THE DYNAMICAL STATE OF FILAMENTARY INFRARED DARK CLOUDS

AUDRA K. HERNANDEZ1 AND JONATHAN C. TAN2
1 Department of Astronomy, University of Florida, Gainesville, FL 32611, USA; audrah@astro.ufl.edu
2 Departments of Astronomy & Physics, University of Florida, Gainesville, FL 32611, USA; jt@astro.ufl.edu

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ABSTRACT

The dense, cold gas of infrared dark clouds (IRDCs) is thought to be representative of the initial conditions of massive star and star cluster formation. We analyze 13CO J = 1–0 line emission data from the Galactic Ring Survey of Jackson et al. for two filamentary IRDCs, comparing the mass surface densities derived from 13CO, Σ13CO, with those derived from mid-infrared small median filter extinction mapping, ΣSMF, by Butler & Tan. After accounting for molecular envelopes around the filaments, we find approximately linear relations between Σ13CO and ΣSMF, i.e., an approximately constant ratio Σ13CO/ΣSMF in the clouds. There is a variation of about a factor of two between the two clouds. We find evidence for a modest decrease of Σ13CO/ΣSMF with increasing Σ, which may be due to a systematic decrease in temperature, increase in importance of high 13CO opacity cores, increase in dust opacity, or decrease in 13CO abundance due to depletion in regions of higher column density. We perform ellipsoidal and filamentary virial analyses of the clouds, finding that the surface pressure terms are dynamically important and that globally the filaments may not yet have reached virial equilibrium. Some local regions along the filaments appear to be close to virial equilibrium, although still with dynamically important surface pressures, and these appear to be sites where star formation is most active.

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

Online-only material: color figures

1. INTRODUCTION

Massive, high column density infrared dark clouds (IRDCs), typically identified as being opaque against the Galactic background at ~10 μm, are thought to contain the sites of future massive star and star cluster formation (e.g., Rathborne et al. 2006), since their densities (nH ≥ 104 cm–3) and mass surface densities (Σ ≥ 0.1 g cm–2) are similar to regions known to be undergoing such formation activity (Tan 2007). Studies of molecular line emission from IRDCs can help determine their kinematics. In particular, we would like to know if they are gravitationally bound, if they are near virial equilibrium, and if there is evidence for coherent gas motions that might indicate that IRDC formation involves converging atomic flows (Heitsch et al. 2008) or converging molecular flows from cloud collisions (Tan 2000).

In this study, we use 13CO J = 1–0 line emission data from the Galactic Ring Survey (GRS; Jackson et al. 2006) for two filamentary IRDCs, clouds F (l = 34:437, b = 0:245, d = 3.7 kpc) and H (l = 35:395, b = −0:336, d = 2.9 kpc) from the sample of 10 relatively nearby massive and dense IRDCs of Butler & Tan (2009, hereafter BT09), comparing 13CO-derived mass surface densities, Σ13CO, with small median filter (SMF) mid-infrared (MIR) (8 μm) extinction mapping derived mass surface densities, ΣSMF, using the method of BT09 applied to the Spitzer Infrared Array Camera (IRAC) band 4 images of the Galactic plane taken as part of the Galactic Legacy Mid-Plane Survey Extraordinaire (GLIMPSE; Benjamin et al. 2003). We consider systematic errors in each of these methods, which is necessary before analyzing larger samples of clouds. We are also able to look for evidence of changing CO abundance with column density, e.g., due to possible depletion of CO at high densities. We then perform a virial analysis of the clouds to determine their dynamical state.

There have been a number of other studies comparing 13CO derived mass surface densities with those from other methods. For example, Goodman et al. (2009) compared near-infrared (NIR) dust extinction, far-infrared (FIR) dust emission, and 13CO line emission in the Perseus giant molecular cloud (GMC), probing values of Σ up to ~0.02 g cm–2 (i.e., up to AV ~ 8 mag). Even after accounting for temperature and optical depth variations they concluded that 13CO emission was a relatively unreliable tracer of mass surface density, perhaps due to threshold, depletion, and opacity effects. Our study probes higher values of Σ, from ~0.01 to ~0.05 g cm–2, and compares 13CO emission with MIR extinction in order to investigate these processes.

Battersby et al. (2010) used 13CO emission, MIR extinction, and FIR dust emission methods to measure Σ and mass of clumps in eight IRDCs, one of which is IRDC F of our study. They did not present a specific comparison of Σ13CO with other methods, although derived clump masses were in reasonable agreement. Their sample also included MIR-bright regions, associated with ultra-compact H ii regions, for which the MIR extinction method cannot be applied. As we describe below, our approach differs in a number of ways, including by focusing on filamentary and mostly quiescent regions of IRDCs for which the MIR extinction method is most reliable and which are likely to be closer to the initial conditions of the massive star and star cluster formation process. We note that while IRDC F in particular does contain some regions of quite active star formation, including an ultra-compact H ii region, here we have concentrated on its more quiescent portions.

2. MASS SURFACE DENSITY ESTIMATION FROM 13CO

We evaluate the column density of 13CO molecules, dN13CO, in a velocity interval dv from their J = 1 → 0 emission via

$$dN_{13CO}(v) = \frac{8\pi Q_{rot} g_l}{A_{13CO}^3 g_u} \frac{d^3}{dv} \left[ 1 - \exp \left( -\frac{h \nu}{k T_{ex}} \right) \right]^{-1}, \quad (1)$$

where Q_{rot} is the partition function, A = 6.3355 × 10–8 s–1 is the Einstein coefficient, λ_0 = 0.27204 cm, g_l = 1 and
\[g_\ell = 3\] are the statistical weights of the lower and upper levels, \(\tau_\nu\) is the optical depth of the line at frequency \(\nu\), i.e., at velocity \(v\), and \(T_{ex}\) is the excitation temperature (assumed to be the same for all rotational levels). For linear molecules, the partition function is

\[Q_{rot} = \sum_{J=0}^{\infty} (2J + 1) \exp(-E_J/kT_{ex})\]

with \(E_J = J(J + 1)\hbar B\) where \(J\) is the rotational quantum number and \(B = 5.5101 \times 10^{10} \text{ s}^{-1}\) is the rotational constant. Thus for \(^{13}\)CO(1–0) we have \(E_J/k = 5.289 \text{ K}\). For \(J = 1\), \(Q_{rot} = 4.134, 6.018\), and 7.906 for \(T_{ex} = 10, 15, \text{ and } 20 \text{ K}\).

