Filament Rotation in the California L1482 Cloud

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Abstract

We analyze the gas mass distribution, the gas kinematics, and the young stellar objects of the California Molecular Cloud L1482 filament. The mean Gaia DR2 YSO distance is 511±12 pc. In terms of the gas, the line-mass (M/L) profiles are symmetric scale-free power laws consistent with cylindrical geometry. We calculate the gravitational potential and field profiles based on these. Our IRAM 30 m multi-tracer position–velocity diagrams highlight twisting and turning structures. We measure the C18O velocity profile perpendicular to the southern filament ridgeline. The profile is regular, confined (projected r ≤ 0.4 pc), antisymmetric, and, to first order, linear, with a break at r ~ 0.25 pc. We use a simple solid-body rotation toy model to interpret it. We show that the centripetal force, compared to gravity, increases toward the break; when the ratio of forces approaches unity, the profile turns over, just before the implied filament breakup. The timescales of the inner (outer) gradients are ~0.7 (6.0) Myr. The timescales and relative roles of gravity to rotation indicate that the structure is stable, long lived (~a few times 6 Myr), and undergoing outside-in evolution. This filament has practically no star formation, a perpendicular Planck plane-of-the-sky magnetic field morphology, and 2D “zig-zag” morphology, which together with the rotation profile lead to the suggestion that the 3D shape is a “corkscrew” filament. These results, together with results in other regions, suggest evolution toward higher densities as rotating filaments shed angular momentum. Thus, magnetic fields may be an essential feature of high-mass (M ~ 10^5 M_☉) cloud filament evolution toward cluster formation.

Unified Astronomy Thesaurus concepts: Molecular clouds (1072); Interstellar filaments (842); Interstellar magnetic fields (845); Interstellar dynamics (839); Giant molecular clouds (653); Young stellar objects (1834)

1. Introduction

Using the 12CO (1-0) Dame et al. (2001) data, Miville-Deschênes et al. (2017) show that the mass function of Milky Way clouds peaks near M = 10^5 M_☉. Moreover, most of the molecular mass is contained in high-mass clouds, with 50% of the mass in clouds above M = 8.4 × 10^5 M_☉. Therefore, characterizing the physical properties of spiny star-forming filaments in clouds near and above the M = 10^5 M_☉ regime is essential for studying “typical” star formation conditions in our Galaxy.

Meanwhile, the clouds that we can observationally access and scrutinize in extreme detail because of their proximity to us (with distances ≤ 500 pc) typically have significantly lower masses (e.g., Lada et al. 2010). The exceptions to this are the California Molecular Cloud (CMC), Orion A, and Orion B, with masses ~ 10^6 M_☉ (e.g., Lada et al. 2009, 2010; Megeath et al. 2012; Kong et al. 2015; Stutz & Kainulainen 2015; Fischer et al. 2017). Only recently identified as a separate massive cloud (Lada et al. 2009 and see below), the properties of the CMC dense gas and young stars are significantly less well characterized than those of the Orion complex. In this paper, our primary focus is on the CMC L1482 filament (red box in Figure 1) gas kinematics. We place these gas measurements in the framework required for robust comparison to recent work in Orion A (Stutz & Kainulainen 2015; Stutz & Gould 2016; Stutz 2018; González Lobos & Stutz 2019) in order to identify possible physical differences that may explain the variations in the observed properties of filaments and their young stars embedded in the gravitational potentials of M ~ 10^5 M_☉ clouds.

The CMC, named after its proximity to the California Nebula, was first thought to be part of the Taurus-Auriga complex (e.g., Ungerechts & Thaddeus 1987; Herbig et al. 2004; Andrews & Wolk 2008). It was identified as a separate region just over a decade ago by Lada et al. (2009). They found this structure to be at a much larger distance (450 pc) compared to the nearby Taurus-Auriga (150 pc) and Perseus (240 pc) clouds. Lada et al. (2009) noted that the CMC had a similar mass (~10^5 M_☉) and filamentary morphology to Orion A, both being nearby giant molecular clouds (GMCs).

Another important similarity between the two was presented in Tahani et al. (2018). Using Faraday rotation measurements, they found that in both the CMC and Orion A, the magnetic field flips its line-of-sight direction from one side of the filament to the other. They interpreted these results as a possible indicator of a helical field morphology on larger (cloud) scales (but see below and Tahani et al. 2019 for results in Orion A). However, the exact 3D magnetic field morphology in filaments (including Orion A and the CMC) remains the subject of ongoing debate (e.g., Heiles 1987, 1997; Fiege & Pudritz 2000a; Matthews & Wilson 2000; Falgarone et al. 2001; Hennebelle 2003; Stutz & Gould 2016; Reissl et al. 2018a; Schleicher & Stutz 2018;
Law et al. 2019, 2020; Tahani et al. 2019; Reissl et al. 2021). For example, one suggested field morphology that could account for the directional flip in the field is a “bow”-type morphology (see e.g., Gómez et al. 2018; Inoue et al. 2018; Reissl et al. 2018a; Li & Klein 2019; Tahani et al. 2019). However, the simultaneous detection of filament rotation may be incompatible with this particular field geometry. Thus, the detection of rotation in filaments may present one avenue to distinguish between plausible magnetic field geometries. Moreover, geometries such as helical or toroidal may play a crucial role in filament formation. They prevent expansion, maintaining the filamentary structure, and may also influence the formation of clumps, thereby impacting the star formation within (e.g., Uchida et al. 1991; Fiege & Putz 2000a, 2000b; Contreras et al. 2013; Stutz & Gould 2016).

More broadly, the detection of rotation in filaments (see, e.g., González Lobos & Stutz 2019 for a possible rotational signature in the Orion A integral-shaped filament, ISF) presents the opportunity to address the angular momentum evolution of massive star- and cluster-forming systems (e.g., Motte et al. 2018; Kong et al. 2019) in the presence of potentially coherent and smoothly varying magnetic fields. It is also essential to connect large- and small-scale field properties in star-forming systems, as will be facilitated in the near future with the Primacam instrument (Choi et al. 2020) on the Fred Young Submillimeter Telescope (formerly CCAT-prime; Terry et al. 2019).

In the southeast of the CMC, we find L1482, which is one of the most massive filaments in the CMC and contains about 100 YSOs (Lada et al. 2009, 2017; Kong et al. 2015). L1482 hosts the reflection nebula NGC 1579, composed of a young stellar cluster and LkHα 101, the only massive (B-type) star in the region (e.g., Herbig et al. 2004; Andrews & Wolk 2008). Thus, the CMC is mostly unaffected by massive-star feedback. By scrutinizing millimeter-wave gas lines, Li et al. (2014) found that the filament structure is most likely coherent, presenting gas velocity gradients (VGs) that they interpreted as possible inflows feeding the stellar cluster in the northern portion of L1482.

As described above, the CMC and Orion A share several important physical attributes. They both have similar mass, similar elongated shape, both contain twisting and winding filaments, and both have comparable magnetic field geometry (along the line-of-sight component) and strengths as probed by Faraday rotation (Tahani et al. 2018). However, despite these similarities, their respective dense gas fraction (Lada et al. 2009) and YSO content are strikingly different. In Orion A, there are more than 3000 YSOs (Megech et al. 2012), whereas the CMC only has about 177 YSOs (Lada et al. 2017). Thus, the CMC is sometimes referred to as a “sleeping giant” (Lada et al. 2017). As this name clearly implies, there is a plausible evolutionary progression between the two clouds. Hence, assuming that the differences can be explained by the CMC being in an earlier evolutionary state at the same mass, the CMC may provide a window into the initial stages of filament evolution and star-cluster formation in GMCs, before reaching the typical yet extreme embedded cluster conditions such as those present in the Orion Nebula Cluster (ONC) and other bona fide (and hence more distant) protoclusters.

