Resolving the Formation of Cold H\textsc{i} Filaments in the High-velocity Cloud Complex C

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Abstract

The physical properties of galactic halo gas have a profound impact on the life cycle of galaxies. As gas travels through a galactic halo, it undergoes dynamical interactions, influencing its impact on star formation and the chemical evolution of the disk. In the Milky Way halo, considerable effort has been made to understand the spatial distribution of neutral gas, which is mostly in the form of large complexes. However, the internal variations of their physical properties remain unclear. In this study, we investigate the thermal and dynamical state of the neutral gas in high-velocity clouds. High-resolution observations (1′1) of the 21 cm line emission in the EN field of the DHIGLS H\textsc{i} survey are used to analyze the physical properties of the bright concentration CIB located at an edge of a large H\textsc{v} complex, complex C. We use the Gaussian decomposition code ROHSA to model the multiphase content of CIB and perform a power spectrum analysis to analyze its multiscale structure. The physical properties of some 200 structures extracted using dendrograms are examined. Each phase exhibits different thermal and turbulent properties. We identify two distinct regions, one of which has a prominent protrusion extending from the edge of complex C that exhibits an ongoing phase transition from warm diffuse gas to cold dense gas and filaments. The scale at which the warm gas becomes unstable and undergoes thermal condensation is about 15 pc, corresponding to a cooling time of about 1.5 Myr. Our study characterizes the statistical properties of turbulence in the fluid of an H\textsc{v} for the first time. We find that a transition from subsonic to transonic turbulence is associated with the thermal condensation, going from large to small scales. A large-scale perspective of complex C suggests that hydrodynamic instabilities are involved in creating the structured concentration CIB and the phase transition therein. However, the details of the dynamical and thermal processes remain unclear and will require further investigation through both observations and numerical simulations.

Unified Astronomy Thesaurus concepts: High-velocity clouds (735); Neutral hydrogen clouds (1099); Interstellar medium (847)

1. Introduction

In their H\textsc{i} survey of neutral high-velocity clouds (H\textsc{v}) in the Galactic halo, in the EN field of DHIGLS,\textsuperscript{3} Blagrave et al. (2017) remarked on an intricate pattern of coherent narrow ribbons of emission associated with narrow line widths, reminiscent of the cold neutral medium (CNM) in the interstellar medium (ISM) in the Milky Way. In this paper, we quantitatively investigate the multiphase structure of this H\textsc{v} gas, its thermal and dynamical state, and the origin of the structured concentration itself.

The EN field or simply EN is a subfield at an edge of complex C\textsuperscript{4} (Hulsbosch & Raimond 1966). Complex C was mapped in three parts (I, II, and III) by Hulsbosch (1968). With higher resolution (10′), Giovanelli et al. (1973) identified bright concentrations within more diffuse gas. The EN field coincides with their concentration called CIB. Higher spectral resolution observations documented by Cram & Giovanelli (1976) confirmed that the H\textsc{v} concentrations have narrower line widths than the diffuse gas, and this was interpreted as evidence for two different thermal phases. In particular, their Gaussian decomposition of line profile number 26 within a 20′ beam toward CIB revealed a narrow component with an FWHM of 7.58 km s\textsuperscript{-1}. Building on this pioneering work, and benefiting from the high-resolution (1′1) EN data mapping of the entire CIB concentration, our spectral decomposition below further quantifies that the narrow components noted by Blagrave et al. (2017) have a typical FWHM of 4.2 km s\textsuperscript{-1} (velocity dispersion \(\sigma = \text{FWHM}/2.355\) about 1.8 km s\textsuperscript{-1}).

1.1. The H\textsc{v} Context

The reservoir of gas in halos is key to understanding the life cycle of galaxies. Halo gas exists in several forms: hot plasma (\(T_k \gtrsim 10^8\) K; Kerp et al. 1999; Wang et al. 2005), largely ionized warm and warm–hot gas (\(T_k \sim 10^5–10^7\) K; Weiner & Williams 1996; Tuft et al. 1998; Putman et al. 2003; Gaensler et al. 2008), and neutral gas (\(T_k \lesssim 10^4\) K; Mulder et al. 1963; Giovanelli et al. 1973; Putman et al. 2002). The hot and warm ionized phases are difficult to detect due to their very diffuse nature, but the neutral phase of the Milky Way halo provides a major probe of its dynamical state and content (Kalberla et al. 1999).

The physical properties of the neutral Milky Way halo gas are needed to assess the fuel available for star formation (Putman et al. 2012) and the impact on galactic chemical evolution (Chiappini et al. 2001) due to its low metallicity (Wakker et al. 1999; Gibson et al. 2001; Collins et al. 2003, 2007; Tripp et al. 2003). The H\textsc{v} gas contributes to the mass influx through the Galactic halo, \(\sim 0.14 M_\odot\) yr\textsuperscript{-1} from complex C alone (Thom et al. 2008). The neutral gas also indirectly probes the properties of the warm/hot ionized Galactic halo and the origin and evolution of the gas throughout the halo (Marasco et al. 2012; Fraternali et al. 2015).

\textsuperscript{3} DRAO H\textsc{i} Intermediate Galactic Latitude Survey: https://www.cita.utoronto.ca/DHIGLS/.

\textsuperscript{4} Among H\textsc{v} complexes, complex C has the largest sky coverage (~1600 deg\textsuperscript{2}) and, using a distance \(D = 10 \pm 2.5\) kpc, the largest mass of atomic gas, \(\mu_m(4.9_{-2.3}^{+5.3}) \times 10^8 M_\odot\) (Thom et al. 2008; see also Wakker et al. 2007), where \(\mu_m = 1.4\) accounting for helium.
From the broadening of the observed H I lines, the internal structure of HVCs is turbulent (Brüns et al. 2001), but the statistical properties of the energy cascade in the multiphase medium remain largely unexplored. The external dynamics can be probed through the interactions with the surrounding halo gas, for example, how the morphology and velocity of HVC gas is affected near interfaces (Brüns et al. 2000).