The optical depth is determined via

\[\tau_{\nu} = (\eta f_{\text{clamp}}) T_{B,\nu}/(\eta f_{bg}) T_{B,\nu},\]

where \(T_{B,\nu}\) is the brightness temperature at frequency \(\nu\), \(f(T) \equiv [\exp(h\nu/(kT)) - 1]^{-1}\), and \(T_{B,\nu} = 2.725 \text{ K}\) is the background temperature. \(T_{B,\nu}\) is derived from the antenna temperature, \(T_{A}\), via \(T_{A} = (\eta f_{\text{clamp}}) T_{B,\nu}\). The GRS has an angular resolution of 46\(^\prime\), with sampling every 22\(^\prime\). The velocity resolution is 0.22 km \(s^{-1}\) (Jackson et al. 2006). From a morphological examination of the \(^{13}\)CO emission in \(l, b, v\) space and comparison to the MIR extinction maps of BT09 we identify the velocity range of the gas associated with each IRDC filament (see Figures 2–4). For cloud F we consider associated gas to be at LSR velocities 48–65 km \(s^{-1}\) and for cloud H at 40–50 km \(s^{-1}\). The total \(^{13}\)CO column is then evaluated over the velocity range of the cloud \(N_{13\text{CO}} = \int dN_{13\text{CO}}\).

To convert from \(N_{13\text{CO}}\) to total mass surface density \(\Sigma_{13\text{CO}}\) we first assume (Milam et al. 2005)

\[n_{12\text{CO}}/n_{13\text{CO}} = 6.2 \frac{R_{\text{gal}}}{\text{kpc}} + 18.7,\]

where \(R_{\text{gal}}\) is the galactocentric radius. For clouds F and H we estimate \(R_{\text{gal}} = 5.37, 5.89\) kpc, respectively (assuming \(R_{\text{gal,0}} = 8.0\) kpc), which would yield \(n_{12\text{CO}}/n_{13\text{CO}} = 52, 55\), respectively. For simplicity we adopt \(n_{12\text{CO}}/n_{13\text{CO}} = 54\) for both clouds. We then assume

\[n_{12\text{CO}}/n_{\text{H}_2} = 2.0 \times 10^{-4},\]

similar to the results of Lacy et al. (1994). The observed variation in this abundance in GMCs is about a factor of two (Pineda et al. 2008), and this uncertainty is a major contributor to the overall systematic uncertainty in our estimate of \(\Sigma_{13\text{CO}}\). Thus, our assumed abundance of \(^{13}\)CO to \(\text{H}_2\) is 3.70 \times 10^{-6} and

\[\Sigma_{13\text{CO}} = 1.26 \times 10^{-2} \frac{N_{13\text{CO}}}{10^{16} \text{cm}^{-2}} \text{ g cm}^{-2},\]

assuming a mass per H nucleus of \(\mu_{\text{H}} = 2.34 \times 10^{-24} \text{ g}\).
Figure 2. Column density profiles with velocity for IRDCs F (left) and H (right). The dashed lines show the profiles assuming optically thin emission, while the solid lines show the profiles after correction for optical depth. A temperature of 20 K was assumed for IRDC F and 15 K for IRDC H (see the text). For each cloud the upper, offset profile is that of the average for the cloud and the lower profile is that of the highest column density position.

(A color version of this figure is available in the online journal.)

Figure 3. Morphology of IRDC F. Top left: Spitzer GLIMPSE IRAC 8 μm image, with linear intensity scale in MJy sr⁻¹. The horizontal line shows a scale of 3′. The image has 1′2 pixels and the point-spread function (PSF) has an FWHM of 2′. Top middle: mass surface density, \( \Sigma_{\text{SMF}} \), with linear intensity scale in g cm⁻², derived from the previous image using the small median filter MIR extinction mapping method of Butler & Tan (2009). The inner, red rectangle (centered at \( l = 34.483, b = 0.276 \), with P.A. = +60° and size 0.0582 by 0.198) along the filament shows the “on source” region we consider to contain the main filamentary structure of the IRDC. The outer, blue rectangle extends to “off source” regions we consider to be representative of the surrounding GMC envelope. These rectangles are divided into seven orthogonal strips to aid in the separation of components of CO emission from the filament and GMC envelope. Top right: the same extinction map convolved with a Gaussian of 46′ FWHM to match the resolution of the CO maps and pixelated to 22′ on the same grid as the GRS survey image. The two black hatched squares show regions with unreliable measures of \( \Sigma_{\text{SMF}} \) because of the presence of bright MIR sources. These are excluded from the comparison with \( \Sigma_{13\text{CO}} \). Bottom left: integrated intensity map of \(^{13}\text{CO}(1–0)\) emission over the full velocity range of −5 to 135 km s⁻¹ of the GRS survey, with linear intensity scale in K km s⁻¹. Bottom middle: integrated intensity map of \(^{13}\text{CO}\) over the velocity range of 48–65 km s⁻¹, i.e., the gas we believe is associated with the IRDC, with linear intensity scale in K km s⁻¹. Bottom right: mass surface density of the filament derived from \(^{13}\text{CO} \) emission, \( \Sigma_{13\text{CO}} \), with linear intensity scale in g cm⁻².