The gas gravitational potential is a crucial parameter in a gas-mass-dominated system, such as L1482, because it sets the overall dynamics of the system (e.g., Stutz & Gould 2016). Hence, it forms the basis for any study addressing gas (and stellar) kinematics. In this framework, after presenting the data (Section 2), the first parameter that we must determine is the distance to the system using Gaia (Section 3). We then estimate the gas gravitational potential and field based on the Herschel and Planck mass map (Section 4). This sets the stage for analyzing the gas motions (Section 5) with the goal of characterizing the physical state, specifically highlighting the detection of filament rotation of L1482-south (Section 6). We discuss these results in Section 7 and conclude in Section 8.

2. Observations

2.1. Herschel N_H and T Maps

We use the publicly available Herschel pipeline data from the Harvey et al. (2013) program. These observations were made using the PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) cameras in parallel mode at 160 μm, 250 μm, 350 μm, and 500 μm with beam sizes of 11′′, 18′′, 24′′, and 36′′3, respectively. Well-calibrated flux data are crucial when estimating the temperature (T) maps of a cloud. Here we use the Abreu-Vicente et al. (2017) method to improve the Herschel absolute calibration by using the Planck all-sky dust model and combining the two data sets in Fourier space. We refer the reader to Abreu-Vicente et al. (2017) for more details.

After combining the Herschel and Planck emission maps, we convolve the data to the 500 μm resolution. The convolved images are then regridded to the same pixel scale of 14″ (~0.035 pc at D = 511 pc; see Section 3). We then extract a spectral energy distribution (SED) for each pixel (e.g., Stutz et al. 2010, 2013; Launhardt et al. 2013; Stutz & Kainulainen 2015; Abreu-Vicente et al. 2017). This SED is fit with the modified blackbody function of the form

$$B_\nu = \frac{ΩB_\nu(T_d)}{(1 - e^{-\tau_\nu})},$$

(1)

where Ω is the beam solid angle, B_\nu(T_d) is the Planck function at a dust temperature T_d, and τ_\nu is the optical depth at a frequency ν. Here τ_\nu = N_H m_HI R_d H2 ν / ν, where N_HI = 2 × N(H2) + N(H) is the total hydrogen column density, m_HI is the mass of the hydrogen atom, κ_\nu is the dust opacity, and R_d is the gas-to-dust mass ratio, which is assumed to be 110 (Sodroski et al. 1997). We use the dust opacities from Ossenkopf & Henning (1994), Table 1, column 5. Stutz et al. (2013), Launhardt et al. (2013), and Lombardi et al. (2014) discuss the systematic
uncertainties produced by the model. In Figure 2, we show the resulting \( N_H \) (left panel) and \( T_d \) (right panel) maps. We obtain similar maps to those presented in Lada et al. (2017).

### 2.2. IRAM 30 m Molecular Line Data

We mapped the C\(^{18}\)O (1-0), N\(_2\)H\(^+\) (1-0), HCO\(^+\) (1-0), and HNC (1-0) molecular lines with the IRAM 30 m telescope with the primary goal of measuring the gas kinematics. We choose C\(^{18}\)O (1-0) (109.782 GHz) as our main tracer with the goal of obtaining measurements of the kinematics of the gas. We also measure N\(_2\)H\(^+\) (1-0) (93.173 GHz), a high-density gas tracer that enables us to observe the spine of the filament (e.g., Caselli et al. 2002; Tafalla et al. 2002; Lippok et al. 2013) when detected. We also include HCO\(^+\) (1-0) (89.188 GHz) and HNC (1-0) (90.663 GHz) in our observations for mapping filament motions (such as rotation and infall) that may be present in L1482.

We use the EMIR receiver with the Fast Fourier Transform Spectrometers (FTS) backend for all tracers. For N\(_2\)H\(^+\), the Versatile Spectrometric and Polarimetric Array (VESPA) backend is also used. All of the observations were made using the on-the-fly mapping mode. The central coordinates, sizes, and observation dates are shown in Table 1. In Table 2, we list the spectral resolution, half-power beamwidth (HPBW), and noise levels of our observations. We combine the fields and reduce the data of all tracers using the CLASS package from GILDAS, a software developed by the Institute de Radioastronomie Millimétrique (IRAM). Figure 2 shows the location of our fields of observation. Field 1 covers the northern portion of L1482. Field 2 covers the “transition” zone between the north and the south. Fields 3 and 4 cover the southern portion of L1482.

We also include the \(^{13}\)CO(2-1) data from Kong et al. (2015). These data cover the L1482 filament as a whole and were observed with the 10 m Heinrich Hertz Submillimeter Telescope (SMT) on Mount Graham, Arizona. These data have a 35\(^{\prime}\) beam and a spectral resolution of 0.15 km s\(^{-1}\). We refer the reader to Kong et al. (2015) for further details.

### 2.3. Gaia-detected Spitzer Young Stellar Objects

We use Gaia DR2 data (Gaia Collaboration et al. 2018b) crossmatched with the young stellar object (YSO) catalog from Lada et al. (2017). In Section 3, we obtain a robust sample for astrometric analysis based on the parameters of Gaia-detected YSOs.

| Field | \( \alpha (\degree) \) | \( \delta (\degree) \) | Size (\( ^{\prime} \times ^{\prime} \)) | Observation Date |
|-------|-----------------|-----------------|-----------------|----------------|
| 1     | 67.62           | 35.85           | 900 \times 900  | 2018 Jun 21–23 |
| 2     | 67.69           | 35.72           | 300 \times 300  | 2018 Jul 16    |
| 3     | 67.73           | 35.67           | 300 \times 300  | 2019 Jan 7     |
| 4     | 67.66           | 35.59           | 450 \times 300  | 2019 Jan 7     |

Note: Central field coordinates, sizes, and observation dates. See Figure 2.

### 3. Gaia Distance to L1482

Most of the YSOs in the Lada et al. (2017) catalog are located in projection on the filament (Figure 3). We therefore infer that most YSOs are embedded in the filament, so that their parallaxes provide a good estimate of the gas filament distance (Stutz et al. 2018).

We begin by constraining the region of our analysis to L1482, or \( 66^\circ.99 < \alpha < 68^\circ.27 \) and \( 35^\circ.13 < \delta < 36^\circ.18 \). We correct the zero-point offset in the Gaia parallaxes based on Zinn et al. (2019). For the crossmatch, we set the maximum separation limit to 0.5\(^{\prime}\), because all Gaia-detected sources are within that limit. We accept YSOs with \( G \leq 19 \) mag (Lindegren et al. 2018) and positive parallax measurements in the Gaia catalog. Based on these criteria, we match 34 out of 100 total YSOs in the area of interest. See Figure 3 for the YSO locations relative to the \( N_H \) ridgeline and IRAM 30 m observations.

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9 http://www.iram.fr/IRAMFR/GILDAS
Figure 3. L1482 YSOs from Lada et al. (2017). We show YSOs with Gaia counterparts as filled circles (34 sources); of these, proper motion outliers are indicated in red (7 sources), with the remainder shown in black (see Section 3 and Figure 4). YSOs without Gaia counterparts are shown as black open circles (66 sources). We show the B-star LkHα 101 (Herbig et al. 2004) as an orange star. The N_H ridgeline is represented as a gray line (see Section 4). Vertical black lines indicate the extent of the north (N) and south (S) regions (see Section 5.2).

Figure 4 shows the resulting “raw” proper motion (μ_α, and μ_δ) distribution of the initial 34 YSOs that fulfill the above conditions. Here we observe seven outliers with |Δμ| > 2.4 mas yr^{-1} from the median of the distribution. As noted above, these outliers are located in projection on the filament (Figure 3). Some of these sources have elevated astrometric excess noise in the Gaia catalog, while others have magnitudes near the G = 19 mag threshold, which may worsen the reliability of their properties. We conclude that the μ outliers show indications of corrupted astrometry, possibly due to variability, nebulosity, and/or binarity (see below). We therefore exclude these from subsequent analysis. We obtain a final sample of 27 YSOs with reliable Gaia DR2 measurements.