Empirically, some HVCs exhibit a multiphase structure (Giovanelli et al. 1973; Cram & Giovanelli 1976; Giovanelli & Haynes 1976; Cohen & Mirabel 1979; Wakker & Schwarz 1991; Brüns et al. 2001; Kalberla & Haud 2006), as might be expected for colder structures in pressure equilibrium with warmer, more diffuse gas (Wolfire et al. 1995a, 1995b), in this case, the diffuse halo. However, multiphase structure is not universal and varies between HVCs (Kalberla & Haud 2006; Hsu et al. 2011).

In the ISM, thermal instability is thought to be the main process that leads to thermal condensation of the neutral phase, and therefore its multiphase structure (Field 1965; Wolfire et al. 1995a; Hennebelle & Pérault 1999, 2000; Audit & Hennebelle 2005; Stanimirović et al. 2008; Sobacchi & Sormani 2019; Sormani & Sobacchi 2019; Marchal & Miville-Deschênes 2021). However, for the condensation mode of thermal instability to grow freely, the cooling time must be shorter than the dynamical time. For HVCs, both timescales are different than those in the disk and less constrained observationally. But the thermal state of HVCs seems likely to be intimately linked to the dynamical state.

1.2. Our Goals

This motivates our investigation of both thermal and dynamical aspects. Using the high-resolution EN observations, we quantify the multiphase structure of the concentration CIB in HVC complex C in detail. Furthermore, the EN data cover a projected edge of the complex, providing insight into the dynamics of the interaction and the origin of the structured concentration produced.

The paper is organized as follows. In Section 2, we present the data used in this work and the Gaussian decomposition performed to model its multiphase content. A power spectrum analysis is presented in Section 3. In Section 4, we analyze the physical properties of structures from EN, including their scaling laws. Thermal equilibrium and instability are discussed in Section 5. Section 6 examines the origin of the concentration and its relationship to the triggering of the thermal instability in the large-scale context of complex C. A summary is provided in Section 7.

2. H I Spectral Data and Decomposition

2.1. Data

The 14.6 deg$^2$ EN data set used in this paper, located at ($\alpha$, $\delta$) = (16h14m, 54$'$49") or ($l$, $b$) = (84$^\circ$5, 44$'$3), was part of the DHIGLS H I survey (Blagrave et al. 2017) with the Synthesis Telescope (ST) at the Dominion Radio Astrophysical Observatory. The 256-channel spectrometer, spacing $\Delta v = 0.824$ km s$^{-1}$ and velocity resolution $1.32$ km s$^{-1}$, was centered at $v_c = -60$ km s$^{-1}$ relative to the local standard of rest (LSR). The spatial resolution of the ST interferometric data was about $1'$. The EN is embedded in the N1 field of the GBIGLS$^5$ H I survey (Martin et al. 2015) with the Green Bank Telescope (GBT), with a spatial resolution of about $9'.4$. The DHIGLS EN product has the full range of spatial frequencies, obtained by a rigorous combination of the ST interferometric and GBT single-dish data (see Section 5 in Blagrave et al. 2017). The pixel size is $18''$.

The mean H I spectrum of the EN data set is shown in Figure 1. A velocity range of at least $\Delta v \sim 20$ km s$^{-1}$ with little emission cleanly separates the emission of HVC gas associated with complex C and a low-velocity component (LVC) associated with the Milky Way disk. This important gap, coupled with a relatively high fraction of HVC emission, limits the confusion between different Galactic environments and, along with the dynamic structure already seen in the N1 data, is what motivated the deep observations with the ST (Blagrave et al. 2017). The top axis of the figure gives the velocity with respect to the Galactic standard of rest (GSR),

$$v_{GSR} = v_{LSR} + 220 \sin(l) \cos(b),$$

(1)

the radial component of the velocity relative to the Sun in a reference frame in which the Galaxy rotates, i.e., removing the effect of the rotation of the LSR about the Galactic center. This is often thought to be more directly relevant to assessing the kinematics of the HVC gas (Woorden et al. 2004). For a tiny patch like that covered by the EN data, the conversion is a simple translation, but in the wide-angle context of an entire complex (Section 6), it is of more interest.

Figure 2 presents channel maps of HVC emission for $v_{LSR} = -121$ km s$^{-1}$, at which the bright concentration CIB was first identified by Giovanelli et al. (1973). On the left is the 6.55 deg$^2$ field from the EN data that we analyzed, and on the right is a corresponding map from the N1 data with the GBT. Both the extent of the bright concentration and the finer spatial structure now available are clearly seen.

As we shall see in much more detail below, most of the diffuse emission is in the upper left triangle of the map; the lower right is relatively void except for a prominent protrusion (“finger”) extending from the main body of emission. The boundary between these triangular areas corresponds to the local “edge” of the much larger complex C and is oriented at a

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5 GBT H I Intermediate Galactic Latitude Survey: https://www.cita.utoronto.ca/GBIGLS/.

6 Specifically, counting pixels from (0, 0) at the lower left of the full EN data set, this is the 512 pixel square with lower left corner at coordinates (89, 109).
position angle of about 120° or −60°. The wider-scale context of the concentration CIB is discussed in Section 6 and can be seen in Figures 26, 27, and 31 (top right).

