The DR21(OH) Trident—Resolving the Massive Ridge into Three Entangled Fibers as the Initial Condition of Cluster Formation

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Received 2020 December 12; revised 2021 December 15; accepted 2021 December 26; published 2022 March 8

Abstract

DR21(OH) ridge, the central part of a high-mass star- and cluster-forming hub-filament system, is resolved spatially and kinematically into three nearly parallel fibers (f1, f2, and f3) with a roughly north–south orientation, using the observations of molecular transitions of H13CO+ (1−0), N2H+ (1−0), and NH2D (1,1−I0,1) with the Combined Array for Research in Millimeter Astronomy. These fibers are all mildly supersonic (σ velocity dispersions about 2 times the sound speed), having lengths around 2 pc and widths about 0.1 pc, and they entangle and conjoin in the south where the most active high-mass star formation takes place. They all have line masses 1–2 orders of magnitude higher than their low-mass counterparts and are gravitationally unstable both radially and axially. However, only f1 exhibits high-mass star formation all the way along the fiber, yet f2 and f3 show no signs of significant star formation in their northern parts. A large velocity gradient increasing from north to south is seen in f3, and can be well reproduced with a model of freefall motion toward the most massive and active dense core in the region, which corroborates the global collapse of the ridge and suggests that the disruptive effects of the tidal forces may explain the inefficiency of star formation in f2 and f3. On larger scales, some of the lower-density, peripheral filaments are likely to be the outer extensions of the fibers, and provide hints on the origin of the ridge.

Unified Astronomy Thesaurus concepts: Interstellar filaments (842); Dense interstellar clouds (371); Star formation (1569); Star forming regions (1565); Young massive clusters (2049); Dust continuum emission (412); Interstellar line emission (844)

1. Introduction

Filamentary structures have been widely known to pervade the cold interstellar medium (e.g., André et al. 2010, 2014; Molinari et al. 2010; Schisano et al. 2014). While molecular filaments span a wide range in length and density, over the past decade dense filaments of clump-to-cloud scales, i.e., 1–10 pc, are extensively studied as they may bridge relatively diffuse molecular gas and compact cores capable of forming individual stars or multiple stars. Although it is not impossible to find filaments in relative isolation (e.g., Hacar et al. 2016), more often they appear to be organized into more complex structures, such as a web-like network or nest (e.g., Men’shchikov et al. 2010; Arzoumanian et al. 2011; Hill et al. 2011; Busquet et al. 2013), or a system of several filaments converging at a high-density region, i.e., a hub-filament system (HFS, e.g., Galván-Madrid et al. 2010; Liu et al. 2012; Schneider et al. 2012; Kirk et al. 2013; Peretto et al. 2014; Williams et al. 2018). Massive and elongated hub regions are sometimes referred to as ridges (e.g., Hill et al. 2011; Hennemann et al. 2012; Tigé et al. 2017; Motte et al. 2018). HFSs are of particular interests to the formation of massive stars and clusters since the hubs or ridges are located close to the gravity center and thus may aid in global collapse or large-scale gas inflow along the filaments (Myers 2009; André et al. 2014; Kumar et al. 2020). And observed velocity fields in some massive filaments and HFSs are consistent with global collapse at a high accretion rate of order 10−3 M⊙ yr−1 (e.g., Schneider et al. 2010; Zernickel et al. 2013; Hu et al. 2021), pointing to a dynamic picture of cluster formation (Krumholz et al. 2019). Relatively diffuse molecular gas also show filamentary features, and such low-density, tenuous striations were first observed in CO lines (Goldsmith et al. 2008), and then seen in a dust continuum with Herschel observations (Palmeirim et al. 2013).

There is growing evidence that filaments are not monolithic but have substructures. Hacar et al. (2013) identified multiple velocity components in position–position–velocity (PPV) space in the gas of the low-mass star-forming filament in Taurus, and suggested that the filament is indeed a bundle of those “velocity-coherent structures,” which are also termed fibers. After that work, similar fiber-like substructures have been detected in other dense, both low-mass and high-mass, molecular filaments (Henshaw et al. 2014; Fehér et al. 2016; Hacar et al. 2018; Shimajiri et al. 2019), while the physical origin of the fibers remains unclear (Tafalla & Hacar 2015; Clarke et al. 2017). The methodologies used to extract fibers (or fiber-like substructures) all work in PPV space, but vary in practice for the detailed techniques. There is caution that features identified in PPV space do not really represent density structures in 3D space (see Clarke et al. 2018), but this issue could be mitigated with interferometer high-angular-resolution observations that have started to spatially resolve the internal structure of a filament. Filament substructures may also play a role in the formation and dynamical evolution of hubs or ridges in massive HFSs. Henshaw et al. (2017) observed a protostellar hub within a massive infrared dark cloud with the Atacama Large Millimeter/submillimeter Array in the 1 mm continuum, and detected multiple intra-hub sub-filaments, which are...
narrow (0.028 pc) and analogous to fibers. Hacar et al. (2018) identified dozens of dense fibers in the central region of the well-known Integral-Shape Filament (ISF) in Orion, and recognized multiple hub-like associations along a dense bundle of the fibers. Nevertheless, observational studies capable of resolving massive filaments and hubs are still very limited, leaving several key questions in the context unsolved: (1) What are the physical properties of the substructures in massive HFSs, and how do they differ from their low-mass counterparts? (2) What role do these substructures play in shaping the initial conditions of high-mass star and cluster formations? (3) How are they related to the large-scale filaments connected to the peripherals of the hubs or ridges? To shed light on these questions, we carry out interferometer-molecular spectral-line observations toward the central ridge of a pronounced massive HFS, and successfully resolve its inner structures both spatially and kinematically. By deriving the physical properties of the substructures and investigating their kinematics and dynamics, we try to understand their relation with the ongoing high-mass star formation.