In Figure 5, we show the parallax distribution of these 27 YSOs. We see that the intrinsic dispersion in the data cannot be fully accounted for by the uncertainties, suggesting that the uncertainties are underestimate of the true uncertainties. To correct for this, we first find the mean value of the parallax, ⟨π⟩, the mean error, and resulting χ^2 = Σ_n(π_n - ⟨π⟩)^2/σ^2, where π_n and σ_n are the Gaia-reported values. Using the formal errors, we obtain ⟨π⟩ = 1.956 ± 0.064 mas and a corresponding χ^2 ≈ 147. This value is large compared to the expected range χ^2 = 26 ± 52 for a χ^2 distribution with N - 1 = 26 degrees of freedom (dof; see Gould 2003). It is plausible that the true Gaia errors are larger than the reported formal uncertainties in the region of the filament. Measurements can be adversely affected by nebulosity, crowding, binaries, and differential extinction to a substantially greater degree than for field stars (Arenou et al. 2018; Gaia Collaboration et al. 2018; Lindegren et al. 2018; Zinn et al. 2019; Penoyre et al. 2020; Rao et al. 2020). We therefore define the augmented reported errors as σ^2 = σ^2 + ε^2, where ε is an error floor. We choose ε to enforce χ^2 = 26 using the renormalized errors. We find ε = 0.29 mas. We measure the error-weighted mean parallax and its standard error on the mean of ⟨π⟩ = 1.956 ± 0.064 mas for the parallax, corresponding to D = 511±17 pc for the distance. The measured distance is consistent with the Zucker et al. (2019) distance of 524±17 pc.

To test for a possible signature of inclination in the filament, we fit the π values as a function of δ (Stutz et al. 2018). We find no robust trend, in agreement with the visual impression from Figure 5. Given the small number of data points and their corresponding errors, this is not a strong constraint, and hence the filament could still have significant inclination.

Table 2

| Tracer          | Frequency (GHz) | HPBW (") | ΔV (km s^{-1}) | Backend | Field 1 | Field 2 | Field 3 | Field 4 |
|-----------------|----------------|----------|----------------|---------|---------|---------|---------|---------|
| C^18O (1-0)     | 109.782        | 22.41    | 0.133          | FTS     | 0.26    | 0.20    | 0.20    | 0.21    |
| N_2H^+ (1-0)    | 93.173         | 26.40    | 0.157          | FTS     | 0.18    | 0.12    | 0.11    | 0.11    |
| HNC (1-0)       | 90.663         | 27.13    | 0.161          | FTS     | 0.19    | 0.13    | 0.12    | 0.13    |
| HCO^+ (1-0)     | 89.188         | 27.58    | 0.164          | FTS     | 0.16    | 0.12    | 0.12    | 0.12    |

Notes. ΔV is the spectral resolution for the respective observation. The last four columns show the noise levels of the data.

4. Mass, Line Mass, Gravitational Potential, and Acceleration

Here we present the mass distribution analysis based on the Herschel N_H map (see Section 2.1). In order to carry out this analysis, we start with the identification of the N_H ridgeline. We use the N_H map (Figure 2) to identify the ridgeline of peak gas surface density as a function of decl. δ. Using the N_H ridgeline, we separate the map into east and west sides. In Figure 6, we show the cumulative mass along δ at different projected radii.
from the \( N_\text{H} \) ridgeline. We show the extents of the north and south regions (see Section 5.2).

From this figure, we appreciate two important features of the mass distribution. First, at each projected radius, the mass increases almost linearly without jumps along \( \delta \). Hence, the cumulative mass distribution is, to first order, only dependent on the projected radius. Second, the distributions are mostly symmetric on each side of the filament, simplifying the geometry of the system. Combined, these features allow us to extract an average cumulative line-mass (M/L) profile for the structures as a whole (Stutz & Gould 2016).

We show the enclosed M/L profile of L1482 in Figure 7. We include the profiles for the north and south regions, separately. The distributions are well approximated by a power law down to the resolution limit of the data. We apply a power-law fit (i.e., a red-line linear fit to the log-log representation in Figure 7) to the filament profiles, including the north and south regions:

\[
\lambda_{\text{app}}(w) = \zeta \left( \frac{w}{\text{pc}} \right)^{\gamma},
\]

where \( w \) is the plane-of-the-sky (POS) projected radius; this expression gives the apparent line-mass distribution in the POS (see Table 3 for the values of \( \zeta \) and \( \gamma \)). This demonstrates that the north region has a higher line-mass profile than the south region. Meanwhile, the total line-mass profile of L1482 is lower than those of Orion L1641, Orion ISF, and the ONC (Stutz & Gould 2016; Stutz 2018), respectively.

Because of the symmetry and radial dependence of the cumulative mass profiles, and the fact that the line-mass profiles are well characterized by scale-free power laws down to the resolution limit of the Herschel data (see Figures 6 and 7), we assume a cylindrical morphology for the filament, with axial symmetry around the \( N_\text{H} \) ridgeline. Below we follow the formalism presented in Stutz & Gould (2016) and Stutz (2018) for the calculations of the apparent POS volume density, gravitational potential, and gravitational acceleration. Table 3 presents the power-law indices and normalizations for the expressions presented below.

The apparent volume density is estimated as

\[
\rho_{\text{app}}(r) = \frac{\gamma(-\gamma/2)!}{2(-\gamma/2 - 1/2)!((-1/2)! \text{ pc}^2)} \left( \frac{r}{\text{pc}} \right)^{\gamma-2}
\]

and the gas gravitational potential follows as

\[
\Phi_{\text{app}}(r) = \psi \left( \frac{r}{\text{pc}} \right)^{-\gamma}.
\]

Given that the gravitational acceleration is defined as \( g(r) = -\nabla \Phi(r) \), then

\[
g(r)_{\text{app}} = -\zeta \left( \frac{r}{\text{pc}} \right)^{\gamma-1}.
\]

The expressions in Equations (2), (4)–(6) represent the POS inferred quantities. They must be multiplied by the unknown projection factor \( \cos(\theta) \), where \( \theta \) is the inclination angle of the filament relative to the POS (see Section 3 for inclination discussion). In Table 3, we give the \( \zeta, \beta, \psi, \xi, \) and \( \gamma \) values for all regions in Figure 7, under the assumption that \( \cos(\theta) = 1 \).

We also analyze the inner mass distribution of IRDC G035.39–00.33 (henceforth G035), located in the W48 complex at a distance of 2.9 kpc. This cloud has a total mass of \( \sim 2 \times 10^4 M_\odot \), presents a filamentary morphology, gas VGs, and low star formation activity in the northern portion (Simon et al. 2006; Nguyen Luong et al. 2011; Kainulainen & Tan 2013; Henshaw et al. 2014). We start with the 8 \( \mu \)m extinction map from Kainulainen & Tan (2013) to derive an \( N_\text{H} \) map of the region. We repeat the mass distribution analysis described above to the subregion analyzed in Henshaw et al. (2014). See Table 3 for the parameters. After the ONC, G035
has the highest line mass of the regions shown in Figure 7 (see Section 7).

5. Filament Gas Velocities

Gas radial velocity maps provide VGs, which may be signatures of rotation, outflows, and/or infall in L1482. Measurements of the line widths allow us to scrutinize the nonthermal velocity dispersion. When compared to the gas gravitational potential, we can then evaluate the physical state of the filament (e.g., González Lobos & Stutz 2019). In our analysis below, we use IRAM 30 m data (Section 2.2) and the Kong et al. (2015) 13CO(2-1) data (Section 2.2).

5.1. Line Fitting

We employ the line-modeling Python package PySpecKit (Ginsburg & Mirocha 2011) to fit line profiles and remove noise from our data. For the line fitting of C18O, HCO+, HNC, and 13CO, we use a single Gaussian fit, included in PySpecKit. The derived parameters for these tracers are the peak of the spectrum, velocity centroid, and velocity dispersion. To model the hyperfine line structure of N2H+, we use the built-in fitter “n2hp_vtau” (Ginsburg & Mirocha 2011) that adjusts multiple Gaussians to the raw spectrum. The derived parameters are the excitation temperature, optical depth, integrated intensity, velocity centroid, and velocity dispersion.