(A color version of this figure is available in the online journal.)
The assumption of LTE breaks down if the density of the gas is lower than the effective critical density, $\beta n_{\text{crit}}$, i.e., the critical density of $^{13}$CO ($J = 1–0$), $n_{\text{crit}} = 1.9 \times 10^3$ cm$^{-3}$, allowing for radiative trapping with escape probability $\beta = e^{-\bar{\tau}}$, where we approximate $\bar{\tau}$ as the column density weighted mean value of $\tau_\nu$. Note, for a spherical cloud we would set $\bar{\tau}$ equal to the average of $\tau_\nu/2$, but we use $\tau_\nu$ for these clouds with a filamentary geometry since we expect $\tau_\nu$ seen along our line of sight to be relatively small compared to other viewing angles. Heyer et al. (2009) argued sub-thermal excitation of $^{13}$CO rotational levels may be common in GMCs, causing lower values of line emission than expected under LTE conditions and thus causing estimates of $\Sigma$ based on LTE assumptions to be underestimates. The IRDC filaments we are considering are generally of higher density than the typical GMC volumes considered by Heyer et al. (2009). For the average and highest intensity spectra in each IRDC (see Figure 2), we evaluate $\beta$ (see Table 1). We also estimate $n_{\text{H}_2}$, assuming a filament line-of-sight thickness that is equal to its observed width. A comparison of $n_{\text{H}_2}$ with $\beta n_{\text{crit}}$ shows that the densities are close to or greater than the effective critical densities, thus justifying the assumption of LTE conditions. Furthermore, we expect that the typical density at a given location is greater than our estimated values due to clumping on angular scales that are smaller than the 46$''$ resolution of the CO observations. Such clumping is apparent in the MIR extinction maps (Figures 3 and 4).

3. COMPARISON OF $\Sigma_{^{13}\text{CO}}$ AND $\Sigma_{\text{SMF}}$: POSSIBLE TRENDS IN TEMPERATURE, CO DEPLETION, AND DUST OPACITY WITH $\Sigma$

The morphologies of IRDCs F and H are shown in Figures 3 and 4, respectively. The $^{13}$CO emission is more extended than the structure traced by the BT09 MIR extinction maps, which are derived by comparing the observed 8 $\mu$m intensity at the cloud position with the expected background intensity interpolated...
from nearby regions. Uncertainties in this estimation of the background lead to a lack of sensitivity of the MIR extinction maps to mass surface density contrasts $\Delta \Sigma \lesssim 0.013 \, \text{g cm}^{-2}$.

Since there is a significant amount of molecular gas in the surrounding “envelope” regions around the filaments, to compare the ratio of $\Sigma_{\text{SMF}}$ and $\Sigma_{\text{13CO}}$ in the filaments we must first subtract the contribution to $\Sigma_{\text{13CO}}$ from the envelopes. To do this we consider orthogonal strips across each IRDC filament and measure $^{13}$CO emission on either side (see Figures 3 and 4). The spectra of these “off-source,” envelope regions are corrected for optical depth effects, as described above, averaged, and then subtracted from the central “on-source,” filament region (see Figure 5). We find that the envelope-subtracted spectra are generally narrower than the total. We also find that the size of negative residuals created in the subtraction process is quite significant variation in the envelope spectra from one side to the other suggests that this is one of the major sources of uncertainty in measuring the molecular emission of the filament to the other suggests that this is one of the major sources of uncertainty in measuring the molecular emission properties of these embedded filaments. After this procedure, we are now in a position to compare the envelope-subtracted values of $\Sigma_{\text{13CO}}$ with those derived from the SMF extinction mapping method of BT09.

We also note that the MIR extinction derived values of $\Sigma$ suffer from their own systematic uncertainties, including corrections due to foreground dust emission (BT09), scattering in the IRAC array (Battersby et al. 2010), adopted dust opacities and dust to gas ratios. However, saturation due to large $8 \, \mu$m optical depth and/or an insufficiently subtracted foreground is not an important source of error for our present study, since the values of $\Sigma_{\text{SMF}}$ are in any case reduced when the maps are smoothed to the lower resolution of the $^{13}$CO data.

As noted by BT09, the MIR extinction mapping technique fails for locations where there are bright MIR sources. If the intensity of the source is greater than the background model, then formally an unphysical, negative value of $\Sigma$ is returned by this method. In the analysis of BT09, negative values of $\Sigma$ are allowed up to a certain threshold value to account for noise-like, approximately Gaussian, fluctuations in the background intensity. For the more extreme fluctuations caused by bright sources, BT09 set $\Sigma = 0$. Thus, the effect of a bright MIR region within an IRDC is to cause the extinction mapping method to underestimate the true mass surface density. For most point-like MIR sources, this effect is quite minor after the extinction maps are averaged to the $22'' \times 14$ pixel scale of the CO observations. However, in IRDC F we identify two regions (indicated in Figure 3), which are significantly affected by bright MIR sources and exclude them from the subsequent analysis.

The values of $\Sigma_{\text{13CO}}$ (after envelope subtraction) and $\Sigma_{\text{SMF}}$ for each pixel in the filament regions of IRDCs F and H are compared in Figure 6. We note that both these measures of $\Sigma$ are independent of the distance to the cloud. Considering just the data with $\Sigma_{\text{13CO}}$ and $\Sigma_{\text{SMF}} > 0.01 \, \text{g cm}^{-2}$, the best-fit power-law relation $\Sigma_{\text{13CO}} / (\text{g cm}^{-2}) = A(\Sigma_{\text{SMF}} / (\text{g cm}^{-2}))^\alpha$ has $\alpha = 0.77 \pm 0.18, 0.32 \pm 0.28$ and $A = 0.58 \pm 0.44, 0.074 \pm 0.069$ for IRDCs F and H, respectively.