The physical scale of 50 pc shown is 17/3 at an assumed distance of 10 kpc at this position in complex C.7 The range of spatial scales accessible (4 pc ≤ l ≤ 300 pc) makes CIB a unique laboratory for probing the multiscale and multiphase properties of neutral gas in HVCs.

2.2. Gaussian Decomposition

2.2.1. Model and Optimization

We performed multiphase separations of EN and N1 spectra of CIB using the publicly available code ROHSA,8 a multi-Gaussian decomposition algorithm originally developed for just such analyses. As described by Marchal et al. (2019, hereafter M19), ROHSA is based on a regularized nonlinear least-squares criterion that takes into account the spatial coherence of the emission across a field at coordinates r and the multiphase nature of the gas.

The model $\tilde{T}_b(v_z, \theta(r))$ used to fit the measured brightness temperature $T_b(v_z, r)$ at a radial velocity $v_z$ and coordinates $r$ is

$$\tilde{T}_b(v_z, \theta(r)) = \sum_{n=1}^{N} G(v_z, \theta_n(r)),$$

where each of the $N$ Gaussians

$$G(v_z, \theta_n(r)) = a_n(r) \exp \left(\frac{(v_z - \mu_n(r))^2}{2\sigma_n^2(r)}\right)$$

is parameterized by three 2D spatial fields across $r$: $\theta_n(r) = (a_n(r), \mu_n(r), \sigma_n(r))$, with amplitude $a_n \geq 0$, mean velocity $\mu_n$, and standard deviation $\sigma_n$.

The initialization of each Gaussian is accomplished in ROHSA by a multiresolution procedure from a coarse to a fine grid (see Section 2.4.3 in M19). The parameters $\theta$ are optimized by minimizing a cost function that goes beyond the standard $\chi^2$. As described in M19, to penalize variations at the smallest spatial frequencies, the cost function includes Laplacian filtering of each of the three parameter maps $(a_n, \mu_n, \sigma_n)$, with cost controlled by three hyperparameters. A fourth penalty term, for minimizing the variance of $\sigma_n$ across the whole field, is added to enable the multiphase separation. As examined and recommended in M19, the magnitudes of these four hyperparameters, $\lambda_a$, $\lambda_{\mu}$, $\lambda_{\sigma}$, and $\lambda_{\sigma'}$, are chosen empirically so that the solution converges toward a noise-dominated residual and a signal that is encoded with a minimum number of Gaussian components.

2.2.2. Decomposition of EN Data from DHIGLS

We decomposed the spectra for EN from DHIGLS for the area shown in Figure 2 (left) and the HVC spectral range (−162.21 ≤ $v_{LSR}$ [km s$^{-1}$] ≤ −60.82) using $\lambda_a = 1000$, $\lambda_{\mu} = 100$, $\lambda_{\sigma} = 1000$, and $\lambda_{\sigma'} = 10$. Because of the relative simplicity of the HVC spectra, as opposed to complex LVC emission from the Milky Way disk, only a small number of Gaussians, $N = 6$, is needed, and only four of the six encode emission associated with the HVC; the other two deal with noise at the extreme of the spectral range toward intermediate velocities.

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7 Complex C is of large angular extent. Among the probes used by Thom et al. (2008) to bracket the distance, no HVC absorption was present in the line of sight to SDSS J153915.24+575731.7 (S441), thus setting a lower limit of 10.2 ± 2.6 kpc at its position, $(l, b) = (91.2, 47.5)$, only −6° from CIB.

8 https://github.com/antoinemarchal/ROHSA
The simple model fits the data well. A map of the reduced $\chi^2$ $\chi^2_r$ of the decomposition shows no structure, only random fluctuations. Figure 3 shows the 1D probability distribution function (PDF) of $\chi^2_r$, which peaks near the expected value of 1 denoted by the vertical line.

Across the field, the spectra are quite varied. Figure 4 illustrates the different decompositions obtained for six lines of sight marked in Figure 2. Some spectra, particularly in the lower row, contain narrow Gaussian components, indicating the presence of colder gas. Each of these spectra also has emission spread broadly over many channels. This can be fit by broader components, indicating warmer gas, similar to that in the pioneering work of Giovanelli et al. (1973) and Cram & Giovanelli (1976).

It is clear from the original spectra that the mean velocities ($\mu_1$) and dispersions ($\sigma$) of the fitted components vary with position. Figure 5 summarizes the outcome in a 2D PDF of $\sigma_1$–$\mu_1$ weighted by the column density of each Gaussian along each line of sight. In the regularized decomposition obtained with ROHSA, these properties are clustered, each cluster corresponding to one of the four Gaussian components. In particular, the separation vertically into clusters of broader and narrower components results from the hyperparameter $\lambda_\sigma$. Table 1 summarizes the spatially averaged mean dispersion $\langle \sigma(n) \rangle$ of each component $n$ and also the mean velocity $\langle \mu(n) \rangle$ of both the GSR and LSR.

Clusters $G_1$ and $G_2$ have similarly large velocity dispersions (separated by only about 1 km s$^{-1}$) but cover two distinct velocity ranges and are statistically uncorrelated in their spatial distributions (see Section 3.3). Hereafter, these components for two physically distinct regions in this field will be more memorably called WNM$_A$ and WNM$_F$, respectively, adopting the standard abbreviation WNM for a warm neutral medium “phase” with subscripts A (“arc”) and F (“filaments”) motivated by their different morphologies as described in Section 2.4.