To set a signal-to-noise ratio (S/N) threshold for the fitter, we need to determine the S/N for each spectrum. We create an error map by taking the rms ($\sigma_{\mathrm{rms}}$) values of the spectra in a velocity range without gas emission. We set this velocity range between $-40$ km s$^{-1}$ to $-10$ km s$^{-1}$ for the IRAM 30 m tracers. The mean $\sigma_{\mathrm{rms}}$ for each field is shown in Table 2. For 13CO, we set the velocity range between $-25$ km s$^{-1}$ and $-10$ km s$^{-1}$. For C18O, HCO+, and HNC we find an S/N threshold of 3.5. For both 13CO and N2H+, S/N = 3 produces well-fitted models. These values remove most of the noise without affecting the emission from the filament.

The fitting process requires a user-defined starting point inside the cube and initial guesses to fit the spectrum in this pixel. For all tracers, we use starting values based on the peak of the spectra, first-moment map, and second-moment map values. For N2H+, we also adopt an excitation temperature and optical depth of 6 K and 0.5, respectively. These last two parameters were selected by testing different values until fitter...
result convergence is obtained. In Figure 8, we show one pixel example of the N$_2$H$^+$ modeled cube. In the top panel, we show the original spectrum (black line) and the fit (red line). In the lower panel, we show the residuals.

For the single-component IRAM 30 m models, we remove artifacts produced by bad fits, located in the outer parts of the filament at low S/N. We define S/N = $I_{\text{peak}}/\sigma_{\text{rms}}$, where $I_{\text{peak}}$ is the peak intensity of the modeled spectra and $\sigma_{\text{rms}}$ is derived from the original data in the same velocity range as in the fitter. We measure the S/N in all cubes. For consistency with the fitter procedure, we remove spectra with S/N < 3.5. We obtain good results with this approach, giving us clean models to work with.

In Figure 9, we present the cleaned version of the modeled C$^{18}$O mean line velocity (moment 1) map. In the left panel, we show the standard moment 1 map, while in the right panel we align the map at each $\delta$ to the $N_{\text{H}}$ ridgeline. From this figure, it is immediately obvious, especially in the south region, that we detect a clear and confined VG going from negative $\rightarrow$ positive velocities from east $\rightarrow$ west, “hugging” the $N_{\text{H}}$ ridgeline. Gas VGs have been detected in different filamentary systems with different proposed origins such as filamentary rotation, shear, gas inflow, and cloud–cloud collisions (e.g., Uchida et al. 1991; Fernández-López et al. 2014; Henshaw et al. 2014; Jiménez-Serra et al. 2014; Lee et al. 2014). We study this VG in detail in Section 6.

For $^{13}$CO, C$^{18}$O, HCO$^+$, and HNC, the line widths present large variations along $\delta$. Here we test whether the large velocity dispersions are the result of fitting a double-component or more complex line profile with a single Gaussian by using a double-component model. From the double-velocity-component fitting results, we find that most spectra can be fitted with only one Gaussian, while the secondary component generally has low S/N compared to the defined threshold. In order to identify spectra with reliable double components, we define a temperature threshold. If the peaks of both components are above the threshold, we consider them well detected. For C$^{18}$O, we identify two well-fitted velocity components when we set this threshold to 0.8 K, almost three times the noise value of Field 1 (see Table 2). From the above procedure, we conclude that $\sim$13% of the C$^{18}$O data contains double components. These are mainly located at or near the $N_{\text{H}}$ ridgeline. When fit individually, the components of these spectra have slightly lower line widths compared to the single components. The north region presents more double-component spectra compared to the south, as we expect (see discussion below). In order to avoid line-width and velocity contamination or confusion in the subsequent analysis, we remove the pixels in which double-component spectra are detected (see Figure 10).

In short, the single-component spectra dominate the spectral cubes, and the measured velocities and the line widths of the fitting procedure agree well with previous observations of L1482 (e.g., Li et al. 2014; Kong et al. 2015). The removal of the double-component spectra does not affect the results of our analysis below. Moreover, we find no C$^{18}$O or HCO$^+$ spectra.
exhibiting a clear blue asymmetry or an inverse P Cygni–like profile. Such profiles would indicate infall along the line of sight (e.g., Myers et al. 2000; Smith et al. 2012; Evans et al. 2015). The absence of an infall signature may be caused by the resolution of our data. We conclude that our procedure adopting single-component fits is robust. In the sections that follow, we use these to analyze the velocity structure of L1482.

5.2. Intensity-weighted Position–Velocity Diagrams

Using the fitter results described above, we generate intensity-weighted position–velocity (PV) diagrams for the IRAM 30 m data, presented at different velocity offsets in Figure 11. Here we show the best-fit gas velocities as a function of $\delta$ along the filament, weighing by the integrated line intensity. This technique is described in detail in González Lobos & Stutz (2019); it removes noise present in the traditional PV diagram method while highlighting structure that would otherwise be muddled or invisible (see their Figures 3 and 4).

In Figure 11, we see similar structures in C$^{18}$O and HCO$^+$ across most of the extent of the filament. High-density gas, as traced by N$_2$H$^+$, is mostly not detected at $\delta \lesssim 35^\circ$71. Moreover, at $\delta \sim 35^\circ$71, there is a discontinuity in the filament that is coincident with a jump in the N$_{HI}$ map (see Figures 2 and 9). This jump marks the transition between two physically distinct filament environments. Above this location, we have a higher M/L region, which contains more YSOs (see Figure 3), while below the jump we find a more confined filament with lower M/L values (see Figure 7 and Table 3). We therefore divide the filament into two subregions. The northern region encompasses $\delta = 35^\circ$71 $\rightarrow$ 35$^\circ$98. The southern region encompasses $\delta = 35^\circ$71 $\rightarrow$ 35$^\circ$54.

In Figure 11, we observe in all tracers the presence of elongated structures with gradients. These have slopes, given the axis ratio of the plot, approximately consistent with 1 Myr timescales (but see discussion below). Along the filament, we also identify structures that have an appearance consistent with wrapping or winding, perhaps most obvious in C$^{18}$O in the southern portion of the filament. In this region the filament has a clear “zig-zag” morphology in N$_{HI}$ (see Figure 2), potentially indicating a corkscrew or helical-like morphology in 3D. Overall, the velocity wiggles are reminiscent of the structures in the ISF in Orion A (see Figure 4 of González Lobos & Stutz 2019).

At $\delta \sim 35^\circ$83, we observe a large spike in velocity where the filament appears to have two well-separated velocity components, most obvious in HCO$^+$, HNC, and to a lesser extent in N$_2$H$^+$. The region at the east of the ridgeline in the C$^{18}$O first-moment map (see Figure 9) exhibits compact blue- and redshifted velocities near this location. These alone might plausibly indicate some YSO-associated outflow activity. However, the appearance of this feature, albeit at fainter levels, in N$_2$H$^+$ indicates that this velocity pattern persists in the denser gas, where outflow signatures may be less likely to arise.

The feature bears some resemblance to the N$_2$H$^+$ velocity spike observed by González Lobos & Stutz (2019) in Orion A at $\delta \sim 5^\circ$4, that is, in the center of the ONC gas filament. In the present case, the maximum velocity shift between the two N$_2$H$^+$ loci is $\sim$1.5 km s$^{-1}$, while in the ONC it is $\sim$4 km s$^{-1}$. The C$^{18}$O velocity pattern continues to the south to $\delta \sim 35^\circ$74, progressing through a series of back-and-forth wiggles until $\delta = 35^\circ$71, where the filament breaks and jumps over both in projected position (in the N$_{HI}$ map and see above) and in velocity, which may bear some relation to the drastic break in the ISF near $\delta \sim 5^\circ$5. The general appearance of the velocity patterns in L1482 is somewhat similar to the ISF (González Lobos & Stutz 2019), but with smaller amplitudes.

5.3. Mach Number Profiles across the Filament

Here we analyze the gas line widths. Variations in the velocity dispersion across the filament are useful for identifying variations in the gas kinematics within the filament (see, e.g., Federrath 2016). In the top-right panel of Figure A1, we show the C$^{18}$O second-moment map. In what follows, we compare the line-width profiles in the north and south regions of L1482.