Over the range $0.01 < \Sigma_{\text{SMF}} / (\text{g cm}^{-2}) < 0.07$ we find that $\Sigma_{\text{13CO}} \approx \Sigma_{\text{SMF}}$ to within a factor of $\sim 2$ for the mean values in each IRDC filament. The dispersion within an individual IRDC from pixel to pixel is also at about this level. The systematic offsets may reflect real systematic variations of the assumed temperature, $^{13}$CO abundance, dust opacities, or envelope subtraction method for each IRDC compared to our adopted values and methods. The dispersion may reflect local systematic variations and errors introduced by measurement noise.

In both IRDCs, the ratio $\Sigma_{\text{13CO}} / \Sigma_{\text{SMF}}$ decreases with increasing mass surface density as measured by $\Sigma_{\text{SMF}}$. We gauge the significance of this trend by noting that the above values of $\alpha$ for IRDCs F and H differ from unity by 1.3 and 2.4 standard deviations, respectively, assuming errors are distributed normally. There are several physical processes that may be causing such a trend. A systematic temperature decrease from the lower column density, outer regions of the filaments to the higher column density centers would lead us to systematically underestimate $\Sigma_{\text{13CO}}$ in the latter, while having little direct effect on dust opacities (although there may be an indirect effect via formation of ice mantles, see below). For the temperature ranges we expect to be present, i.e., from $\sim 10$ to $20 \, \text{K}$ (e.g., Pillai et al. 2006)—although note these are based on measurements of NH$_3$, which may trace different conditions to those of the $^{13}$CO), this effect becomes important for values of $T_{\text{B, v}} > 4 \, \text{K}$ (see Figure 1(b)). We illustrate the size of this effect for the highest $\Sigma_{\text{SMF}}$ positions in IRDCs F and H in Figure 6. A systematic temperature decrease of $5 \, \text{K}$ in the high $\Sigma$ regions could remove much of the observed trend.

Another possibility is that our corrections for the optical depth of the $^{13}$CO emission are systematically underestimated at the higher column density positions. This would be expected if a significant amount of mass is contained in unresolved dense cores. The largest optical depth corrections in the highest column density centers presently lead to an increase in the estimated column by factors $\gtrsim 2$. Future higher angular resolution $^{13}$CO and C$^{18}$O observations of these filaments are required to investigate this issue further.

Depletion of CO molecules onto dust grains is known to occur in cold, high volume density gas (Caselli et al. 1999). This process could systematically reduce the gas phase CO abundance in the high $\Sigma$ regions of the IRDCs. For depletion to be fully responsible for the observed trends in IRDCs F and H would require a factor of two depletion as $\Sigma_{\text{SMF}}$ increases from 0.01 to 0.05 g cm$^{-2}$. Because of depletion, CO is not expected to be an ideal tracer of the densest, coldest parts of IRDCs. High-resolution studies of other tracers, such as NH$_3$, will likely be needed to measure the kinematics of these regions.

### Table 1

| IRDC Spectrum (See Figure 2) | $N_{\text{H}_2}$ (10$^{16}$ cm$^{-2}$) | $\Sigma_{\text{13CO}}$ (g cm$^{-2}$) | $\beta$ | $n_{\text{H}_2}$ (cm$^{-3}$) | $\beta n_{\text{H}_2}$ (cm$^{-3}$) | $n_{\text{H}_2}/(\beta n_{\text{H}_2})$ |
|-----------------------------|-------------------------------|--------------------------|-----|-------------------|-------------------------------|--------------------------------|
| $F_{\text{mean}}$          | 2.73                          | 0.0344                   | 0.873| 1340              | 1660                          | 0.807                         |
| $F_{\text{high}}$          | 4.94                          | 0.0622                   | 0.765| 2430              | 1340                          | 1.81                          |
| $H_{\text{mean}}$          | 2.75                          | 0.0347                   | 0.696| 2850              | 1322                          | 2.15                          |
| $H_{\text{high}}$          | 3.46                          | 0.0436                   | 0.587| 3590              | 1120                          | 3.22                          |
The depletion of CO via formation of CO ice mantles on dust grains would also have some effect on the MIR opacities of these grains, thus affecting our measurement of $\Sigma_{\text{SMF}}$. The grains would become larger and absorption features due to pre-existing water ice mantles may become obscured. The Ossenkopf & Henning (1994) grain models show a $\sim$50% increase in 8 $\mu$m opacity, $\kappa_{8\mu m}$, going from bare grains to those with thick ice mantles. The BT09 estimates of $\Sigma_{\text{SMF}}$ assumed a constant value of $\kappa_{8\mu m}$ consistent with the thin ice mantle model of Ossenkopf & Henning (1994). Thus, the observed decrease in the ratio of $\Sigma_{13\text{CO}}/\Sigma_{\text{SMF}}$ with increasing mass surface density could be caused by thickening of grain ice mantles, causing us to systematically overestimate $\Sigma_{\text{SMF}}$.

Another possible explanation for a trend of decreasing $\Sigma_{13\text{CO}}/\Sigma_{\text{SMF}}$ with increasing mass surface density is active chemical fractionation (Langer et al. 1980, 1984; Glassgold et al. 1985; Vissere et al. 2009), which enhances the abundance of $^{13}$CO in regions where $^{13}$C$^+$ is present via the ion–molecule exchange reaction (Watson et al. 1976), $^{12}$CO+13C$^+ \rightarrow 12$C$^++^{13}$CO+35 K. FUV irradiation maintains a relatively high abundance of $^{13}$C$^+$ in the outer regions of the cloud, with $A_V \lesssim 1$ mag. The relative abundance of $^{13}$CO to $^{12}$CO can be enhanced by factors of $\sim 10$. For $A_V \gtrsim 2$, the enhancement factor is only about 20% (e.g., for a model with $n_{\text{H}_2} = 10^3$ cm$^{-3}$ and $T = 20$ K; Glassgold et al. 1985). For IRDCs F and H, the filaments are typically embedded inside “envelope” gas with $\Sigma_{13\text{CO}} \approx 0.01$ g cm$^{-2}$.