This motivated us to identify the unstable (lukewarm) and cold phases, LNM$_{A,F}$ and CNM$_{A,F}$, that are associated with these two regions. To accomplish this within this simple decomposition, the $G_3$ and $G_4$ clusters each need to be divided with respect to velocity $\mu_1(r)$. The location of this split was determined by examining the spatial distribution of the emission encoded in the Gaussians, looking for spatial correlations with WNM$_A$ and WNM$_F$. The resulting split adopted is at $v_{GSR} = 44$ km s$^{-1}$, marked by the black vertical line in Figure 5. Not surprisingly, this is close to the velocity extremes where the $G_1$ and $G_2$ clusters (WNM$_A$ and WNM$_F$) separate. Hereafter, gas in clusters $G_1$ and $G_4$ with $v_{GSR} \gtrsim 44$ km s$^{-1}$ (to the right in the figure) will be called LNM$_A$ and CNM$_A$, respectively, with the complementary gas being LNM$_F$ and CNM$_F$.

2.3. Sensitivity Limits

Noise in the spectral data varies over the field, though only by a factor of 2 within the white dashed contour in Figure 2. In this low-noise central area, the average noise ($3\sigma$) is 1.53 K. Based on this, the corresponding column density sensitivity limit for each phase of regions F and A was evaluated from

$$N_{HIlim} \approx 0.414 \sqrt{\langle \sigma(r) \rangle} \times 10^{19} \text{cm}^{-2},$$

where $\langle \sigma(r) \rangle$ is the average dispersion (kilometers per second) of the relevant Gaussians from Table 1. Values are tabulated in Table 2. These are marked on the color bars in Figures 6 and 29 and can be seen to be reasonable estimates.

2.3.1. The Impact of Spatial Resolution

To evaluate the impact of spatial resolution, we performed a decomposition of N1 HVC spectra from the GHIgLs survey in the same velocity range as for the EN data, as detailed in Appendix A. Again, ROHSA converges toward four components, and a phase separation is still detectable. As seen in Table 1, the mean kinematic properties of Gaussians are fairly similar. The most notable difference is the larger velocity dispersion of $G_3$ at the lower spatial resolution of the N1 data (9'4 compared to 1'1), which would be classified as warm gas. This foreshadows the finding in Section 3 that emission in narrow lines (by LNM and CNM gas) has more significant fluctuations on small spatial scales and so is more affected by beam smearing (mixing physically distinct structures inside one beam leads to an unresolved crowding along the velocity axis if their respective velocities are not exactly aligned). In the following, only the higher-resolution results are used to analyze the physical properties of the gas toward the concentration CIB.

2.4. Multiphase and Multiscale Structure

Figure 6 shows HVC column density maps of the six phases modeled in CIB. Column density detection limits ($3\sigma$; see Table 2) are shown by white marks on the color bars. In region F (right panels), WNM$_F$, LNM$_F$, and CNM$_F$ are clearly associated spatially, underlying the split of the $\sigma_1$–$\mu_1$ clusters, especially LNM ($G_3$), in Figure 5. By contrast, region A shows a dearth of cold gas and emission only in the upper left corner of the field with a continuous “arc” parallel to the edge in the total column density maps described in Section 2.1, Figure 2.

The finger protruding beyond the edge is traced by WNM$_F$, LNM$_F$, and CNM$_F$ and includes very striking elongated filaments along the structure. The close relationship of these filaments to each phase is brought out in Figure 7 (left), which displays the phases simultaneously, the $N_{HI}$ maps of CNM$_F$, LNM$_F$, and WNM$_F$ being represented by RGB, respectively.10

9 For comparison, maps from an analysis of lower-resolution DHIGLS/N1 are shown in Figure 28 in Appendix A.

10 Figure 7, based on the phase decomposition here, is complementary to the RGB image in Figure 27 of Blagrave et al. (2017), which encodes kinematic information of the CNM gas by using three channel maps.
Correlations between phases within each environment and between regions will be quantified statistically in Section 3.3.

The other characteristic feature of each $N_{HI}$ map in Figure 6 is the multiscale structure. In both regions F and A, lukewarm filaments are visible, often within warmer envelopes. Environment F is furthermore populated with smaller cold filaments within warmer envelopes. Building on this, we focus our analysis on the correlated phases WNMF, LNMF, and CNMF from region F, which are suggestive of an ongoing phase transition where all three phases are present simultaneously. The dearth of cold gas in region A will be discussed in Section 6.2.

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**Figure 4.** Example Gaussian decomposition by ROHSA for six lines of sight toward CIB, those annotated (a)–(f) in Figure 2 (left). The original signal is shown in gray and the total signal encoded by ROHSA in black. The four individual Gaussians are color coded: $G_1$ (light blue), $G_2$ (blue), $G_3$ (green), and $G_4$ (red).

**Figure 5.** The 2D PDF $\sigma - \mu$ weighted by the column density of each Gaussian along each line of sight. For the two lower clusters, $G_3$ and $G_4$, the vertical black line shows the velocity split between region A ($v_{GSR} \geq 44$ km s$^{-1}$) and region F.