We measure nonthermal motions in the gas through the nonthermal line width ($\sigma_{NT}$) and Mach number ($M$). We derive...
the nonthermal line width as 

\[ \sigma_{NT} = \sqrt{\sigma_{obs}^2 - kT_k/m} \]

(Liu et al. 2019; González Lobos & Stutz 2019), where \( \sigma_{obs} \) is obtained from the moment 2 velocity dispersion data, \( m \) is the mass of the molecule, \( k \) is the Boltzmann constant, and \( T_k \) is the gas kinetic temperature. We assume that \( T_k \) is equal to the dust temperature \( T_d \) in the filament, where the hydrogen densities are higher than \( 10^4 \) cm\(^{-3} \) and the gas and dust are coupled (e.g., Lippok et al. 2013). In Appendix B, we fit a softened power-law profile to the Herschel \( T_d \) map (see Section 4). We derive the Mach number profile \( \mathcal{M} = \sigma_{NT}/c_s \), where \( c_s = \sqrt{kT_k/\mu m_H} \) is the sound speed, \( \mu = 2.33 \) is the mean molecular weight, and \( m_H \) is the hydrogen atomic mass (González Lobos & Stutz 2019; Liu et al. 2019).

In Figure 12, we present the mean \(^{13}\text{C} \text{O} \) Mach number profiles as a function of distance from the \( N_H \) ridgeline in the north and south regions separately (see above and González Lobos & Stutz 2019 for a similar analysis in the ISF). \(^{13}\text{C} \text{O} \) has a mildly supersonic profile (\( \mathcal{M} \sim 1.2 \)) in the south but a more elevated supersonic profile in the north. For \(^{13}\text{C} \text{O} \) North, the portion of the filament with actual star formation, the profile peaks toward the filament ridgeline, as opposed to decreasing with density toward the center. This centrally increasing trend is the opposite of that found in the simulations of Federrath (2016). They measure the Mach number profiles in simulations that aim to capture the primary agents that will affect the velocities, such as gravity, turbulence, magnetic fields, and jet and outflow feedback, all of which should be in operation in the CMC/L1482 North filament. In contrast, when we look in the south, the Mach number profile is almost flat over the extent that we are able to probe. In either the north or the south, over the spatial scales that we probe, we observe no transition to a subsonic regime as reported in Federrath (2016). The elevated values of \( \mathcal{M} \) that we observe could be caused by various observational effects, of which line-of-sight averaging and spatial resolution may be the first-order culprits. Both of these effects may broaden the measured line widths to some extent. However, with a higher density tracer such as \(^{13}\text{C} \text{O} \), we do not expect these effects to be dominant.

As already noted above and by González Lobos & Stutz (2019), our measured Mach number profiles can be compared to simulated profiles, similar to those presented in Federrath (2016) and in particular their Figure 5, so long as the simulations capture the high-mass regime (which the Federrath 2016 simulations do not). Moreover, these should be compared to observations in other filaments at the same mass regime, such as those presented in González Lobos & Stutz (2019). See discussion below.

### 6. \(^{18}\text{O} \) VG across the Filament

Here we characterize the VG of \(^{18}\text{O} \) across the filament in the south region, observed as a prominent feature in Figure 9. Given the confined symmetry of the gradient on either side of the ridgeline (see also Figure A1), the fact that it is detected along the entire \( \delta \) range that we probe, and the lack of clear infall detections on these scales (see above), this signature is consistent with a rotational origin as opposed to arising from, for example, cloud–cloud collisions (e.g., Olmi & Testi 2002; Fukui et al. 2018).

We characterize the magnitude and spatial extent of this gradient as follows. In Figure 13, we show the \(^{18}\text{O} \) velocity vs. radius map and corresponding gradients. In order to measure the gradients, we must first construct mean aligned velocity versus radius maps. We accomplish this by:

1. Aligning the data cube w.r.t. the \( N_H \) ridgeline in \( \delta \) (see Figure 9).
2. Marginalizing over the aligned \( \delta \) coordinates in the south region.
3. Fitting the gradient in projected radius versus velocity.

We obtain the intensity–weighted mean velocity as a function of radius, shown in Figure 13 as the blue and red curves, and the intensity–weighted standard deviation of the velocity distribution at each radius, represented with dotted black curves in the figure. Because we wish to compare a single VG, we average the blueshifted (east side) and redshifted (west side) velocity profiles (mean profiles are shown as the dashed black
we fit a line to these mean V(r) curves (shown as white arrows) to obtain the VGs (VGapp), or equivalently timescales τapp = 1/VGapp presented as translucent white arrows in the figure with corresponding inner (outer) timescales of 0.7 (5.9) Myr. As above, we must correct for the (unknown) inclination of the filament by dividing VGapp by the factor cos(θ), where θ is (as defined above) the inclination of the filament relative to the POS.

Figure 13 reveals that the C18O South velocity profile (and therefore associated gradients) is approximately antisymmetric about the N1 ridge (which defines r = 0), as illustrated by the similarity between the red- and flipped blushed curves in the diagram. Moreover, the transition to the shallower gradient at r ≈ 0.25 pc is also antisymmetric. This high degree of antisymmetry lends very strong support to the rotational interpretation of the velocity profile. Moreover, the inner gradient is approximately constant with radius. This may imply, to return to this in Section 7 below. To second order, the diagram interpretation of the velocity profile. Moreover, the transition to the shallower gradient at r ≈ 0.25 pc is also antisymmetric. This high degree of antisymmetry lends very strong support to the rotational interpretation of the velocity profile. Moreover, the inner gradient is approximately constant with radius. This may imply, to return to this in Section 7 below. To second order, the diagram interpretation of the velocity profile. Moreover, the transition to the shallower gradient at r ≈ 0.25 pc is also antisymmetric. This high degree of antisymmetry lends very strong support to the rotational interpretation of the velocity profile.

In addition to the differences between the north and south, we find that in particular, in the C18O South diagram (Figure 13), the gradient exhibits a clear and regular radial dependence, mentioned above. In the inner portion of the filament, the gradient appears somewhat steeper, indicating a shorter timescale (τapp = 0.7 Myr), while the outer portion transitions to a shallower gradient and correspondingly longer timescales. At a radius of r ≈ 0.25 pc, the velocity profile flattens significantly, departing from the regular velocity pattern that we observe at smaller r. This outer flatter region has a gradient consistent with timescales of τapp ≈ 5.9 Myr (see discussion below).

Moreover, such structures will benefit from detailed modeling of the velocity field. We defer this investigation to future work using, e.g., the POLARIS line radiative transport modeling capabilities (see, e.g., Reissl et al. 2018a, 2018b).

### 7. Discussion

In Figure 13, we have shown that the filament exhibits a clear, regular, and linear velocity profile pattern consistent with rotation. To first order, the inner portion of the velocity profile is consistent with solid-body rotation. However, clear departures from this simple model are obvious: the velocity profile has a clear break at r ≈ 0.25 pc, where the velocity profile transitions to a shallower gradient. Moreover, in Figure 12 we show that the gas line widths and thus nonthermal motions are only moderately supersonic (with Mach numbers ≈1.2).

The question that we must address now is how the gas motions, inferred from the rotation signature (Section 6), compare to gravity (Section 4). We do this by comparing the gravitational force to the centripetal force, taking advantage of the simplicity of the solid-body rotation implied by the linear appearance (to first order) of the gradients presented in Figure 13 (also see Section 6). We estimate the centripetal force as

\[
F_c(r) = ma_c; \quad a_c = \frac{v^2}{r \cos^2(\theta)};
\]

where m is the gas mass, θ is the inclination of the filament relative to the POS, and v is the velocity profile at each radius (see Figure 13). The force of gravity is given by

\[
F_g(r) = mg(r) = mg_{app}(r) \cos(\theta),
\]

where \(g_{app}(r) = \frac{\xi(\frac{r}{pc})^{-1}}{\cos^3(\theta)}\) is the gravitational acceleration from Equation (6) and Table 3. From Equations (7) and (8), we obtain the ratio

\[
\frac{F_c}{F_g} = \frac{v^2}{rg_{app}(r) \cos^3(\theta)} = \frac{v^2 pc^{-1} (r pc)^{-\gamma}},
\]

or

\[
\frac{F_c}{F_g} = \frac{pc}{\tau_{app}^2 \xi \cos^3(\theta)} (r pc)^{-2-\gamma},
\]

where \(\xi\) and \(\gamma\) are listed in Table 3.