Figure 5. Subtraction of IRDC envelopes. (a) Top left: filament and envelope of IRDC F, with the seven sets of spectra (top to bottom) corresponding to the seven orthogonal strips (top left to bottom right) shown in Figure 3. In each, the dotted, red line shows the total $^{13}$CO column density distribution, including optical depth corrections, from the filament region, which includes an assumed contribution from “envelope” material along the line of sight. The long dashed and dot-dashed, blue lines show the total $^{13}$CO column density from the northern and southern envelope regions, respectively. (b) Top right: filament and envelope of IRDC H, with the four sets of spectra (top to bottom) corresponding to the four orthogonal strips (top left to bottom right) shown in Figure 4. The line styles have the same meaning as in (a). (c) Bottom left: for the same strips as in (a), we subtract the average of the northern and southern envelope spectra (short dashed blue lines) from the filament (dotted red line), to leave an estimate of the material in the filament (solid, black line). The vertical solid line indicates the mean velocity. (d) Bottom right: same analysis and labels as (c) applied to IRDC H.

(A color version of this figure is available in the online journal.)
Figure 6. (a) Top left: direct comparison of $\Sigma_{13CO}$ (after envelope subtraction) and $\Sigma_{SMF}$ in IRDC F. The crosses show locations where both $\Sigma_{13CO}$ and $\Sigma_{SMF} > 0.01 \text{ g cm}^{-2}$. The dots show locations of lower surface densities. The uncertainties in the individual measurements are assumed to be 15% plus a systematic error of 0.01 g cm$^{-2}$. The dotted line shows the one-to-one linear relation and the long dashed line shows the best-fit offset linear relation. The solid line shows the best-fit power-law relation (see the text). (b) Top right: same as (a) but for IRDC H. (c) Bottom left: logarithm of the ratio of $\Sigma_{13CO}$ to $\Sigma_{SMF}$ as a function of $\Sigma_{SMF}$ for IRDC F, with the same symbol notation as in (a). The cross in the upper right corner indicates typical estimated uncertainties. The solid (dashed) arrow shows the effect on the highest $\Sigma$ position of reducing the assumed temperature from 20 K to 15 K (10 K). (d) Bottom right: same as (c) but for IRDC H. The arrow shows the effect on the highest $\Sigma$ position of reducing the assumed temperature from 15 K to 10 K.

(A color version of this figure is available in the online journal.)

4. THE DYNAMICAL STATE OF THE IRDC FILAMENTS

4.1. IRDC Masses from $^{13}$CO Emission and MIR Dust Absorption

We calculate IRDC masses using the observed mass surface densities and angular sizes, and by assuming near kinematic distances, since the clouds are seen in absorption against the Galaxy’s diffuse MIR emission. We adopt the kinematic distances of Simon et al. (2006), who assumed the Clemens (1985) rotation curve. This leads to a distance of 3.7 kpc for IRDC F and 2.9 kpc for IRDC H. We assume uncertainties of 0.5 kpc, which could result, for example, from line-of-sight noncircular motions of $\sim 8 \text{ km s}^{-1}$. Temperature uncertainties of 5 K would lead to $\Sigma_{^{13}CO}$ uncertainties of $\sim 20\%$. We estimate similar levels of uncertainty in $\Sigma_{SMF}$ due to foreground correction and background interpolation uncertainties (BT09). Then, for IRDC F, the $^{13}$CO-derived mass assuming $T = 20 \text{ K}$ in the on-source filament region after envelope subtraction is $M_{^{13}CO} = 3300 \pm 1100 M_{\odot}$ and the dust extinction mass is $M_{SMF} = 1900 \pm 640 M_{\odot}$. For IRDC H, we find $M_{^{13}CO} (T = 15 \text{ K}) = 370 \pm 150 M_{\odot}$ and $M_{SMF} = 580 \pm 230 M_{\odot}$. For our calculations involving the total mass of the clouds we take averages of the above estimates while still assuming 20% uncertainties in the averaged values of $\Sigma$. Thus, we adopt $M = 2600 \pm 870 M_{\odot}$ for IRDC F and $M = 580 \pm 230 M_{\odot}$ for IRDC H.
\[ M = 480 \pm 190 \, M_\odot \text{ for IRDC H. These results are summarized in Table 2.} \]

### 4.2. Ellipsoidal Cloud Virial Analysis

Following Bertoldi & McKee (1992, hereafter BM92), we consider an ellipsoidal cloud with radius \( R \) normal to the axis of symmetry and size \( 2Z \) along the axis. The aspect ratio is defined as \( y = Z/R \), while \( R_{\text{max}} \) and \( R_{\text{min}} \) are the semimajor and semiminor axes of the ellipse obtained by projecting the cloud onto the plane of the sky.