The DR21 ridge (also called DR21 filament) is an elongated massive gas structure connected by several filaments with varying orientations, forming a remarkable HFS in the Cygnus X molecular-cloud complex (Motte et al. 2007; Schneider et al. 2010; Hennebelle et al. 2012). It contains a massive clump in the southern end and a filamentary structure to the north. The southern clump is embedded with at least two compact H II regions, namely DR21 (Cyganowski et al. 2003). The filamentary structure in the north contains a chain of ∼0.1 pc massive dense cores (MDCs), and the most massive one is DR21(OH), which is associated with various masers and actively forming a cluster of high-mass stars (Zapata et al. 2012). While the DR21 ridge in the literature refers to the whole structure including both DR21 and DR21(OH), in this work we only focus on the continuous structure in the north; we leave out the DR21 clump for its discontinuity with the northern part and its more advanced evolutionary stage (thus of less relevance to the initial conditions of high-mass star formation). And to avoid confusion, we refer to this structure as the DR21(OH) ridge. Located at a distance of 1.5 kpc (Rygl et al. 2012), this structure has a projected length of ∼2.5 pc and a total gas mass of ∼9000 M_☉, making its line mass two orders of magnitude higher than those of the low-mass filaments (e.g., Hill et al. 2011; Hacar et al. 2013) and about 10 times higher than that of the ISF in Orion (Schuller et al. 2021). Given its relatively close distance and great mass, the DR21(OH) ridge is an ideal target for disentangling the substructures of high-mass cluster-forming HFSs.

2. Observations

The DR21(OH) ridge was observed in the 3 mm wave band, covering H^{13}CO^+ (1−0), N_2H^+ (1−0), and NH_2D (1_{1,1} − 1_{0,1}), with the 15-antenna Combined Array for Research in Millimeter-wave Astronomy (CARMA) in the D configuration during 2014 June 29–July 14 (Project ID: c1212; PI: Keping Qiu). The CARMA-D array provides a baseline range of 11–148 m, yielding a synthesized beam size of ∼5″ (0.036 pc@1.5 kpc) and a largest recovering scale of ∼70″ (0.5 pc@1.5 kpc). Mosaic observations toward four phase centers (RA = 20°39′01″; decl. = 42°22′25.5″, 42°23′25.5″, 42°24′25.5″, and 42°25′25.5″) were conducted to map the ridge. Observations toward each phase center were made with one or two scheduling blocks, leading to a total observing time of about 5 to 6 hr and an on-source integration time of 2 to 3 hr each. Spectral windows #7, #4, and #8 of the CARMA correlator were centered at the rest frequencies of the H^{13}CO^+, N_2H^+, and NH_2D transitions, respectively, with a uniform bandwidth of 31.152 MHz and a spectral resolution of 97.7 kHz (0.33 km s^{-1} @ 90 GHz; 319 channels). J1927+739 was used as the bandpass calibrator, and MWC349 was used for both the flux calibration and time-dependent phase and the amplitude gain calibration. The raw data were flagged, calibrated, and imaged with the Miriad software (Sault et al. 1995). We used the Briggs weighting with the robust parameter set to 0.5 to image the data. The final data products contain three mosaic spectral-line cubes with a map size of about 3′×3′ and a pixel size of 1″×1″. The velocity resolutions are 0.34, 0.31, and 0.34 km s^{-1}, and the 1σ noise levels are 36.9, 42.4, and 34.7 mJy beam^{-1} per velocity channel for the H^{13}CO^+, N_2H^+, and NH_2D data cubes, respectively. Detailed observational setups and logs can be found at the CARMA Data Archive.\footnote{http://carma-server.ncsa.uiuc.edu:8181/}

3. Results, Analysis, and Discussion

Figure 1 shows the velocity channel maps of the H^{13}CO^+ (1−0) emission, where the original channel width of 0.34 km s^{-1} is smoothed to 1.0 km s^{-1}. The H^{13}CO^+ emission is detected at ∼1 to 1 km s^{-1}, with the emission at ≥−3.0 km s^{-1} mostly tracing the high-density peaks as visualized by a chain of active MDCs (Motte et al. 2007). On the other hand, the emission at ≥−2.0 km s^{-1} reveals new features to the west of the MDC chain. Overall the results here are consistent with the single-dish H^{13}CO^+ (1−0) observations by Schneider et al. (2010), except that our data have a factor of 6 better angular resolution. Because of the missing zero-spacing information, our interferometer observations filter out extended emission (larger than 0.5 pc; see Section 2). We anticipate, however, that the extraction and analysis of the substructures within the DR21(OH) ridge are not strongly affected. We do not show the velocity channel maps in N_2H^+ (1−0) and NH_2D (1_{1,1} − 1_{0,1}), since these transitions have blended hyperfine lines. The velocity-integrated emissions of the three lines are all highly biased to the structure coincident with the MDC chain (Figure 2). Thus, more sophisticated analyses of the spectral-line data are needed to better unravel the velocity structure of the ridge (see Section 3.2).

3.1. High-resolution H\_2-column-density Map and Dust Temperature Map Derived from Continuum Data

To calculate the mass and other physical properties, high-resolution (13′′.7) H\_2-column-density (N\_H\_2) and dust temperature (T\_dust) maps of the DR21(OH) ridge are derived by fitting the dust-continuum emissions at submillimeter wavelengths with a modified blackbody model (Hildebrand 1983):

\[ I_v = B_v(T_{dust})(1 - e^{-\tau_v}), \]

\[ \tau_v = \mu_{H_2} m_H N_{H_2} k_{\nu} / \Gamma, \]

where \( B_v(T_{dust}) \) is the Planck function, \( \mu_{H_2} = 2.8 \) is the mean molecular weight per H\_2 molecule, \( m_H \) is the mass of the hydrogen atom, \( k_{\nu} \) is the dust mass opacity, and \( \Gamma = 100 \) is a canonical gas-to-dust mass ratio for the interstellar medium. We evaluate \( k_{\nu} \) following the equation \[ k_{\nu} = k_0 (\nu / \nu_0)^{\beta}, \]