In Figure 14, we present the apparent (POS) \(F_c/F_g\) profile for the south portion of the filament as traced by C18O. The basic features of this diagram show that the role of rotation relative to gravity increases with radius until r ≈ 0.25 pc, inside of which the timescales are ≈0.7 Myr. At r ≈ 0.25 pc, gravity takes over, regulating the filament structure just when the rotational profile would imply breakup or near breakup of the filament.

Moreover, the VG (on both sides of the filament) is very smooth and regular (see Figure 13), which can be interpreted as the filament being in a dynamically relaxed state. To arrive at such a state, the filament must have undergone a ~couple of orbits. This then raises the question of timescales. The outer timescale (~6 Myr) is long compared to the inner one, implying that this structure is stable and long lived, with a lifetime of ~a few times 6 Myr. Gómez & Vázquez-Semadeni (2014) and Gómez et al. (2018), based on simulations with and without magnetic fields, find stable and long-lived filamentary structures with approximately similar lifetimes. They attribute these longer timescales to the stability imparted by mass accretion from the immediate environment. This agreement between the timescales we measure here and the previously simulated ones is encouraging. However, the comparison may be limited as the simulated filaments in Gómez & Vázquez-Semadeni (2014) and Gómez et al. (2018) have lower line masses (~40 \(M_e\) pc~3), are embedded in lower mass clouds, and do not show obvious rotation signatures.

If the inclination is nonzero, the role of rotation will be larger compared to gravity, driving the outer force ratio profile closer to unity, and thus closer to breakup. The basic appearance of this diagram therefore implies outside-in evolution of this filamentary structure as the action of gravity and the removal of angular momentum progressively remove support, allowing for progressive mass concentration (see Figure 7) and eventual star formation to take place.

In Figure 14, we also include the \(F_c/F_g\) profile for the G035 (e.g., Henshaw et al. 2013; Jiménez-Serra et al. 2014) \(N_2H^+\) data presented in Henshaw et al. (2014), which has been
previously proposed to be in an early evolutionary state. The gas kinematics in this filament exhibit a VG, with an east to west orientation, similar to L1482. These authors measure a gradient of $-13.9 \ km\ s^{-1}\ pc^{-1}$, for which the $F_z/F_r$ profile is presented as the solid black line in Figure 14, labeled as “B12–B16” (see appendix of Henshaw et al. 2014). However, we note that their figures are consistent with a somewhat shallower average gradient of $-8.7 \ km\ s^{-1}\ pc^{-1}$, which we present in the $F_z/F_r$ profile as a dashed black line in the same figure. Whatever measure of rotation, G035 appears much more rotationally dominated compared to the L1482 filament. This may partially be caused by the higher density tracer used by Henshaw et al. (2014), or the proposed early evolutionary state of the G035 filament (Henshaw et al. 2013). If the latter, the G035 filament may not have had time to dissipate its angular momentum to collapse toward cluster formation. Another possibility is that the inclinations of L1482 versus G035 are different, which may account for some of the observed differences. At present, we have no strong constraints on the inclination for either system.

If the L1482 filament inclination is significant, then rotation will play a larger role. In Section 3 we find no significant correlation between $\delta$ and $\pi$ over the filament as a whole. As discussed, this represents a weak constraint on the system inclination due in part to the small number of Gaia-detected YSOs and their corresponding $\pi$ errors. Meanwhile, the clear “zig-zag” POS morphology of the south region as a whole may indicate a corkscrew or “pig-tail”-like morphology (and see below). Such undulations would cause us to again underestimate the role of rotation relative to that of gravity. Hence, the basic appearance of Figure 14 is consistent with rotation playing a significant role in the south while being comparatively less dominant in the north, which is clearly gravitationally dominated since it is presently forming stars, and has a larger accompanying line-mass profile.

A velocity feature similar to that measured in L1482 has been studied in the Orion A ISF, reported by González Lobos & Stutz (2019 and references therein) which they interpret as rotation. Based primarily on $^{12}$CO PV diagrams, they identify two velocity components in the northern half of the ISF (see their Figure 8 and Section 4.4) with estimated mean spatial separations of $\sim1.3\ pc$ and angular velocities (assuming circular rotation) of $\sim1.4\ Myr^{-1}$. On smaller scales, they also present N$_2$H$^+$ “bumps and wiggles” (see their Figure 4) that appear consistent with torsional-type structures with short timescales. While the relation between the larger $^{12}$CO and smaller-scale N$_2$H$^+$ velocity features in Orion A is not presently understood, they both present the appearance of rotational structures. The features that we characterize here in L1482, in contrast, are found in a lower density filament (see Figure 7), are closer to the central axis of the filament (the $N\_H^\text{top}$ ridgeline) than the $^{12}$CO Orion velocity feature, and may present different inner-filament timescales.

In terms of the magnetic field as probed by linear polarization, we can compare L1482, Orion, and G035. In G035, the projected magnetic field orientation presented by Liu et al. (2018) in the central portion “M” (high density) is perpendicular to the filament. The north and south portions (lower density) show a magnetic field almost parallel to the filament. This trend has been studied in multiple systems, including L1482 and the Orion A ISF region, containing the ONC. In Figure 15, we show the Planck polarization data (Planck Collaboration et al. 2014), which exhibits a projected field orientation that is preferentially perpendicular to the main filament axis (e.g., Li et al. 2015; Planck Collaboration et al. 2016; Tahani et al. 2018; Soler 2019). The magnetic field morphology can be interpreted in 3D as

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**Figure 14.** Ratio between the centripetal ($F_c$) and gravitational ($F_g$) forces (see Equation (9)). We represent the C$^{18}$O South profile with a dashed red line. We include the profiles of slices B12–B16 (black solid line) and B14 (black dashed line) from the IRDC G035 (Henshaw et al. 2014). We show $F_z/F_r = 1$ with a dashed gray line. These curves, taken at face value, assume $\cos(\theta) = 1$, that is, that the filament is not inclined relative to the plane-of-the-sky (see text). For C$^{18}$O South, we see that gravity dominates over rotation, presenting a turning point at $r \sim 0.25\ pc$. If the inclination of the filament is significant, then rotation will be more dominant.

**Figure 15.** Planck $N\_H$ map (background) of the Orion ONC (top) and L1482 (bottom), both regions highlighted with red boxes. Red lines show the polarization vectors rotated by 90° to indicate the orientation of the magnetic field projected on the plane of the sky. For both the ONC and L1482, the projected magnetic field is perpendicular to the filaments.
either helical or bow-like (e.g., Gómez et al. 2018; Inoue et al. 2018; Tahani et al. 2018, 2019; Li & Klein 2019). Moreover, close inspection of Figure 9 reveals that the northern portion of L1482-south has more prominent blueshifted velocities, while the southern portion has more prominent redshifted velocities, a signature that may be consistent with a helical velocity field in a filament with a 3D morphology similar to a corkscrew. One key question here is if the filament rotational motions may be linked to the 3D structure of the magnetic field in these systems, as seen for example in L1641 (Uchida et al. 1991). The combination of rotational motion about the long axis and a helical, or possibly bow-like (but see below), magnetic field morphology may be the most natural explanation that accounts for the combination of the observed gas radial velocities, the linear polarization patterns, and the overall “zig-zag” morphology of the filament. As discussed above, we suggest that future modeling of molecular line emission under various assumptions for the 3D density, velocity, and magnetic field properties would shed light on the structures we observe (e.g., Reissl et al. 2018a, 2018b) and potentially yield constraints on the pitch angle of the magnetic field in this system.