IRDCs F and H both have relatively thin, filamentary morphologies; we set \( R_{\text{max}}/R_{\text{min}} = 3.40, 1.78 \), respectively, i.e., the same elongation as the rectangular regions we consider to define the filaments (Figures 3 and 4). Given these morphologies, we expect the symmetry axes of the clouds to be close to the plane of the sky. Thus, for both we adopt a fiducial value of the inclination angle between the cloud symmetry axis and the line of sight of \( \theta = 60^\circ \). We assume \( R = R_{\text{max}} \) and \( Z = R_{\text{max}}/\sin \theta \), so \( y = 3.93, 2.06 \) for IRDCs F and H, respectively. An uncertainty of 15\(^\circ\) in inclination would cause \( \sim 15\% \) uncertainties in \( y \). It is also useful to introduce a geometric mean observed radius, \( R_{\text{obs}} \equiv (R_{\text{max}}R_{\text{min}})^{1/2} \), which is also related to \( R \) via \( R_{\text{obs}} = R \cos^{1/2} \theta (1 + (y \tan \theta)^2)^{1/4} \). BM92 also define \( R_{\text{m}} \) as the mean value of \( R_{\text{obs}} \) averaged over all viewing angles, but for our individual clouds we will express quantities in terms of \( R \) and \( R_{\text{obs}} \). It should be noted that the treatment of these IRDC filaments as simple ellipsoids is necessarily approximate, and we consider the filamentary analysis of Section 4.3 to be more accurate.

If the cloud is in an environment that is evolving with a timescale longer than the clump’s dynamical timescale or signal crossing time \( t_s = 2R/c \), then it should obey the equilibrium virial equation (McKee & Zweibel 1992):

\[ 0 = 2(T - T_0) + M + W. \tag{8} \]

Here, \( T \) is the clump kinetic energy, \( T_0 \) is the kinetic energy resulting from the surface pressure on the clump, \( M \) is the magnetic energy associated with the cloud, and \( W \) is the gravitational binding energy, which for an ellipsoidal cloud is (BM92)

\[ W = \frac{3}{5} a_1 a_2 \frac{GM^2}{R}, \tag{9} \]

where for a power-law density distribution \( \rho \propto r^{-k_\rho} \), \( a_1 = (1 - k_\rho/3)/(1 - 2k_\rho/5) \), and

\[ a_2 = \frac{\text{arcsinh}(y^2 - 1)^{1/2}}{(y^2 - 1)^{1/2}} \tag{10} \]

for prolate clouds. Note, our definition of \( W \) and \( a_2 \) differs slightly from BM92 since we do not need to consider \( M_{\text{obs}} \).

We adopt \( k_\rho = 1 \) (based on a study of the density profiles in IRDCs—M. J. Butler & J. C. Tan 2011, in preparation) so that \( a_1 = 10/9 \). For our measured values of \( y \), we have \( a_2 = 0.53 \) and 0.71 for IRDCs F and H, respectively. For the mass of the cloud we take the average values of the estimates from MIR dust extinction and \(^{13}\)CO line emission. Using these values we estimate \( W = -(11.0, 1.08) \times 10^{46} \) erg for IRDCs F and H, respectively (see Table 2). The uncertainties in \( W \) are relatively large given the measurement errors of \( \Sigma \) and \( R \).

The clump kinetic energy is \( T = (3/2)M \sigma^2 \), where \( \sigma \) is the average total one-dimensional velocity dispersion, which we derive from the \(^{13}\)CO line emission (counting only those parts of the envelope-subtracted spectra with positive signal greater than or equal to one standard deviation of the noise level) including corrections for the molecular weight of \(^{13}\)CO and our adopted cloud temperatures. We estimate that we measure \( \sigma \) to a 10% accuracy. We find \( T = (16.4, 2.06) \times 10^{46} \) erg for IRDCs F and H, with uncertainties at about the 40% level.

The surface term for the kinetic energy is \( T_0 = (3/2)P_0V \).

We estimate this term in two ways. First (method A), we can measure the mass surface density of the surrounding molecular cloud from the \(^{13}\)CO emission of the envelope regions. We find \( \Sigma_{^{13}\text{CO}}(\text{env}) = 0.0196, 0.0212 \, \text{g cm}^{-2} \) for IRDCs F and H, respectively. We scale these values by \( M/M_{^{13}\text{CO}} \), i.e., 0.79 and 1.30. If the envelope is self-gravitating, it has mean internal pressure \( P(\text{env}) = 1.85\Sigma_{^{13}\text{CO}}(\text{env}) \), adapting the analysis of McKee & Tan (2003) with parameters \( f_g = 1 \) (i.e., fully gas dominated), \( \phi_{\text{geom}} = R^3/(2R^2Z) = 1.4 \) (adopting an intermediate value for the two IRDCs accurate to about 20\%), \( \phi_g = 2.8 \) (the fiducial value of McKee & Tan, measuring the ratio of the total pressure including magnetic fields to that assuming they were absent), and \( \sigma_{\text{env}} = 1 \). Then setting \( P_0 = P(\text{env}) = (2.96, 9.38) \times 10^{-11} \) cgs for IRDCs F and H and with the cloud volume \( V = 4\pi R^2Z/3 \), we find \( T_0(A) = (14, 2.7) \times 10^{46} \) erg.

Second (method B), we estimate the density in the envelope region, assuming it has a cylindrical, annular volume with outer radius \( 2R \) and inner radius \( R \). For IRDCs F and H, we find densities of \( \rho = 42(\text{env})/(3\pi R) = (1.43, 3.20) \times 10^{-21} \, \text{g cm}^{-3} \), equivalent to \( n_{\text{H}_2}(\text{env}) = (610, 1600) \, \text{cm}^{-3} \). We again scale these values by \( M/M_{^{13}\text{CO}} \), i.e., 0.79 and 1.30 for IRDCs F and H, respectively. We then equate \( P_0 = \rho(x^{1/2})(v^2) \), where \( x^{1/2} \) is the velocity dispersion of the envelope gas (we find 3.65, 1.89 km s\(^{-1}\) for IRDCs F and H) and evaluate \( T_0(B) = (3/2)V P_0 \rightarrow (73, 4.3) \times 10^{46} \) erg, with \( V = (4/3)\pi R^2Z \).