where
κ_0 = 10 \text{ cm}^2 \text{ g}^{-1}, \nu_0 = 1 \text{ THz}, and \beta = 2. This dust opacity law is widely used by the Herschel large survey projects (e.g., Andrè et al. 2010; Tigé et al. 2017). The continuum maps used for the fitting were obtained from Cao et al. (2019), which include the Herschel/PACS 160 μm map and the James Clerk Maxwell Telescope (JCMT)/SCUBA-2 450 and 850 μm maps. The beam sizes of the 160, 450, and 850 μm maps are 12″, 7″, and 13″, respectively. We did not use the Herschel 70 μm data due to the possible contaminations from the emissions of very small grains (Draine & Li 2001) that are not considered in the single-temperature model (see Figure 12 of Cao et al. 2019). The Herschel maps at 250, 350, and 500 μm were not used since their resolutions are too coarse (>18″) compared with the CARMA data. The continuum maps used for the fitting were cropped to the same size as the CARMA data (3′ × 6′), smoothed to a common beam size of 13″, and resampled to the same gridding with a pixel size of 2″. The flux uncertainties of the continuum maps are conservatively estimated to be 20% following Cao et al. (2019) and are considered in the fitting procedure. We use the minimize function in the Scipy (Jones et al. 2001) package to implement the fitting. The derived N_H2 map is shown in Figures 1 and 2, and the T_dust map is shown in Figure 2 (also see the N_H2 and T_dust uncertainties in Appendix A). To test the robustness of the results derived from the 3-band fitting, we generate another set of N_H2 and T_dust maps with 6-band data (Herschel 160, 250, 350, and 500 μm; JCMT 450 and 850 μm) and compare them at the same resolution (see Appendix A). We find that 93% of the total map area has T_dust differences less than 2 K, and 90% of the map area has relative differences in N_H2 less than 25%, indicating that the 3-band fitting is robust.

N_H2 and T_dust in the DR21(OH) ridge range from 5 × 10^{21} to 1 × 10^{22} cm^{-2} and from 15 to 31 K, respectively, where the highest column density and temperature are both found toward the DR21(OH) core. The ridge can be defined with a N_H2 contour level of 10^{23} cm^{-2} as suggested by Hennemann et al. (2012). In Figure 1, if we define the outer edge of the ridge with a slightly lower N_H2 value of 5 × 10^{22} cm^{-2}, the H^13CO^+...
emissions, including the bright emission tracing the MDC chain and the new features to the west, are all confined to be within the ridge. In Figure 2(a), to the west of the MDC chain, the 8 μm dark patches (absorption), coincident with the H13CO+ emission features, are also perceptible. All this indicates that H13CO+ emission is probing high-density substructures within the DR21(OH) ridge.

3.2. Spectral Fitting and the PPV Structures of the DR21(OH) Ridge

To exact the PPV structures and derive the physical properties of the DR21(OH) ridge, we fit the data cubes of the three transitions pixel-by-pixel with a multi-velocity-component spectral-line model based on the theoretical work of Mangum & Shirley (2015). In this model, the ith velocity component along the line of sight (LoS) of a pixel has a total column density \( N_{\text{trc},i} \) for a certain tracer and an excitation temperature \( T_{\text{ex}} \). From Equation (32) of Mangum & Shirley (2015), we have the velocity distribution of the tracer column density

\[
N_{\text{trc},i}(v) = \frac{3h}{8\pi^{3/2} \mu^2 g_u} \frac{Q_{\text{rot}}}{E_{\text{rot}}} \left( \frac{\mu_{\text{rot}}}{\mu_{\text{rot}}-1} \right)^{-1} T_{\text{truc},i}(v),
\]

where \( h \) is the Planck constant, \( k_B \) is the Boltzmann constant, and \( S, \mu, g_u, Q_{\text{rot}}, E_{\text{rot}}, \nu_0 \) are the line strength, dipole moment, degeneracy of the upper energy level, rotational partition

\[
T_{\text{truc},i}(v) = \frac{\mu_{\text{rot}}}{\mu_{\text{rot}}-1} T_{\text{ex}}.
\]
function, upper level energy, and rest frequency of the transition, respectively. We assume in the model that \(N_{\text{exc,}\,i}(v)\) has a Gaussian distribution with a centroid velocity \(v_0\) and a velocity dispersion \(\sigma_v\), leading to

\[
N_{\text{exc,}\,i}(v) = \frac{N_{\text{exc,}\,i}}{\sqrt{2\pi \sigma_v}} e^{-\frac{(v-v_0)^2}{2\sigma_v^2}}.
\]

(4)

Further taking into account the hyperfine lines for a transition, we derive the opacity of the \(j\)th hyperfine line of a transition for the \(i\)th velocity component

\[
\tau_{ij}(v) = \frac{4\sqrt{2\pi}S^2 R_j \delta v}{3hQ_{\text{tot}}\sigma_v} \sum_{v_0}^v e^{-\frac{\left(\frac{(v-v_0)^2}{2\sigma_v^2} - \frac{E_0}{k_BT}\right)}{\frac{1}{2}\sigma_v}},
\]

(5)

where \(R_j\) and \(\delta v\) are the relative line strength and the velocity offset relative to \(v_0\) for the \(j\)th hyperfine line, respectively. Here we assume that all the velocity components along the LoS of one pixel have a common \(T_{\text{ex}}\); otherwise the radiative transfer equation is not analytically integrable, and the detailed material distribution along the LoS must be known. The modeled spectral intensity as a function of velocity is given by

\[
\Delta I(v; N_{\text{exc,}\,i}, T_{\text{ex}}, v_0, \sigma_v) = (B_v(T_{\text{ex}}) - B_v(T_{\text{bg}})) \\
\times (1 - e^{-\sum_{v_0}^v \tau_{ij}(v)}),
\]

(6)

where \(T_{\text{bg}}\) is the background brightness temperature and is set to the cosmic microwave background value of 2.73 K. Note that this spectral model is quite general and does not rely on additional assumptions such as the Rayleigh–Jeans approximation or the optically thin approximation. By fitting an observed spectrum with this model, one can obtain a parameter set \((N_{\text{exc,}\,i}, T_{\text{ex}}, v_0, \sigma_v)\) for each velocity component toward a pixel.