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### Table 1
Mean Kinematic Properties (in km s$^{-1}$) of Gaussians Modeling DHIGLS/EN and GHIGLS/N1 Data toward CIB

| Component | $G_1$ | $G_2$ | $G_3$ | $G_4$ |
|-----------|-------|-------|-------|-------|
| Field     | WNM$_A$ | WNM$_F$ | LNMF | CNMF |
| EN        | $\langle \sigma \rangle$ | 9.8 | 8.9 | 3.1 | 1.8 |
|           | $\langle \mu_{LSR} \rangle$ | 55 | 34.4 | 44.5 | 36.8 |
|           | $\langle \mu_{GSR} \rangle$ | -103.8 | -124.6 | -114.8 | -121.3 |
| N1        | $\langle \sigma \rangle$ | 9.6 | 9.4 | 7.2 | 2.6 |
|           | $\langle \mu_{LSR} \rangle$ | 57.8 | 25.5 | 41.1 | 33.6 |

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### Table 2
Column Density Sensitivity Limits ($3\sigma$) by Phase (in $10^{19}$ cm$^{-2}$)

| Phase | WNM$_F$ | LNM$_F$ | CNM$_F$ | WNM$_A$ | LNM$_A$ | CNM$_A$ |
|-------|---------|---------|---------|---------|---------|---------|
| $N_{HI}^{3\sigma}$ | 1.24 | 0.73 | 0.56 | 1.30 | 0.73 | 0.56 |

F is furthermore populated with smaller cold filaments within warmer envelopes. Building on this, we focus our analysis on the correlated phases WNMF, LNMF, and CNMF from region F, which are suggestive of an ongoing phase transition where all three phases are present simultaneously. The dearth of cold gas in region A will be discussed in Section 6.2.
Figure 6. Column density maps of the three HVC phase components identified in two regions of CIB from EN data. Left panels: WNM6 (top), LNM6 (middle), and CNM6 (bottom). Right panels: WNM4 (top), LNM4 (middle), and CNM4 (bottom). Note that the color bars have different scales. The coordinates (not shown here) are the same as in Figure 2 (left). The white dots indicate the positions of the six spectra shown in Figure 4. The white dashed contours indicate where the noise has increased by a factor of 2 relative to the central minimum. The white marks on the color bars indicate the column density sensitivity limits (3σ) within the white dashed contours (see Table 2), showing that the features seen with this color representation are well detected (see also Figure 29 for another representation).
3. Power Spectrum Analysis of $N_{\text{HI}}$ Maps from Environment F

To investigate the multiscale properties, here focusing on region F, we make use of three statistical tools: the power spectrum, the cross-power spectrum, and the cross-correlation coefficients. For completeness, the results tabulated in Table 3 for region F have their equivalent for region A in Table 4.

### 3.1. Power Spectrum

All spatial (angular) power spectra $P(k)$ presented here are obtained following the methodology described in Martin et al. (2015) and Blagrave et al. (2017). Each power spectrum $P(k)$ is the azimuthal average of the modulus of the Fourier transform of the corresponding field and modeled as

$$P(k) = B(k) \times P_0 k^\gamma + N(k),$$

where $P_0$ is the amplitude of the power spectrum; $\gamma$ is the scaling exponent; $B(k)$ describes the cutoff of the spectrum at high $k$ due to the beam of the instrument, assumed to be a 2D Gaussian of FWHM = 11; and $N(k)$ is the noise estimated by taking the power spectrum of empty channel maps of the PPV (position-position-velocity) cube. The finite images were apodized using a cosine function to minimize systematic edge effects from the implementation of the Fourier transform.

Figure 8 shows the beam-corrected (deconvolved) spatial power spectra of WNMF, LNMF, and CNMF. Here LNMF and CNMF are well described by power laws in the spatial range 4 pc $\lesssim l \lesssim$ 300 pc. At low spatial frequencies ($k \lesssim 0.15$), the power spectrum of WNMF follows a steeper power law. However, at higher $k$, on scales $l \lesssim 20$ pc, the power spectrum flattens, just as it does for the total $N_{\text{HI}}$ of the HVC toward CIB presented by Blagrave et al. (2017, Figure 22) using the EN data. This is caused by noise. Unlike CNMF and LNMF, the WNMF covers parts of the field where the intrinsic noise of the observation is the highest, notably visible in the upper left of WNMF and WNMF in Figure 6, outside the white dashed contour that indicates where the noise has increased by a factor of 2 relative to the central minimum. Furthermore, compared to CNMF and LNMF, the WNMF Gaussian components WNMF and WNMF span significantly more channels (i.e., have large velocity dispersions; see Figure 4), so that again, the warm phase is more sensitive to noise (Equation (4)).

Therefore, different spatial ranges are used to fit the power spectrum exponents, as denoted by the colored dashed vertical lines on the right. These exponents are reported on the diagonal of

### Table 3

|        | WNMF | LNMF | CNMF |
|--------|------|------|------|
| Exponent | \(-2.68 \pm 0.10\) | \(-2.51 \pm 0.18\) | \(-2.87 \pm 0.37\) |
| Correlation | 1 | 0.27 $\pm$ 0.14 | 0.38 $\pm$ 0.14 |

### Table 4

|        | WNMA | LNMA | CNMA |
|--------|------|------|------|
| Exponent | \(-2.37 \pm 0.10\) | \(-2.91 \pm 0.50\) | \(-2.28 \pm 0.42\) |
| Correlation | 1 | 0.32 $\pm$ 0.15 | 0.10 $\pm$ 0.12 |

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Table 3. The exponents for LNMF and CNMF are significantly less negative (the spectra are flatter) than for WNMF, quantifying that the unstable and cold phases have relatively more structure on small scales. A similar trend is observed in Table 4 for region A. The steeper power spectrum for the WNMF may be caused by more efficient turbulent dissipation from gas cooling (Siltsbee et al. 2020).

3.2. Cross-power Spectrum

The cross-power spectrum $\rho_{ij}(k)$ is the azimuthal average of the Fourier transform of image $i$ times the conjugate of the Fourier transform of $j$. It is also modeled using Equation (5). Figure 9 shows the beam-corrected spatial cross-power spectra of WNMF × LNMF, WNMF × CNMF, and LNMF × CNMF. The cross-power spectrum LNMF × CNMF is well constrained due to the broad spatial coverage 4 pc $\lesssim l \lesssim 300$ pc available. On the other hand, WNMF × LNMF and WNMF × CNMF are dominated by noise on scales $l \lesssim 20$ pc. Exponents from the model fits are reported in Table 3 in the off-diagonal elements. The cross-power spectrum of LNMF × CNMF is significantly flatter than WNMF × CNMF and WNMF × LNMF, considering the uncertainties.