These results indicate that, for both IRDCs, the surface pressure term of the virial equation is comparable to or much larger than the internal kinetic term, although the uncertainties are large. Assuming \( T_0 \gg T \), then for virial equilibrium to be maintained would require \( M = (1/14) \int [\overline{B^2} - B_0^2] \, dV \rightarrow -W, \)
where $B_0$ is the magnetic field strength far from the cloud and $V_a$ is a volume that extends beyond the cloud where the field lines have been distorted by the cloud. Assuming $V_{Va}$ is the volume of the envelope regions and assuming negligible $B_0$, we find $B \gtrsim 10, 13 \mu G$ for IRDCs F and H. If a more realistic value of $B_0 = 10 \mu G$ is adopted (Crutcher et al. 2010), then we find $B \gtrsim 14, 16 \mu G$. Thus, relatively modest magnetic field enhancements could stabilize the clouds.

Bertoldi & McKee (1992) define a dimensionless virial parameter, $\alpha \equiv 5\sigma^2 R_m/(GM)$ to describe the dynamical state of clouds. We adopt a slightly revised definition $\alpha \equiv 5\sigma^2 R/(GM) = a_1a_22T/|W|$, with $a_2$ defined as above. For IRDCs F and H we find $\alpha = 1.78, 3.17$. While these values are quite close to unity, especially for IRDC F, which is commonly taken to infer that self-gravity is important, this is somewhat misleading since the value of $a_2$ is quite small for these elongated clouds and the surface pressure terms seem to be quite important.

It is possible that these IRDCs have not yet reached virial equilibrium if their surroundings are evolving on timescales $\lesssim t_\nu \sim \text{a few Myr}$. The mean velocity of the $^{13}$CO emitting gas in the north and south envelope regions is 55.72, 56.10 km s$^{-1}$, respectively, for IRDC F, and 44.96, 44.28 km s$^{-1}$, respectively, for IRDC H. The north/south velocity dispersions are 3.81/3.38 km s$^{-1}$ for F and 1.69/2.07 km s$^{-1}$ for H. The north/south $\Sigma_{^{13}CO}$’s are 0.040/0.031 g cm$^{-2}$ for F and 0.050/0.051 g cm$^{-2}$ for H. The ratios of north/south pressures (estimated by method B, $\propto \Sigma m^2$) are thus 1.64 and 0.65 for IRDCs F and H. The pressures appear to be fairly similar on the different sides of the filaments, although the uncertainties are such that variation at the level of about a factor of two could be present.

4.3. Filamentary Cloud Virial Analysis

Fiege & Pudritz (2000, hereafter FP00) present a virial analysis of filamentary clouds. They derived the following equation satisfied by pressure-confined, nonrotating, self-gravitating, filamentary (i.e., lengths $\gg$ widths) clouds threaded by helical magnetic fields that are in virial equilibrium:

$$\frac{P_0}{P} = 1 - \frac{m}{m_{\text{vir}}} \left(1 - \frac{M_i}{|W_i|}\right).$$

Here, $P_0$ is the external pressure at the surface of the filament, $P = \rho \sigma^2$ is the average total pressure in the filament, $m$ is the mass per unit length, $m_{\text{vir}} \equiv 2\sigma^2/G$ is the virial mass per unit length, $M_i$ is the magnetic energy per unit length, and $|W_i| = -m^2G$ is the gravitational energy per unit length.

We divide IRDCs F, H into 7, 4 orthogonal strips (see Figures 3 and 4) with angular widths 1.70, 0.955 along the filaments, respectively. Assuming a fiducial value of the inclination angle between the cloud symmetry axis and the line of sight of $\theta = 60^\circ$, these correspond to physical lengths along the filaments of 2.11 and 0.930 pc, respectively.

In Table 3, for each strip in IRDCs F and H, we list the values of $\Sigma_{^{13}CO}$, $\Sigma_{\text{SMF}}$, $M$ (calculated from the mean of these values of $\Sigma$, $m$, $\rho$, $\sigma$, $m_{\text{vir}}$, $P$, $\Sigma_{^{13}CO}(\text{env})$, and $\rho(\text{env})$ (calculated after scaling $\Sigma_{^{13}CO}(\text{env})$ by 0.5($\Sigma_{^{13}CO} + \Sigma_{\text{SMF}}$)/$\Sigma_{^{13}CO}$), $\sigma(\text{env})$, and $P(\text{env})$ $\equiv \rho(\text{env})\sigma^2(\text{env})$). We equate $P_0 = P(\text{env})$.

Following FP00, in Figure 7 we plot $P_0/P$ versus $m/m_{\text{vir}}$. The range of models considered by FP00 allows for positive values of $M_i/|W_i|$ (i.e., poloidally dominated $B$ fields that provide net support to the filament against gravitational collapse) and

![Figure 7](https://example.com/figure7.png)