Since we only have observations of one transition for one molecular species, \(T_{\text{ex}}\) and \(N_{\text{exc}}\) cannot be determined simultaneously in the fitting due to degeneration. Therefore we fix \(T_{\text{ex}}\) to \(T_{\text{dust}}\) obtained in Section 3.1 for each pixel during the fitting procedure, by assuming that the gas and dust temperatures are equal. This assumption is valid if the gas and dust are strongly coupled (e.g., Burke & Hollenbach 1983). At low to intermediate densities \((n \lesssim 10^4 \text{ cm}^{-3})\), relatively weak gas-dust coupling and the depletion of coolant species may conspire a considerably higher gas temperature than the dust temperature; such an effect can be significantly reduced at higher densities thanks to rapid gas-dust coupling, leading to a temperature difference of \(\sim 4\) K at \(n \sim 10^5 \text{ cm}^{-3}\) and completely negligible at \(n \sim 10^6 \text{ cm}^{-3}\) (Goldsmith 2001). Dust evolution in dense cores can affect thermal gas-dust coupling, leading to a higher gas temperature compared to the dust temperature, but the temperature difference is also small at high densities \((\sim 3\) K at \(n \sim 10^5 \text{ cm}^{-3}\) and \(\sim 1\) K at \(n \sim 10^6 \text{ cm}^{-3}\); Ivlev et al. 2019). In our case, we have gas densities \(\gtrsim 10^5 \text{ cm}^{-3}\) \((\text{N}\text{H}_2\text{ in Figure 1)} divided by 0.1 pc, which is derived in Section 3.4; also see Table 1)). Thus the dust temperature approximates the gas temperature within a few K. We further assess, in Appendix B, that a small variation of 4 K in \(T_{\text{ex}}\) induces a 12% difference in the fitted \(N_{\text{exc,}\,i}\). We use the tool curve_fit in Scipy to extract and fit 7625, 7500, and 2141 spectra and obtain a total of 10,152, 7766, and 2141 velocity components for the transitions of H\(^{13}\)CO\(^+\), N\(_2\)H\(^+\), and NH\(_2\)D, respectively (note that one pixel can have multiple velocity components). These velocity components can be identified as points in the PPV space (hereafter PPV points). Figure 3 provides 2D views of the PPV points. While projected on the plane of sky (PoS), these PPV points are grouped into several fiber-like substructures that entangle around the DR21(OH) core and branches to the north (Figures 3(a)–(c)). In the position–velocity (PV) diagrams (Figures 3(d)–(f)), the PPV points exhibit complicated velocity structures, which might be a consequence of supersonic turbulence. A particular interesting feature seen in the H\(^{13}\)CO\(^+\) emission is the westernmost branch in Figure 3(a); we will come back to this substructure later by modeling its PV structure as revealed in Figure 3(d).

### 3.3. Identification of the Fibers

To identify the fibers seen in the PPV space, we apply the agglomerative clustering implementation in the scikit-learn package\(^7\) (Pedregosa et al. 2011) to the PPV points for each transition. The agglomerative clustering algorithm groups points in N-dimensional space via recursively merging points into higher-order clusters such that the pair of points or clusters to be merged minimally increases the linkage distance (Ward 1963). To make the clustering procedure adjustable, we introduce two parameters \(t_x\) and \(t_y\) in defining the linkage distance of two PPV points:

\[
\delta_{\text{link,xy}} = \sqrt{\left|x_1 - x_2\right|^2 + \left|y_1 - y_2\right|^2 + \left(v_1 - v_2\right)^2/\left(t_v\right)^2},
\]

(7)

where \(x\) and \(y\) are the spatial coordinates in physical units, and \(v\) is the LoS velocity. For each transition, we adjust the parameters \((t_x, t_y)\) and run the algorithm with the modified coordinates of the PPV points as input. By practice we found that the best values of \((t_x, t_y)\) for identifying the fiber structures in the H\(^{13}\)CO\(^+\), N\(_2\)H\(^+\), and NH\(_2\)D data are (2.8 pc, 1.0 km s\(^{-1}\) pc\(^{-1}\)), (0.5 pc, 0.8 km s\(^{-1}\) pc\(^{-1}\)), and (1.0 pc, 2.0 km s\(^{-1}\) pc\(^{-1}\)), respectively, with which the DR21(OH) ridge is decomposed into 3, 3, and 2 fibers in the PPV space. Figure 4 shows the identified fibers projected on the PoS and their PPV

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\(^7\) https://scikit-learn.org/stable/
plots, with the color coding representing different velocities. In the H^{13}CO^+ data, three fibers with roughly north–south orientations are clearly seen; these fibers have distinct velocities, forming a trident with the junction approximately coincident with the DR21(OH) core. We name the three fibers as f1, f2, and f3 from east to west. Among the fibers, f1 is
clearly tracing the central-densest part of the dust ridge well known from previous dust-continuum observations (Motte et al. 2007; Hennemann et al. 2012); $f_2$ and $f_3$ are relatively new, not seen in the dust emission, but previous single-dish H$^{13}$CO$^+$ (1−0) observations showed that the ridge slight moves from east to west with the velocity increasing from $-5 \text{ km s}^{-1}$ to $0 \text{ km s}^{-1}$ (Schneider et al. 2010), in a manner consistent with the positions and velocities of the three fibers identified here. In particular, $f_3$ is also discernible in the H$^{13}$CO$^+$ (1−0) map in Schneider et al. (2010; see their Figure A3), though at a much lower resolution. Given the LoS velocities of the fibers and the existing observations suggesting that the DR21(OH) ridge is in a global collapse (Schneider et al. 2010), one may expect that $f_1$ and $f_3$ are on the far side and the near side along LoS, respectively, and that $f_2$ is probably in the middle. The three fibers in the N$_2$H$^+$ line are less prominent yet are still clearly seen with positions and velocities consistent with those in the H$^{13}$CO$^+$ line, indicating that they are tracing the same physical entities. While the whole $f_1$ and the southern part of $f_3$ are detected, $f_2$ is fragmented into several parts, probably due to the regional variations of the abundances of the two molecular tracers. On the other hand, in the NH$_2$D line, the whole $f_1$ (though fragmented into parts) and the northern part of $f_2$ are detected, and $f_3$ is completely absent.
The appearance of the fibers are also different from that in the $^{13}$CO$^+$ and NH$_3^+$ lines by their more compact morphologies and smaller widths. In addition, in contrast to what is seen in the $^{13}$CO$^+$ and NH$_3$H$^+$ lines, the southern end of f1 in the NH$_3$D line is shifted to the west and does not coincide with the DR21(OH) core, indicating that active high-mass star formation has destroyed most of NH$_3$D. The detection information of the fibers in the three transitions is summarized in Table 1.