The cross-power amplitude of LNMF × CNMF is much higher than for the other two cross powers but similar to the amplitudes for these cooler components in Figure 8, revealing a strong correlation between these two maps. The exponent for LNMF × CNMF is somewhat steeper than for the power spectrum of CNMF, indicating a relative decorrelation at the smallest scales.

3.3. Cross-correlation Coefficients

For further statistical quantification of the interrelationship between phases, we combined the power and cross-power spectra results to obtain the cross-correlation coefficients $\rho_{ij}(k)$ for each pair of column density maps, formally

$$\rho_{ij}(k) = \frac{P_{ij}(k)}{\sqrt{P_{ii}(k) P_{jj}(k)}}. \quad (6)$$

Figure 8 shows the cross-correlation coefficients of LNMF × CNMF, WNMF × CNMF, and WNMF × LNMF. Solid lines show the models $\tilde{\rho}_{ij}(k)$ obtained using the spectral fits shown in Figures 8 and 9. Note again the decorrelation toward smaller spatial scales.

In addition, for each pair, we calculated the mean and standard deviation (not uncertainty) of the cross-correlation coefficients in the spatial range 20 pc $< l < 300$ pc. These results are tabulated in Table 3 (bottom section). The correlation of LNMF × CNMF is the highest, and, as seen in Figure 10, the other two are not negligible. But in region A, only WNMF × LNMF has a hint of correlation.

Finally, for WNMF × WNMF, we find a cross-correlation coefficient of $-0.01 \pm 0.13$, which confirms that regions A and F are uncorrelated statistically and should be analyzed independently.

4. Properties of Structures from Segmentation of $N_{HI}$ Maps in Region F

As can be appreciated from Figure 6 (left), the surface coverage of the EN data is large enough to explore substructures within each phase of region F of CIB. The largest scale $(\sim 400$ pc) allows us to segment even the warm phase, and the smallest scale $(\sim 2$ pc) allows us to quantify the finer structures seen in the colder phase. For completeness, the results of a similar analysis for region A are given in Appendix C.

4.1. Hierarchical Clustering of $N_{HI}$ Maps from Region F Using Dendrograms

To perform the clustering analysis, we made use of the astrodendro python package that follows the changing topology of the isosurfaces as a function of their contour levels (Rosolowsky et al. 2008). Our choice of this specific method was motivated by the potentially multiscale nature of the observed phase transition, a direct consequence of turbulence. Also, as noted by Goodman et al. (2009), a dendrogram is almost entirely data-driven and is weakly sensitive to the chosen user parameters.
The mean and standard deviation of the correlation coefficients \( \rho(k) \) of \( \text{LNM}_F \times \text{CNM}_F \) (dark red), \( \text{WNM}_F \times \text{CNM}_F \) (orange), and \( \text{WNM}_F \times \text{LNM}_F \) (teal). Calculated coefficients are shown with colored dots. Solid lines are based on the spectral fits shown in Figures 8 and 9. Vertical dashed lines show the high- and low-k limits within which the mean and standard deviation of the correlation coefficient for each pair are computed (see Table 3).

A detailed description is provided in Appendix B, where visualizations of the extracted structures are shown in the left panels of Figure 29 (see right panels for region A). We obtained \( N_c = 21, 60, \) and 73 structures for \( \text{WNM}_F, \text{LNMF}, \) and \( \text{CNMF}, \) respectively.

In separate subsections below, we have evaluated a number of properties of the structures—physical, thermodynamic, and turbulent—for each phase and the total ensemble. The values have a considerable range, so that their PDFs are best displayed logarithmically. Although the PDFs are not precisely lognormal, they are well summarized by the mean and standard deviation of the log of the parameter. The value of the parameter corresponding to this mean is reported in Table 5, along with the standard deviation (hereafter “spread,” e.g., 2 for a 0.3 dex standard deviation) in parentheses.

### 4.1.1. Evaluation of Uncertainties

To evaluate the uncertainties of the physical properties derived from the dendrograms, we have repeated the segmentation on \( N_{\text{HHII}} \) maps using two series of decompositions obtained with ROHSA. For the first series, composed of 50 runs, in the spectral data for each line of sight, we injected Gaussian random noise with the same dispersion as the noise in the original data. The hyperparameters were kept the same. For the second series, composed of 80 runs, we kept the original data cube (i.e., each run has just the original noise) but randomly perturbed the four ROHSA hyperparameters in a \( \pm 10\% \) interval around the original values. From the catalogs obtained by segmentation for each run, the properties of the structures—physical, thermodynamic, and turbulent—were computed.

The new structures extracted were cross-matched with structures in the original catalogs using their spatial coordinates. The uncertainties of the properties of a structure were estimated by calculating the standard deviation over the cross-matched members for each series. Finally, for each property, the contributions from the two series were summed in quadrature to yield the total uncertainty (the contribution from the first series was generally slightly higher than that from the second).

These uncertainties were then taken into account in producing the PDFs presented below. In each PDF, the bin size (logarithmically constant) was chosen so that it was larger than the relative uncertainty of the quantity being analyzed in each bin.