**Table 3.** IRDC Filamentary Virial Analysis

| Cloud Property | F1 | F2 | F3 | F4 | F5 | F6 | F7 | F7 | H1 | H2 | H3 | H4 | H tot |
|----------------|----|----|----|----|----|----|----|----|----|----|----|----|--------|
| $\Sigma_{^{13}CO}$ (10$^{-2}$ g cm$^{-2}$) | 0.218 | 0.338 | 0.811 | 1.31 | 2.29 | 2.87 | 2.58 | 1.47 | 0.864 | 1.67 | 1.56 | 2.1 | 1.33 |
| $\Sigma_{\text{SMF}}$ (10$^{-2}$ g cm$^{-2}$) | 0.476 | 0.311 | –0.0432 | 0.862 | 1.37 | 1.62 | 1.03 | 0.823 | 1.38 | 1.94 | 1.97 | 3.28 | 2.09 |
| $m (M_\odot pc^{-1})$ | 114 | 107 | 126 | 357 | 601 | 737 | 593 | 2640 | 78.5 | 126 | 124 | 157 | 478 |
| $\rho (10^{-22} g cm^{-3})$ | 54.0 | 50.7 | 59.7 | 169 | 285 | 349 | 281 | 178 | 84.4 | 135 | 133 | 169 | 128 |
| $\sigma (km s^{-1})$ | 3.29 | 3.09 | 3.64 | 10.3 | 38.30 | 21.3 | 17.1 | 10.9 | 22.0 | 35.1 | 34.6 | 44.0 | 33.3 |
| $\alpha (10^{-12} cgs)$ | 1.36 | 1.27 | 1.07 | 1.44 | 1.59 | 1.86 | 2.27 | 1.46 | 1.52 | 1.34 | 1.03 | 0.995 | 1.20 |
| $P (10^{12} cgs)$ | 605.0 | 499.0 | 419.0 | 213.0 | 438.0 | 73.8 | 88.3 | 23.1 | 50.7 | 63.4 | 36.8 | 43.6 | 47.9 |

![Table 3](https://example.com/table3.png)
negative values (i.e., toroidally dominated $B$ fields that provide net confinement of the filament). In all cases, $P_0/P \lesssim 1$. In contrast, we find that all of the filament regions have $P_0/P > 1$, i.e., the pressures in the envelope regions appear to be greater than in the filament. This echoes the results from the ellipsoidal virial analysis, which found large surface pressure terms. Assuming our measurements of pressures are reliable, e.g., are not being adversely affected by systematic effects due to, for example, our assumed filament and envelope geometry, then these results imply that the filaments have not yet reached virial equilibrium.

Very large values of $P_0/P$ are inferred for strips F1, F2, and F3. These are consistent with the filament and envelope spectra shown in Figure 5, which reveal a relatively weak filament and relatively strong and varying envelope velocity profiles. Strips F6, F7, and H2 have the smallest values of $P_0/P \lesssim 2$. Examining the IRAC 8 $\mu$m images (Figures 3 and 4), there is some indication that these are the sites of relatively active star formation (especially F7 and H2). Star formation requires gravitationally unstable conditions in the filament, i.e., regions where self-gravity starts to dominate over external pressure. Our results indicate that this also requires the local region of the filament to reach approximate virial equilibrium, although surface pressure terms still remain dynamically important, i.e., $m/m_\text{vir}$ is significantly less than unity. Given our measurement uncertainties and the fact that the observed regions do not have $P_0/P < 1$, we are not able to determine whether the field geometries are more dominated by poloidal or toroidal components. We note that FP00’s conclusion that observed filaments are dominated by toroidal fields depends on their assumption that the filaments are in virial equilibrium and on their choice of $P_0$, which was not directly measured for most of the sources they considered.

We caution that if independent molecular clouds are present along these lines of sight and with similar velocities to the filaments, then this may cause us to overestimate the velocity dispersion and pressure in the envelope regions around the filaments. From the spectra shown in Figure 5 we do not expect that this is occurring in IRDC H, since the envelope spectra show a very similar velocity range as the filament. The situation in IRDC F is less clear cut, since there appears to be a broader, offset component that dominates more in the envelope region.

5. CONCLUSIONS

We have compared measurements of mass surface density, $\Sigma$, in two IRDC filaments based on $^{13}$CO observations, $\Sigma_{^{13}CO}$, with those derived from MIR extinction mapping, $\Sigma_{\text{SMF}}$, finding agreement at the factor of $\sim 2$ level. A systematic decrease in $\Sigma_{^{13}CO}/\Sigma_{\text{SMF}}$ with increasing $\Sigma$ may be due to a systematic decrease in temperature, increase in the contribution of under-resolved high optical depth regions, increase in dust opacity, or decrease in $^{13}$CO abundance due to depletion in regions of higher column density. Future studies that spatially resolve the temperature structure and MIR dust absorption properties can help to distinguish these possibilities.

We have then used the kinematic information derived from $^{13}$CO to study the dynamical state of the IRDCs. In particular, we have evaluated the terms of the steady-state virial equation, including surface terms, under the assumption of ellipsoidal and filamentary geometries. In both cases, we find evidence that the surface pressure terms are important and possibly dominant, which may indicate that the filaments, at least globally, have not yet reached virial equilibrium.

These results would be consistent with models of compression of dense gas in colliding molecular flows, e.g., GMC collisions. Tan (2000) proposed that this mechanism may trigger the majority of star formation in shearing disk galaxies. The expected collision velocities are $\sim 10$ km s$^{-1}$. It is less clear whether colliding atomic flows (e.g., Heitsch et al. 2008), which form the molecular gas after shock compression of atomic gas, would also produce such kinematic signatures: recall that we are inferring large surface pressures based on $^{13}$CO emission from the envelopes around the IRDC filaments.

Recent observations of extended, parsec-scale SiO emission, likely produced in shocks with velocities $\gtrsim 12$ km s$^{-1}$ in IRDC H by Jiménez-Serra et al. (2010) may also support models of filament formation from converging flows. However, we caution that the observed extended SiO emission is very weak and may also be produced by multiple protostellar outflow sources forming in the IRDC (see Jiménez-Serra et al. 2010 for further discussion).

Our resolved filamentary virial analysis also indicates that the regions closest to virial equilibrium (strips F6, F7, and H2) are those which have initiated the most active star formation. This would be expected if models of slow, equilibrium star formation (Tan et al. 2006; Krumholz & Tan 2007) apply locally in these regions. In this case, these dense regions that have become gravitationally unstable, perhaps due to the action of external pressure and/or converging flows, then persist for more than one local dynamical time and so are able to reach approximate pressure and virial equilibrium with their surroundings. In this scenario, they are stabilized by the ram pressure generated by protostellar outflow feedback from the forming stars (Nakamura & Li 2007).

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