### 3.4. Characterizing the Properties of the Fibers

In this subsection, we derive the physical properties of the fibers with the $^{13}$CO$^+$ data due to their best detections. We first determine the major axes of the fibers in the PoS through linear regression analyses of the coordinates of the PPV points, and divided the PPV points of each fiber into 15 equal-length parts along the major axis. For each part, a bone point is generated with flux-weighted mean positions and other physical parameters ($N_{inc}$, $T_{exc}$, $v_{LoS}$, $\sigma_v$) of the PPV points in that part. The derived bone points of the three fibers are shown in Figure 4, which delineate the axes of the fibers in the PPV space and can be used for calculating the distribution of the physical properties along the fibers. Lengths of the fibers are estimated as the lengths of the bone lines, and the widths are evaluated as the dispersions of the distances of the PPV points to the bone lines. Other physical quantities (e.g., the mean LoS velocity and velocity dispersion) of a fiber are derived as the intensity-weighted averages over all the PPV points belonging to the fiber. Similarly, profiles of a physical quantity along the fibers can be calculated as the intensity-weighted averages over the PPV points with which the bone points are derived. Table 1 lists the geometric and physical parameters of the fibers.

To estimate the total gas masses of the fibers, we need a conversion factor from $N_{inc}$ to $N_{fb}$, i.e., the abundance. This is done by comparing $N_{inc}$ obtained from the spectral fitting with $N_{fb}$ derived from the dust-continuum emissions. We use the $^{13}$CO$^+$ data to derive the total mass since its emission matches the $N_{fb}$ map the best among the three species (see Figure 2). A map of the $^{13}$CO$^+$ column density is generated with the PPV points and was smoothed and resampled to match the resolution and gridding of the $N_{fb}$ map. An abundance map is then derived by dividing the $N_{fb}$ map with the $N_{fb}$ map. The resultant mean abundance for $^{13}$CO$^+$ in the DR21(OH) ridge is $1.72 \times 10^{-10}$ with a regional fluctuation of $\pm 0.25$ dex. In addition, we find that there is no strong correlation between the $^{13}$CO$^+$ abundance and $T_{dust}$ or $N_{fb}$ (see Appendix B for detailed analyses), which indicates that the $^{13}$CO$^+$ abundance does not vary violently with the differentiated chemical conditions (e.g., depletion onto dust grains and formation/destruction through chemical reactions) and that adopting a constant abundance value is sufficient for calculating the mass. By converting $N_{fb}$ to $N_{fb}$ with this abundance, we derive that the total masses of fibers f1, f2, and f3 to be 5117, 1838, and 921 $M_{\odot}$, respectively, and the line masses are 2133, 795, and 511 $M_{\odot}$ pc$^{-1}$, respectively, which is 1–2 orders of magnitude higher than typical low-mass filaments (e.g., Pezzuto et al. 2021). See also Table 1 for more details on the physical properties of the fibers.

### 3.5. Freefall Velocity Profile Seen in Fiber f3

One of the most prominent features of the DR21(OH) ridge in the PPV space is the large velocity gradient in fiber f3, which is clearly seen in the PV diagrams of the $^{13}$CO$^+$ and NH$_3$H$^+$ emissions (Figure 3). This velocity gradient is not constant throughout the fiber, but increases from north to south, i.e., toward the direction of DR21(OH). In addition, the FWHM velocity dispersion of f3 increases almost monotonously from 0.3 to 1.9 km s$^{-1}$ from north to south as seen in the $^{13}$CO$^+$ data. These suggest that f3 is very likely influenced by the gravitational potential of the very MDC, and the gas within the fiber is falling toward DR21(OH). Schneider et al. (2010) made a similar statement based on the emission distribution revealed by their single-dish observations. Here the data with a much higher angular resolution allow us to further test this interpretation, and we fit the PV pattern with a freefall model. The PPV points used in the fitting are highlighted in Figure 3. Based on the morphologies and spatial configuration of f3 and DR21(OH), we assume that f3 is falling directly toward DR21(OH) with no transverse motions and that the freefall velocity is zero at infinity. In the 3D space, the freefall velocity $v_{ff}$ as a function of the distance to the mass center $l$ is

$$v_{ff}(l) = \sqrt{\frac{2GM_c}{l}},$$

where $M_c$ is mass of the gravity center. Since we can only observe LoS velocity, the projected distance on the PoS Equation (8) can be rewritten in a projected form that implicitly contains the inclination angle:

$$v_{LoS}(l_p) = \sqrt{\frac{2GM_{c,p}}{l_p}} + v_{c,LoS},$$

where $l_p = l \cos \theta_{inc}$ and $M_{c,p} = M_c \cos \theta_{inc} \sin^2 \theta_{inc}$ are the projected distance and mass, respectively, $\theta_{inc}$ is the inclination angle of f3 against the PoS, and $v_{c,LoS}$ is the systematic LoS velocity of the gravity center. Since $\theta_{inc}$ is unknown, we use the above equation to fit the velocity profile. The PPV points used for the fitting and the results are shown in Figure 3(g), which yield $M_{c,p} = 582.1 \pm 13.9 M_\odot$ and $v_{c,LoS} = -3.87 \pm 0.04$ km s$^{-1}$. The $v_{c,LoS}$ value is well consistent with the results derived from single-dish spectral-line observations toward DR21(OH) (Mayer et al. 1973; Chandler et al. 1993). The value of $M_{c,p}$ is compatible with the mass of DR21(OH) (446–1048 $M_\odot$; Motte et al. 2007; Cao et al. 2019), but since it is only the lower limit of the mass of the gravity center, it does not rule out the possibility that other MDCs around DR21(OH) also contribute to the gravitational attraction. We stress that the observations and the fitting results all support a scenario that the gas in f3 is falling toward DR21(OH), and the latter seems to be the main (but not necessary the only) source of gravitational attraction. The mass accretion rate of f3 can be estimated by multiplying the line mass and the infall velocity, which is taken from the freefall model (4.9 km s$^{-1}$ without accounting for the projection effect; see Figure 3(g)), and is $\gtrsim 2.5 \times 10^{-3} M_\odot$ yr$^{-1}$, indicating that a mass feeding through f3 is capable of significantly increasing the core mass within a freefall time (typically $10^5$ yr for dense cores) and thus play an important role in the high-mass and cluster formation within and around DR21(OH).
3.6. Instability of the Fibers and the Star Formation in the DR21(OH) Ridge

In this section, we study the instability of the fibers and their relation to the star formation in this region. There are two modes of instabilities for a self-gravitating and isothermal gas cylinder: radial instability and axial instability. For the former, the critical line mass of a cylinder over which gravity overcomes supports of turbulence and thermal pressure is given by

\[
\lambda_{\text{cr,radial}} = \frac{2\sigma^2}{G},
\]

where \(\sigma\) is the sound speed for thermal support and velocity dispersion in case of turbulent support (Ostriker 1964; Fiege & Pudritz 2000). The fibers mostly fall in a temperature range of 15 to 25 K (Figure 2(c)), so they are mildly supersonic with the velocity dispersions about 2 times the sound speed, leading to turbulent support. We then derive the critical line masses of 157, 182, and 130 \(M_\odot\) pc\(^{-1}\) for fibers f1, f2, and f3, respectively, which are only 7.3%, 23%, and 25% of their actual line masses (see Table 1). This indicates that the fibers are unstable against radial gravitational collapse with the turbulent (and thermal) support. We further derive the line mass and critical line mass profiles along the fibers derived with the statistics of the bone points, and find that the line masses are \(\sim 10\) times larger than the critical values for most parts of the fibers (Figure 5).