#### 4.2. Physical Properties

The sky coordinates of a structure in a particular frame (taken to be the International Celestial Reference System for the terminology here) are the mean positions of all pixels, weighted by column density:

\[
(\bar{x}, \bar{y}) = \frac{\sum_r (x(r), y(r)) N_{\text{HHII}}(r)}{\sum_r N_{\text{HHII}}(r)},
\]

where \( x \) and \( y \) denote the R.A. and decl.

The geometry of each structure is modeled by an on-sky ellipse. Following Hennebelle & Audit (2007) and Miville-Deschênes et al. (2017), the inertia matrix of the projected emission is

\[
I = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 \end{bmatrix},
\]

where the matrix coefficients are

\[
\sigma_{xy}^2 = \sum_r (x(r) - \bar{x})(y(r) - \bar{y}) N_{\text{HHII}}(r)/\sum_r N_{\text{HHII}}(r).
\]

#### 4.2.1. Size

Using the eigenvalues \( \lambda_{\text{min}} \) and \( \lambda_{\text{maj}} \) of \( I \) and the pixel area \( S_p = (D\delta)^2 \) (the scaling with distance \( D \) can be tracked), the lengths of the semimajor and semiminor axes are \( L_{\text{min,maj}} = \sqrt{8 \ln(2)} S_p \lambda_{\text{min,maj}} \). Making the assumption that the depth along the line of sight is more likely to be \( L_{\text{min}} \), the volume of the ellipsoid is \( V = (4\pi/3) L_{\text{maj}}^2 L_{\text{min}} \). Finally, our size estimate is simply \( L = V^{1/3} \).

Figure 11 shows the PDFs of the size, with color coding for each phase. The PDF for all phases combined is also shown in black (note the logarithmic scale vertically). Sizes range from \(~3 \) pc (the spatial resolution of the maps for \( \text{LNM}_F \) and \( \text{CNMF} \); see vertical gray dashed line) up to \(~100 \) pc.

Inspection of Figure 11 suggests that the PDF of \( L \) for \( \text{CNMF} \) and \( \text{LNMF} \) might be impacted by the resolution, 1′1 or 3.2 pc at the assumed distance. Perhaps smaller structures would be identified with observations of higher resolution and signal-to-noise ratio. In none of the statistics, here and below, have we applied any correction for this potential bias. Similarly, because the segmentation for \( \text{WNM}_F \) was carried out on maps convolved to 4′4 (a factor of 4 in resolution; see the vertical blue line for the corresponding physical size), that phase too is potentially impacted. Even so, there is some evidence that the typical size of the structures decreases from the warmer to the cooler phases, as expected from the thermal condensation.

#### 4.2.2. Aspect Ratio

Figure 12 shows the PDFs of the aspect ratio \( r = L_{\text{maj}}/L_{\text{min}} \). In each phase, \( r \) is generally higher than 1.5 and can reach values up to 6 in \( \text{CNMF} \) and \( \text{LNM}_F \). The shape of the distributions looks similar among the phases, and the mean of
all distributions is close to 2 (see Table 5), showing that elongated structures are not just seen in the cold phase but rather are a multiphase property.

### 4.2.3. Orientation

The position angle \( \psi \) of each structure is

\[
\psi = \tan^{-1}\left(\frac{v_y}{v_x}\right),
\]

where \((v_x, v_y)\) is the eigenvector corresponding to \( \lambda_{\text{max}} \).

Figure 13 shows the PDF of \( \psi \) for each phase and the whole sample. The CNMF and LNMF clearly show a distribution dominated by positive position angles; the evidence for WNMF is less pronounced. Maximum-likelihood estimates (MLEs) of the location (orientation) and dispersion of a Von Mises distribution fit to the orientations of all of the structures are \(+63^\circ\) and \(31^\circ\), respectively. The purple dashed line shows the model.

In region A, we find an orientation of \(-43^\circ\) and a dispersion of \(38^\circ\) (see Figure 30 in Appendix C). That the mean orientations of structures in regions F and A are roughly orthogonal can be appreciated visually from Figures 6 and 7.

### 4.2.4. Mass

The mass of each structure derived from the column density is

\[
M_{\text{H}_1} = S_A \mu_m m_\text{H} \sum_{\rho} N_{\text{H}_1}^\rho
\]

Here \( m_\text{H} \) is the mass of the hydrogen atom and \( \mu_m = 1.4 \) accounts for the atomic Galactic composition, so that \( M_{\text{H}_1} \) is actually the total mass of the neutral gas.

Figure 14 shows the PDFs of \( M_{\text{H}_1} \). Masses increase systematically from CNMF to LNMF and WNMF, with values ranging from \( \sim 2 M_\odot \) in the cold phase up to \( \sim 3000 M_\odot \) in the warm phase. Note that CNM structures would reach even lower masses if they were segmented more finely at higher spatial resolution.

The total masses of CNMF, LNMF, and WNMF are \((1, 1.5, \text{and } 15) \times 10^3 M_\odot\), respectively. The corresponding mass fractions within region F are 0.06, 0.08, and 0.86. Finally, for perspective, the total mass of the neutral gas of these structures, \(18 \times 10^3 M_\odot\), is just 0.3% of the total atomic mass of complex C (Thom et al. 2008).

### 4.2.5. Average Number Density of H Atoms

For each structure, the average number of H atoms per unit volume is

\[
n = \frac{1}{\mu_m m_\text{H}} \frac{M_{\text{H}_1}}{V}
\]

(or, equivalently, the total column density \( N_{\text{H}_1} \) times \( S_A \) divided by \( (4\pi/3)(L_{\text{maj}}^2 L_{\text{minor}}) \), which scales as \( D^{-1} \). Figure 15 shows the PDFs of \( n \). From the condensation mode of thermal instability, we expect to observe an increase of \( n \) from the warm to the cold
phase. There is some evidence for this, and it is possible that \( n \) for CNMF is underestimated because of the finite resolution.