In terms of simulations, we find none, to the best of our knowledge, that reproduce rotational signatures similar to the ones we observe. In simulated turbulence and gravity-driven filament formation (e.g., Priestley & Whitworth 2020), even when including magnetic fields (e.g., Federrath 2016; Körtgen et al. 2017; Gómez et al. 2018; Li & Klein 2019; Seifried et al. 2020; Wareing et al. 2021), rotation is not present. Moreover, these simulations probe low-mass and mass-per-unit-length scales compared to $\sim 10^4 M_\odot$ clouds and their correspondingly higher M/L filaments like California and Orion (see Table 3). See also Reissl et al. (2021) for a direct comparison between the line mass profiles in Orion and California/L1482 compared to one example of an MHD simulation of a filament.

Moreover, Inoue et al. (2018) and Li & Klein (2019) simulate somewhat higher mass clouds or regions, including models for magnetic fields. Li & Klein (2019) illustrate how the bow-shaped B-field morphology, in particular the directional flip on either side of the filament, is also consistent with the signature of a helical field along specific sight lines (see their Figure 16). While they do not analyze the kinematics of the dense gas in detail, required for comparison to the specific signature presented here, they do detect a simulated flip in the velocity field on either side of the filament along certain sight lines. Furthermore, their simulated filament is mostly very straight along its extent, exhibiting only slight, gentle curvature, and not the “zig-zag” morphology that we observe here. Inoue et al. (2018) simulate the collapse in a small ($r = 1.5$ pc) but massive ($M = 838 M_\odot$) region. Their simulation produces a more massive sink particle ($M \gtrsim 50 M_\odot$) on an extremely short timescale of $\sim 0.45$ Myr. Taking cuts across the sink particle, they recover some simulated VG; however, we observe no such analogies to massive sink particles (presumably these would be massive and very compact “clumps”). On the contrary, we have shown that our observations are consistent with a relatively smooth mass distribution along L1482-south. In summary, the detection in simulations of features resembling VGs are an intriguing possibility for explaining the basic velocity flip that we detect; however, we must not only explain this flip, but also the magnitude compared to gravity, the outer break and transition to shallower gradients, and the basic filament properties. Furthermore, these models require viewing the simulated filaments at specific angles in order to be consistent with the data and reproduce flips about the ridgelines, which may be reasonable for randomly oriented sets of filaments. However, the Gaia data (although this is not a strong constraint at present) would seem to imply that overall, L1482, on larger scales, is not strongly inclined.

Meanwhile, lower density cosmological simulations also produce non-rotating filaments that arise due to the action of gravity (e.g., Springel et al. 2018). This is consistent with the idea that gravoturbulent filaments simply do not rotate. In terms of observations, the situation is less clear but the existing data point toward a scenario where rotation appears not to be found in filaments in lower mass clouds (e.g., Hacar et al. 2013, 2016; Kirk et al. 2013; Shimajiri et al. 2019) but was analyzed for example in the high-mass Orion A L1641 filament (Uchida et al. 1991). In particular, in Shimajiri et al. (2019), they study the VGs in the Taurus B211/B213 in $^{12}$CO and $^{13}$CO (1-0).

These authors interpret their velocity data with a model composed of two intersecting lower density sheets, observed at a specific viewing angle, and conclude that this particular system is well reproduced by this configuration. They also note that because their tracers are optically thick, they require optically thin dense gas tracers to probe the velocity field inside the filament. As noted above, this is a straight filament, it is a lower mass and lower line-mass system: the Taurus B213 has a line mass of $\lambda_{\text{app}} \sim 100 M_\odot$ pc$^{-1}$ at a projected radius of $r \sim 1$ pc, about a factor of 2 lower than our measured $\lambda_{\text{app}} = 205 M_\odot$ pc$^{-1}$ measured at the same projected radius of $r = 1$ pc (see Table 3). The morphologies of the two filaments are very dissimilar, one being straight and mildly curved, while the L1482-south filament has a POS “zig-zag” morphology.

Gradients have also been observed and quantified in other low-mass regions, such as Serpens-Main (e.g., Olmi & Testi 2002; Lee et al. 2014), using optically thin and high-density gas tracers. In particular, Lee et al. (2014) observe a perpendicular gradient in the “FC1” filament in $N_2H^+$, with an apparently sharp velocity jump. However, their main focus was the gradient along the filaments, and they do not suggest a physical origin for the perpendicular VGs. In Serpens-south, a cloud assumed to be associated with Serpens-Main, Fernández-López et al. (2014) find perpendicular gradients in $N_2H^+$ for filament “FE” ($11.9 \text{ km s}^{-1} \text{ pc}^{-1}$) and “NFW,” but also do not compare the VGs to gravity. They postulate that the origin of these gradients is accretion from the local filament environment, and as a result of projection in a flat structure that is inclined. In order to quantify how these gradients and their timescales compare with gravity and the L1482 filament, we suggest that they should be revisited in combination with M/L profiles, similarly to the method we present in this paper. We also note that the simulations outlined above, and the low line-mass filaments analyzed in these observational studies, do not exhibit the two-dimensional “zig-zag” morphology that we observe in L1482. However, see Wareing et al. (2021; in particular their Figure 6) for simulated filaments with “wiggles,” which may be comparable to the “zig-zag” structure we observe. However, the Wareing et al. (2021) numerical experiments do not reveal rotation, emphasizing the importance of a comparison to all observational constraints presented here, and in particular, the kinematic signatures presented in Figure 13.

Moreover, the lack of alignment between YSO outflows and filament orientation reported in Perseus (Stephens et al. 2017) may be consistent with the idea that lower mass clouds have more elevated levels of turbulent (and thus randomized velocity) support compared to higher mass clouds, as suggested
by Stutz & Gould (2016). In contrast to Perseus, Kong et al. (2019) report the detection of filament–outflow orientation anticorrelation in the massive ($M \sim 10^5 M_\odot$) G28.37+0.07 cloud. This may support the view presented in Stutz & Gould (2016) that the internal evolution of high-mass clouds may be qualitatively different from that of low-mass ones, specifically in relation to the role of rotation and the magnetic field in the collapse process.

Given the lack of rotation in lower mass turbulence simulations and lower mass clouds, the observations we present here would then lead to the suggestion that there must be some other mechanism for filament rotation in higher mass clouds. As mentioned above, the magnetic field is the only agent capable of playing this role (see, e.g., Hennebelle 2018; Schleicher & Stutz 2018, and references therein). It may potentially act via magnetic braking (by analogy to stars). This would imply that all filaments that are rotating must remove inner angular momentum via the magnetic field in order to collapse. The magnetic field would transport this rotational energy from small scales near the filament spines to larger radii. The observation of the more evolved L1482-north filament within this same cloud and just to the north, with fragmentation, accompanying protostar formation and no clear rotational signature, may support this idea of filament evolution. On the other hand, if the rotational signature is an imprint set by the earlier and diffuse ISM phase of cloud evolution, the question remains as to why lower mass clouds and their lower line mass still star-forming remnants are not rotating. Either the filaments were never rotating, which could be related to their mass scale as suggested here, or observations and simulations should be able to capture an earlier lower density phase of angular momentum dissipation.

We speculate that the structures reminiscent of helical or double-helix loops seen here (see Figure 11), in Orion A (González Lobos & Stutz 2019) and possibly to be seen in the G28.37+0.07 cloud (Kong et al. 2019), are the anchors of the magnetic fields. In this case, these would also be inevitable features of massive star-forming filaments. If correct, this would make magnetic fields an essential feature of (massive) star- and cluster-forming filaments. Linking the rotational signatures to the magnetic field naturally leads to a torsional, helical, or bow-like field morphology. The observed velocity flip perpendicular to the L1482-south ridgeline (Figure 9) is also accompanied by a flip in the magnetic field (Tahani et al. 2018) in California on larger scales, a flip that these authors interpreted as a possible signature of magnetic field helicity. The connection between the large-scale inferred field geometry and the small-scale velocity feature we detect is not presently understood and must be investigated in future work.