Figure 5. Line mass (solid lines) and critical line mass (dashed lines) profiles along the bones of the three fibers, derived with the \(^{13}\text{CO}^+\) data. The data points are marked as crosses, and the lines are interpolations with order-3 splines. Critical line masses are derived with Equation (10) and reflect the radial instability of the fibers (Section 3.6). All the profiles are aligned in position such that the origins are the closest bone points to DR21(OH). The CARMA beam is shown as a dash.

To estimate the relative importance of magnetic fields in the radial instability, we derive the magnetic energy, \(E_B\), and the gravitational binding energy, \(E_G\), of the fibers:

\[
E_B = \frac{\pi}{4} d^2 L \cdot \frac{B}{2\mu_0} = \frac{\pi^3}{32\mu_0} \nu_{\text{PoS}}^2 d^2 L, \quad (11)
\]

\[
E_G = \frac{GM^2}{(d^2 L)^{3/2}}, \quad (12)
\]

where \(\mu_0\) is the vacuum permeability, and \(d, L, M, B, \nu_{\text{PoS}}\) are the FWHM width, length, mass, average magnetic field strength, and average projected magnetic field strength on the PoS of a fiber, respectively. For \(\nu_{\text{PoS}}\), we adopt the value in Girart et al. (2013) (0.62 mG) derived from the JCMT observations. The resultant gravitational binding energies are \(7.0 \times 10^{48}, 9.5 \times 10^{47}\), and \(2.9 \times 10^{47}\) erg, for fibers f1, f2, and f3, respectively, and the magnetic energies are \(2.9 \times 10^{46}, 2.5 \times 10^{46}\), and \(1.3 \times 10^{46}\) erg, which are only 0.4%, 2.6%, and 4.5% of the gravitational energies, respectively.

The axial instability (also known as the \emph{sausage} instability) of a gas cylinder describes its mass agglomeration along the axial due to the growth of unstable perturbations. For such an instability, there exists a characteristic length scale, \(L_{\text{max,axial}}\), delineating the nearly uniform spacing between the fragments, as a result of the fastest growing unstable perturbation (Nagasawa 1987; Jackson et al. 2010). Nagasawa (1987) finds that, for a self-gravitating isothermal cylinder,
$L_{\text{max, axial}} \sim 22H$, where $H = c_s(4\pi G\rho c)^{-1/2}$ is the scale height, $ho_c$ is the density at the center of the cylinder, and that this length scale does not change with the presence of an axial magnetic field. With the analytical solution for hydrostatic equilibrium in a self-gravitating isothermal cylinder (Ostriker 1964), we derive a relation between the FWHM width $d$ and the scale height as $d = 4.336H$, and find that $L_{\text{max, axial}} = 0.61, 0.57, \text{ and } 0.47$ pc for $f_1$, $f_2$, and $f_3$, respectively (see also Table 1). These length scales are ~4 times shorter than the fiber lengths, and the fibers are thus axially unstable, which is consistent with the fragmented appearance of the fibers in Figures 2 and 4 and the oscillating line masses in Figure 5. In addition, the average separations of the line mass peaks (i.e., fragments) in Figure 5 are 0.54, 0.40, and 0.42 pc for $f_1$, $f_2$, and $f_3$, respectively, which are in good agreement with their $L_{\text{max, axial}}$ considering the projection effect.

The analyses and results above all suggest that, with the great line masses, gravity is playing a predominant role in shaping the dynamics of the fibers, and star formation is expected to happen in the fibers given their radial and axial instabilities. We use the catalogs of Class II methanol masers and ultra-compact H II (UCH II) regions collected by Cao et al. (2019), as well as the MCDs with strong SiO emissions in Motte et al. (2007), to probe the high-mass star-forming activities in the DR21(OH) ridge. To trace low-mass star formation, we use the protostar catalogs in Davis et al. (2007) and Kryukova et al. (2014) generated with the Spitzer data. All these sources are shown in Figures 2–5. It is clear that $f_1$ is active in high-mass star formation with a chain of active MDCs and UCH II regions (Kumar et al. 2007; Cao et al. 2019). And it is widely known that the DR21(OH) core, where the three fibers conjoin, is forming a cluster of high-mass stars (Zapata et al. 2012; Girart et al. 2013). The very active (high-mass) star-forming activities in the DR21(OH) ridge may be attributed to a global collapse of the HFS (see also Schneider et al. 2010). The morphology and kinematics of the three fibers identified here provide new insights into this scenario. The enhancement in $N_{\text{H}}$ from north to south in the ridge (Figure 2(b)), the transverse velocity gradient of fibers, and the freefall velocity profile seen in $f_3$ are all consistent with a physical picture that the three fibers are colliding in the south and that high-mass star formation is enhanced in the colliding region. On the other hand, there is no significant star formation in the northern parts of $f_2$ and $f_3$; despite that, they are still at least one order-of-magnitude more massive than low-mass star-forming filaments (e.g., Pezzuto et al. 2021). In light of the great masses of DR21(OH) and fiber $f_1$, and the freefall signature seen in $f_3$, the disruptive tidal field in this region may act as a force against local gravity and inhibit the star formation (Renaud 2010; Li et al. 2016).

