless cores.

A.M.S. thanks Juna Kollmeier for her early input and stimulating discussions throughout the course of this work. The authors thank Craig A. Kulesa for assistance with the molecular mass models and Chris Walker for helpful comments. We also thank the anonymous referee for their helpful comments. Support for this work was provided through NASA contracts issued by Caltech/JPL to the University of Arizona (1255094). This work was also supported by the National Science Foundation grant AST-0708131 to The University of Arizona. M.K. was supported by the KRF-2007-612-C00050 grant.

REFERENCES

Alves, F. O., Franco, G. A. P., & Girart, J. M. 2008, A&A, 486, L13
Alves, J. F., Lada, C. J., & Lada, E. A. 2001, *Nature*, 409, 159
Arquilla, R., & Goldsmith, P. F. 1986, *ApJ*, 303, 356
Bachmann, A., André, P., Puget, J.-L., Abergel, A., Bontemps, S., & Ward-Thompson, D. 2000, A&A, 361, 555
Bacmann, A., Lefloch, B., Ceccarelli, C., Castets, A., Steinacker, J., & Loinard, L. 2002, A&A, 389, L6
Bacmann, A., Lefloch, B., Ceccarelli, C., Steinacker, J., Castets, A., & Loinard, L. 2003, *ApJ*, 585, L55
Ballesteros-Paredes, J., Klessen, R. S., & Vázquez-Semadeni, E. 2003, *ApJ*, 592, 188
Bergin, E. A., & Tafalla, M. 2007, A&A, 45, 339
Bok, B. J., & McCarthy, C. C. 1974, *AJ*, 79, 42
Burkert, A., & Bodenheimer, P. 2000, *ApJ*, 543, 822
Burkert, A., & Hartmann, L. 2004, *ApJ*, 616, 288
Butler, M. J., & Tan, J. C. 2009, *ApJ*, 696, 484
Caselli, P., Benson, P. J., Myers, P. C., & Tafalla, M. 2002, *ApJ*, 572, 238
Caselli, P., Vastel, C., Ceccarelli, C., van der Tak, F. F. S., Crapsi, A., & Bachmann, A. 2008, A&A, 492, 703
Caselli, P., Walmsley, C. M., Tafalla, M., Dore, L., & Myers, P. C. 1999, *ApJ*, 523, L165
Chapman, N. L., & Mundy, L. G. 2009, *ApJ*, 699, 1866
Chapman, N. L., Mundy, L. G., Lai, S.-P., & Evans, N. J. 2009, *ApJ*, 690, 496
Clemens, D. P., & Barvainis, R. 1988, *ApJS*, 68, 257
Crapsi, A., Caselli, P., Walmsley, C. M., Myers, P. C., Tafalla, M., Lee, C. W., & Bourke, T. L. 2005, *ApJ*, 619, 379
de Wit, W. J., Testi, L., Palla, F., & Zinnecker, H. 2005, A&A, 437, 247
Evans, N. J., Rawlings, J. M. C., Shirley, Y. L., & Mundy, L. G. 2001, *ApJ*, 557, 193
Fallsheer, C., Beuther, H., Zhang, Q., Keto, E., & Sridharan, T. K. 2009, A&A, 504, 127
Flaherty, K. M., Pipher, J. L., Megeath, S. T., Winston, E. M., Gutermuth, R. A., Muzerolle, J., Allen, L. E., & Fazio, G. G. 2007, *ApJ*, 663, 1069
Foster, J. B., & Goodman, A. A. 2006, *ApJ*, 636, L105
Gregersen, E. M., & Evans, N. J., II. 2000, *ApJ*, 543, 822
Gresers, E. M., & Evans, N. J., II. 2000, *ApJ*, 543, 822
Gresers, E. M., Evans, N. J., II, Zhou, S., & Choi, M. 1997, *ApJ*, 484, 256
Gordon, K. D., et al. 2005, *PASP*, 117, 503
Gupta, H., Gottlieb, C. A., McCarthy, M. C., & Thaddeus, P. 2009, *ApJ*, 691, 1494
Gutermuth, R. A., et al. 2008, *ApJ*, 674, 336
Harvey, D. W. A., Wilner, D. J., Lada, C. J., Myers, P. C., & Alves, J. F. 2003a, *ApJ*, 598, 1112
Harvey, D. W. A., Wilner, D. J., Myers, P. C., & Tafalla, M. 2003b, *ApJ*, 597, 424
Hayashi, C. 1966, ARA&A, 4, 171
Heitsch, F., Hartmann, L. W., Slyz, A. D., Devriendt, J. E. G., & Burkert, A. 2008, *ApJ*, 674, 316
Henning, T., Wolf, S., Launhardt, R., & Waters, R. 2001, *ApJ*, 561, 871
Hilton, J., & Lahulla, J. F. 1995, A&AS, 113, 325
Hotzel, S., Harju, J., & Juvela, M. 2002, A&A, 395, L5
Juvela, M., Pelkonen, V.-M., Padoan, P., & Mattila, K. 2008, A&A, 480, 445
Kandori, R., et al. 2005, *ApJ*, 130, 2166
Kang, M., Bieging, J. H., Kulesa, C. A., & Lee, Y. 2009, *ApJ*, 701, 454
Kauffmann, J., Bertoldi, F., Bourke, T. L., Evans, N. J., II., & Lee, C. W. 2008, *A&A*, 487, 993
Kawamura, A., Kun, M., Onishi, T., Vavrek, R., Domsa, I., Mizuno, A., & Fukui, Y. 2001, *PASJ*, 53, 1097
Kenyon, S. J., Dobrzycka, D., & Hartmann, L. 1994, *AJ*, 108, 1872
Kulesa, C. A., Hungerford, A. L., Walker, C. K., Zhang, X., & Lane, A. P. 2005, *ApJ*, 625, 194
Kutner, M. L., & Ulich, B. L. 1981, *ApJ*, 250, 341
Kutner, M. L., & Ulich, B. L. 1981, *ApJ*, 250, 341