8. Conclusions

Previous studies have shown that the CMC is similar to Orion A in terms of mass ($M \sim 10^5 M_\odot$), morphology, undulating filaments, and magnetic field geometry but strikingly different in YSO content (Lada et al. 2009; Megeath et al. 2012; Kong et al. 2015; Lada et al. 2017; Tahani et al. 2018). We present the study of the filament L1482 located in California. L1482 is one of the most massive filaments in California and contains ~56% of the YSOs in the cloud. Here we characterize the physical properties of this filament by combining the analysis of YSO distance information, gas mass distributions, and gas velocities. We summarize our main results as follows.

1. We find a distance of 511+17−16 pc based on Gaia DR2 astrometry of YSOs in the filament.

2. Using Herschel and Planck $N_H$ maps, we characterize the projected mass per unit length (M/L) of the L1482 filament as a whole, and divide the filament into two distinct regions based on differences in the presence of star formation, M/L profiles, morphology, and gas velocities (see below): the south, with a lower M/L, no star formation, a POS “zig-zag” morphology, and coherent velocity patterns, versus the north, with star formation, a higher M/L profile, and more chaotic velocity patterns.

3. All of the above regions of the filament have M/L profiles consistent with a scale-free power-law shape. At 1 pc, the filament as a whole, the north, and the south regions have M/L power-law normalizations of 214, 264, and 205 $M_\odot$ pc$^{-1}$ and power-law indices of 0.62, 0.51, and 0.64, respectively. See Table 3 and Figure 7 for full M/L profiles.

4. Based on the M/L profiles, and assuming cylindrical geometry and axial symmetry motivated by the mass distribution (see Figures 6 and 7), we calculate the volume density, gravitational potential, and gravitational acceleration profiles. See Table 3.

5. We present intensity-weighted PV diagrams of IRAM 30 m observations of $^{13}$CO, HCO$^+$, HNC, and N$_2$H$^+$ (1-0). These reveal complex twisting and turning velocity structures, with timescales of order ~ 1 Myr. These undulations are particularly striking in the south of L1482 in $^{13}$CO.

6. We detect a velocity profile in $^{13}$CO consistent with rotation about the long axis of the south filament. The velocity profile pattern is regular and smooth. Its profile “hugs” the filament, that is, it is confined to within $r \lesssim 0.4$ pc from the $N_H$ ridgeline and is antisymmetric about the ridgeline. See Figure 13.

7. The above velocity profile grows linearly to $r \sim 0.25$ pc, outside of which it softens to a shallower slope. The inner ($r \lesssim 0.25$ pc) timescale of the VG is 0.7 Myr. The outer ($r > 0.25$ pc) timescale is much longer, about 6 Myr.

8. When compared to the gravitational field, and using a simple solid-body rotation toy model, the rotational profile implies that the filament approaches breakup at $r \sim 0.25$ pc, where it transitions to being gravity regulated. See Figure 14.

9. The long timescales on the outside of the rotational profile, combined with the break in the rotational profile, imply that the filament structure is stable and long lived (few times 6 Myr) and that the filament is undergoing outside-in evolution in the process of dissipating its angular momentum toward collapse and eventual star formation (as is observed in the north portion of the larger L1482 filamentary structure).

10. The above results assume the filament is oriented in the POS. While the filament inclination is not well constrained, the role of rotation compared to gravity will only be greater if the inclination is nonzero.

11. The Planck polarization vectors, rotated to infer the POS magnetic field geometry, are approximately perpendicular to the main filament axis, as is also seen in other clouds such as Orion A and in G035. The appearance of the PV diagrams, the rotational signature discussed above, and the POS “zig-zag” morphology of the filament, taken together with Planck, may imply a 3D “corkscrew” filament with a helical magnetic field morphology could be a natural explanation of the various
observational constraints. Meanwhile, a “bow-” shaped field (as reproduced in simulations) may also account for certain observational features, such as the flip in the magnetic field along the line of sight and the magnetic field in the POS being perpendicular to the filament.

Comparison to turbulence and MHD simulations (which do not show rotation in filaments), observations of lower mass filaments (which also do not show rotation; see the related discussion in Section 7), previous results in Orion A, constraints from, e.g., the G035 filament, together lead to the suggestion that high-mass \((M \sim 10^3 M_\odot)\) clouds host rotating filaments that may be more common than previously thought. In this hypothesis, these structures must undergo angular momentum evolution (e.g., Hennebelle 2018 and references therein), for example, losing angular momentum through rotation, in order to collapse as they progress toward star-cluster formation.

We speculate that the observed velocity flip across the filament on small scales may be related to the flip in the magnetic field observed in California on far larger scales (Tahani et al. 2018). We emphasize that the connection between the large-scale signatures of the magnetic field geometry and the small-scale velocity features detected here are not presently understood. Hence, further investigation into the scale dependence of the magnetic field strengths and geometries is essential. Moreover, future observational work should include scrutiny of larger portions of California to more broadly characterize the gas kinematics. Wide-field observations that trace magnetic fields on filament scales (capturing scales of \(\lesssim 0.1 \text{ pc}\) to \(\gtrsim 10 \text{ pc}\)) and cloud scales, including Zeeman when possible, are essential for obtaining further constraints on both field geometry and strength. Constraining gas kinematics in combination with constraints for the magnetic field is critical. Scrutiny of the YSO and stellar kinematics, including radial velocities, and their possible link to the cloud kinematics will explore the link between the stellar and gas content (Stutz & Gould 2016). Besides California and Orion A, it is imperative to kinematically characterize other high-mass filaments like, e.g., G28.37 + 0.07 (Kong et al. 2019). Finally, numerical work should focus on molecular line modeling of the velocity field of “zig-zag” filaments to elucidate the 3D structure filaments that have a significant degree of rotation (see, e.g., Reissl et al. 2018a, 2018b).

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**Appendix A**

**Moment Maps**

In Figure A1, we show the first three moment maps (from left to right) for \(^{13}\text{CO}\) (top) and \(^{13}\text{C}\text{O}\) (bottom). These figures show that the filament is well traced in \(^{13}\text{C}\text{O}\), but less so in \(^{13}\text{CO}\), a fact that is particularly obvious in the velocity and line width (moments 1 and 2) maps.

We find a larger scale \(^{13}\text{CO}\) gradient in the same region we are analyzing. It is tempting to associate the \(^{13}\text{CO}\) gradient with the \(^{13}\text{C}\text{O}\) gradient, but as the moment maps show, the \(^{13}\text{CO}\) tracer is simply not isolating the filament structure (including the radial velocities) nearly as well as the \(^{13}\text{C}\text{O}\). For example, the filament is barely detected in the \(^{13}\text{CO}\) moments 1 and 2 maps, and is only marginally detected in the moment 0 map; moreover, the \(^{13}\text{C}\text{O}\) gradient (not shown) is of a different magnitude from the \(^{13}\text{C}\text{O}\), likely because the \(^{13}\text{CO}\) is not tracing simply the filament but instead the broader and less well-defined cloud environment. Moreover, the rotational signature seen in Figure 13 is not observed in the immediately adjacent north region, as can be appreciated from the moment maps. This is consistent with our interpretation that in the north, gravity has already taken over, as evidenced by the protostar content. In summary, other lower density and optically thick tracers are simply inadequate for isolating the filament and its velocities.
Appendix B

Temperature Profile

In Figure B1, we show the average projected radial temperature profile (black solid line) of CMC/L1482. We calculate this profile following the ridgeline (see above). We also present the east and west temperature profiles. Inside the radial range where the profile is used (see Section 5.3), that is, at $r \lesssim 1$ pc, the profile is approximately symmetric and variations are small. Therefore, we fit the average temperature profile with a softened power law (red solid line). We obtain the following best-fit temperature profile:

$$T(r) = 12.3 \left(1 + \frac{r}{a}\right)^{0.04} \text{K} \quad a = 0.9 \text{ pc.} \quad (B1)$$
Figure B1. Average CMC/L1482 temperature profile derived from the Herschel temperature map (black solid line). The dotted (dashed) curve corresponds to the east (west) profile. The profiles are highly symmetric over the inner width of the filament. The red curve shows the best fit (see Equation (B1)) to the solid black line and is plotted over the radial range that is used in Section 5.3 and in Figure 12.

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