### 3.7. Fibers of the DR21(OH) Ridge in a Bigger Picture: Relation with the Outer Filaments

Besides the DR21(OH) ridge (or the DR21 clump), another prominent feature of this massive HFS seen in the Herschel maps is the lower-density filaments connected to the ridge/hub. These filaments stretch in all directions, and are mostly too gravitationally unstable to form fragments (i.e., filaments N, F1N, F1S, F3N, F3S, SW, and S in Hennemann et al. 2012), in contrast to the striations connected to low-mass filaments (Goldsmith et al. 2008; Palmeirim et al. 2013). Kinematic analyses using spectral observations show that these filaments are involved in the global collapse of the HFS and are probably feeding materials to the central regions (Schneider et al. 2010). In comparison, these filaments have lengths comparable to the fibers seen in the ridge, but their line masses are a factor of a few to 10 lower (Hennemann et al. 2012); only the most massive filaments have masses and line masses comparable to those of the least massive fiber ($f_3$).

One of the key questions regarding the outer filaments and inner fibers in this remarkable HFS is about whether the filaments are natural extensions of the fibers, or whether they are independent structures without actual connection. In Figure 6, we plot the bones of our fibers and of the seven filaments in Hennemann et al. (2012) overlaid on the $N_{\text{H}}$ map of Cao et al. (2019). Apparently there are five filaments (N, F1N, F1S, F3N, and F3S) having potential connection with the fibers. Filament N seems to be the extension of fiber $f_1$ in the map, yet there is possibility that it is instead the extension of fiber $f_2$. Filaments F1N/F1S are more likely to be the extension of fiber $f_2$, and the single-dish $^{13}$CO (1–0) observations in Schneider et al. (2010) show that F1N/F1S joins the ridge at velocities of $-2$ to $-3\text{ km s}^{-1}$, well matching the velocity of $f_2$, further supporting that F1N/F1S is connected to $f_2$. Schneider et al. (2010) suggested that $f_3$ (resolved into F3N and F3S further out in Figure 6) is connected to a “sub-filament” seen in $^{13}$CO $^+\text{ (1–0)}$ (corresponding to our fiber $f_3$). But F3N/F3S has a nearly east–west orientation whereas $f_3$ is roughly in a north–south direction. There is also a velocity difference of $1–2\text{ km s}^{-1}$ between the two structures. Moreover, with a clear identification of the filbers based on our high-resolution observations and an improved picture of the outer filaments constructed with the Herschel data, the bones of the two structures do not connect with each other (Figure 6). Thus, it is more likely that $f_3$ is an independent structure rather than being the inner part of $f_3$.

Overall it appears that the filaments more parallel to the ridge (such as filaments N, F1N/F1S in Figure 6) are more likely to be the extensions of the inner fibers. This is consistent with a scenario that the large-scale filaments collide to form a ridge/hub, which will further grow in mass by gravitationally attracting the gas along the filaments, making the fibers in the ridge/hub more massive than the outer filaments. As the ridge/hub continues to gain mass, its gravitational well gets deeper and may attract new accretion flows with an even, perpendicular orientation (such as filaments F3N/F3S in Figure 6). Future high-resolution observations of massive HFSs covering both the hub/ridge and outer filaments may help to testify the above scenario and to advance our understanding of the initial conditions of high-mass star and cluster formation.

### 4. Summary

We have observed the prominent DR21(OH) ridge in the high-density tracing spectral lines with the CARMA, and analyzed the data to extract the multiple velocity components, identified the fibers, and characterized the fiber properties, aimed at understanding the formation and evolution of the ridge and its relation to high-mass star and cluster formation. Our main findings are summarized below:

1. We clearly resolve the ridge into three fibers ($f_1$, $f_2$, and $f_3$), which are not seen in existing (sub)millimeter continuum observations. The fibers have lengths around...
2 pc, widths about 0.1 pc, and are mildly supersonic with velocity dispersions about 2 times the sound speed. They are nearly parallel in the north and conjoin in the south around the most massive and active star-forming core DR21(OH).

2. A velocity gradient increasing from north to south is clearly seen in f3, confirming previous single-dish observations (Schneider et al. 2010). We find that the velocity gradient can be well reproduced with a model of gas flow in freefall and that the infall rate is \( \gtrsim 2.5 \times 10^{-3} M_\odot/\text{yr} \). Thus the materials in f3 seem to be falling toward DR21(OH) due to strong gravitational attraction from the MDC (and possibly other MDCs around as well), a scenario also proposed by Schneider et al. (2010).

3. The three fibers have line masses significantly larger than the critical value, and from the instability analyses, they are unstable against gravitational collapse both axially and radially. While the most massive fiber, f1, exhibits active high-mass star formation all the way from north to south, the other two fibers, f2 and f3, show essentially no star formation in their northern parts. Given the freefall velocity field seen in fiber f3, the gravitational tidal forces exerted by the massive materials in this region may account for some local inefficiency in star formation.

4. On larger scales, some of the peripheral filaments are likely to be the outer extensions of the fibers inside the ridge. By comparing the morphologies and masses between the peripheral filaments and the ridge fibers, we speculate that large filaments of more parallel orientations collide to form a HFS, and the central hub/ridge continues to grow in mass by gravitationally attracting the gas from the outer parts of the filaments, feeding the central colliding parts into massive fibers and promoting high-mass star and cluster formation. As the ridge gets more massive, its strong gravitational attraction may induce additional accretion flows of all the orientations.

Y.C. and K.Q. are partially supported by National Key R&D Program of China No. 2017YFA0402600, and acknowledge the support from National Natural Science Foundation of China (NSFC) through grants U1731237 and 11629302. Y.C. acknowledges the funding supports from the Scholarship No. 201906190105 of the China Scholarship Council and from the Predoctoral Program of the Smithsonian Astrophysical Observatory (SAO). G.L. acknowledges the supports from Yunnan University grant C176220100028.

Facility: Telescope.
Software: Astropy (Astropy Collaboration et al. 2013), SciPy (Jones et al. 2001), scikit-learn (Pedregosa et al. 2011), MIRIAD (Sault et al. 1995).

Appendix A
Robustness of the \( N_{\text{H}_2} \) and \( T_{\text{dust}} \) Maps

In this section, we discuss the uncertainties in the \( N_{\text{H}_2} \) map and the \( T_{\text{dust}} \) map (Figure 2) of the DR21(OH) ridge. The maps...
are derived through fitting the spectral energy distributions (SEDs) obtained from the continuum images in the three bands of Herschel 160 μm, JCMT 450 and 850 μm with a modified blackbody model (see Section 3.1). The flux uncertainty of each band used in the fitting is estimated as 20%. The 1σ uncertainty maps of N\textsubscript{H2} and T\textsubscript{dust} derived in the SED fitting are shown in Figure A1, which give a mean value of 0.11 dex and 1.6 K, respectively.

In the reduction of JCMT/SCUBA-2 data, a largest angular scale is used to filter the independent low-frequency noise on the images (see Mairs et al. 2015). Its effect on the SED fitting can be seen as rises of temperature and temperature uncertainty on the map edges (Figures 2(b) and A1(b)). For both our 450 and 850 μm data, this scale is 480" (3.5 pc@1.5 kpc), which is larger than our map sizes and thus has limited filtering effects in our region of interest (the three fibers in the middle of the maps).

The 850 μm continuum flux at DR21(OH) could potentially be contaminated by the strong free–free emission of this region. To evaluate this effect, we adopt the radio-SED relation of DR21(OH) in Araya et al. (2009; see their Figure 5) and extrapolate it to 850 μm, which yields 66 mJy per 13″.7 beam. This is ∼1/400 of the actual continuum intensity of DR21(OH) at 850 μm and can be neglected.

To examine the robustness of the 3-band SED fitting, we derive another set of N\textsubscript{H2} and T\textsubscript{dust} maps using the same techniques in deriving the 3-band ones but with continuum images in 6 bands of Herschel 160, 250, 350, 500 μm, and JCMT 450 and 850 μm. The resultant maps have a coarser resolution of 38″.5 and are presented in Figure A2. The 3-band maps were then smoothed to this resolution and compared with the 6-band values as in Figure A3. As indicated in the figure, 93% of the pixels in the temperature map have differences less than 2 K, and 90% of the pixels in the column-density map have relative differences less than 25%. The N\textsubscript{H2} values derived with the 3-band data are on average 9% higher than the 6-band results, which is a result of the higher Herschel intensities at longer wavelengths compared with the JCMT ones (due to the large-scale filtering effect of the latter). The two fitting results agree with each other, with the overall uncertainties of fiber masses (see Appendix B).

**Figure A1.** Maps of the 1σ uncertainties of (a) N\textsubscript{H2} and (b) T\textsubscript{dust} derived from the SED-fitting procedure (Section 3.1).
Appendix B
Uncertainties of the Fiber Masses

In this section, we estimate the uncertainties of fiber masses. Figure B1 presents the main sources of uncertainties in the derivation procedure of fiber masses, which can be divided into (1) uncertainties of assuming $T_{\text{ex}} = T_{\text{dust}}$ in fitting the H$^{13}$CO$^+$ spectra; (2) regional variations of the H$^{13}$CO$^+$ abundance; (3) SED-fitting errors of the $N_{\text{H}_2}$ as discussed in Section A; (4) distance uncertainty in parallax measurement. Here we discuss them respectively.

In the spectral fitting procedure, we made the assumption of $T_{\text{ex}} = T_{\text{dust}}$ (Section 3.2). This assumption seems to be reasonable for the DR21(OH) ridge since the H$_2$ volume densities of its parts exceed a few $10^4$ cm$^{-3}$, which is sufficient for the dust and gas to be thermally coupled via collision (Hollenbach et al. 1991). At positions where the fibers are seen, the density is even higher. Here we implement the spectral
Figure B1. Diagram showing the sources of errors in fiber masses and their transfer along the derivation procedure. The red, green, and blue connecting arrows represent the three major sources of errors in NH2 of fibers discussed in Appendix B. Percentages in brackets on the connecting arrows are the uncertainties of the next blocks contributed from the previous ones. The overall uncertainty of fiber masses is estimated to be 68%.

Figure B2. (a) H13CO+ column densities derived from the original spectral fitting (Section 3.2) vs. those derived with simulated excitation temperatures (Appendix B). (b) Distributions of the ratios of the two column densities. A Gaussian fitting is shown as the red dashed line.

Figure B3. H2 column density vs. the abundance of H13CO+ of each pixel of the H2-column-density map (Figure 2(b)). Histogram of the H13CO+ abundance is also shown on the right.
fitting with varying $T_{\text{ex}}$ to study its influence on the resultant tracer density $N_{\text{H}^1\text{CO}^+}$. We randomly select 1000 out of the 7625 $\text{H}^1\text{CO}^+$ spectra, and for each spectrum, we assign the fixed $T_{\text{ex}}$ parameter with 50 random values respectively and do the spectral fitting repeatedly. The random temperature values observe a normal distribution with a mean equal to the dust temperature of that pixel and a standard deviation of 4 K. The resultant $N_{\text{H}^1\text{CO}^+}$ values obtained from the spectral fitting are compared with the original ones. As shown in Figure B2, the uncertainties in $T_{\text{ex}}$ introduce a 1σ relative error of 12.1% in $N_{\text{H}^1\text{CO}^+}$ and $N_{\text{H}}$ of the fibers.

When converting $N_{\text{H}^1\text{CO}^+}$ to $N_{\text{H}}$, for the fibers, a constant $\text{H}^1\text{CO}^+$ abundance is assumed (Section 3.4), which can be violated if the abundance has regional variations. To compare the two column densities, we generated a $N_{\text{H}^1\text{CO}^+}$ map with the spectral fitting results, smoothed it to the resolution of the $N_{\text{H}}$ map (Figure 2(b)), and regridded it to the same pixel frame. Figure B3 plots the relation of $N_{\text{H}^1\text{CO}^+}$ versus the abundance and the distribution of the abundance. There is no significant correlation between the two quantities, which indicates that $N_{\text{H}^1\text{CO}^+}$ is an overall good tracer of $N_{\text{H}}$, and that adopting a constant abundance value is robust. The 1σ regional variation of the $\text{H}^1\text{CO}^+$ abundance is 0.25 dex, which results in a relative uncertainty of $61\%$ in $N_{\text{H}}$ of the fibers.

To summarize, the uncertainty of $T_{\text{ex}}$, the regional variation of $\text{H}^1\text{CO}^+$ abundances, and the errors in SED fitting contribute independently to the relative uncertainty of fiber $N_{\text{H}}$ by 12.1%, 61%, and 25.6%, respectively, which yield an overall uncertainty of $67.3\%$. For fiber masses, the uncertainty in distance measurements should be considered given $M \propto N_{\text{H}}D^2$. We adopt the number of 5% in Rygl et al. (2012), which causes an uncertainty of 10% in the mass. The overall uncertainty of the fiber masses is then estimated to be $68\%$.

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