4.3. Thermodynamic Properties

4.3.1. Separation of Thermal and Nonthermal Motions

The observed Doppler dispersions \( \sigma_{cT} \) of the structures (Table 5) measure the total velocity dispersion of gas along the line of sight. This is often modeled as a quadratic sum of a thermal and a nonthermal component,

\[
\sigma_{cT} = \sqrt{\sigma_{cth}^2 + \sigma_v^2}. \tag{13}
\]

Separation of the two components is not possible using data for a single line of sight but can be done statistically for an ensemble. According to studies by Ossenkopf et al. (2006, and references therein), for a turbulent medium, the statistics of the 3D velocity field can be recovered from its 2D projection if the density fluctuations are small compared to the mean density of the fluid \( \rho / \rho_0 \approx 0.5 \).

To verify that a sufficiently small density contrast is the case here, the methodology proposed by Brunt et al. (2010) and applied to 21 cm line emission data in Marchal & Miville-Deschênes (2021) was used to calculate, for each structure, the density contrast of its 3D density field from the column density contrast of its projection along the line of sight \( \rho / \rho_0 \).

Brunt et al. (2010), assuming that the statistical properties of \( \rho \) are isotropic and using Parseval’s theorem, showed that the ratio of these contrasts is

\[
R = \left( \frac{\sigma_{N/N_0}}{\sigma_{cT/\rho_0}} \right)^2 \tag{14}
\]

\[
= \frac{\left( \sum_{k_x = -L_{min}/2}^{L_{maj}/2} \sum_{k_y = -L_{maj}/2}^{L_{maj}/2} \sum_{k_z = -L_{min}/2}^{L_{min}/2} P_{\rho}^{3D}(k) \right)^2 - P_{\rho}^{3D}(0)} {\sum_{k_x = -L_{min}/2}^{L_{maj}/2} \sum_{k_y = -L_{maj}/2}^{L_{maj}/2} \sum_{k_z = -L_{min}/2}^{L_{min}/2} P_{\rho}^{3D}(k) - P_{\rho}^{3D}(0)}, \tag{15}
\]

where \( P_{\rho}^{3D}(k) \) is the azimuthally averaged power spectrum of \( \rho \).

For a structure of size \( L_{min} \times L_{maj} \), two parameters control the ratio \( R \): the slope of \( P_{\rho}^{3D}(k) \) and the depth of the structure. For this model, we consider \( P_{\rho}^{3D}(k) \propto k^{-11/3} \), representative of a sub/transonic turbulence. The depth over which velocity fluctuations are averaged is assumed to be \( L_{min} \), so that \( R \)
depends on the aspect ratio $r$ of each structure. For the whole sample, we find a mean value $\sigma_{\text{D}/v_{\text{ls}}}$ ≈ 0.2 and a standard deviation of 0.1. This result is not sensitive to a variation of \pm 1/3 for the slope of $P_{\text{D}}^3(k)$. Having verified that density fluctuations are sufficiently small, using the same formalism (i.e., the same coefficient $R$ for each structure), we can infer the nonthermal velocity dispersion $\sigma_{\text{v}}$ of the 3D velocity field from the observed dispersion of its projection along the line of sight, $\sigma_{\text{v}}(u)$. We find a similar velocity dispersion $\sigma_{\text{v}}$ across phases (Table 5), with a value of about 0.8 km s$^{-1}$ overall. This is a significant part of the Doppler dispersion only for the CNM, as reflected in the thermal velocity dispersions $\sigma_{\text{th}}$, derived using Equation (13). Formally, nothing prevents the inferred value of $\sigma_{\text{th}}$ from being less than the channel spacing of the observations. However, this occurs for only nine out of the 73 structures in CNMF, and for these, there is considerable uncertainty.

Properties derived below that are dependent on these separated velocity dispersions are less directly data-driven than the physical quantities in Section 4.2. Nevertheless, tabulating these provides a global view of the properties of the fluid constituting the concentration CIB, which is useful for interpreting our results in the context of condensation via thermal instability.

4.3.3. Thermal Pressure

Given the kinetic temperature and average number density of H I of a structure, the thermal pressure is

$$P_{\text{th}}/k_B = \mu_p n T_k \equiv \mu_p n \sigma_{\text{th}}^2 m_{\text{H}}/k_B,$$

with $\mu_p = 1.1$ accounting for He. Figure 16 shows the PDFs of $P_{\text{th}}/k_B$ for the phases. There is an apparent decrease of the mean thermal pressure from WNM F to LNMF and CNMF (see also Table 5). As mentioned in Section 4.2.5, because of finite resolution, the average number of H atoms per unit volume of CNM structures might be higher than that above, which would increase the thermal pressure. A secondary compensating effect might be less beam smearing, possibly leading to a lower estimate of the thermal broadening and therefore a lower thermal pressure.

4.4. Turbulent and Total Pressure

The turbulent pressure can be calculated using the deduced turbulent velocity dispersion,

$$P_t/k_B = 3 \mu_p n \sigma_{\text{v}}^2 m_{\text{H}}/k_B,$$

where the factor 3 accounts for the dimensionality of $\sigma_{\text{v}}$ (from 1D to 3D). As expected from the typical relative sizes of $\sigma_{\text{v}}$ and $\sigma_{\text{th}}$ (Table 6), this pressure is of most interest in the CNM phase. The total pressure is just $P_{\text{tot}}/k_B = (P_t + P_{\text{th}})/k_B$. Table 6 gives the mean and spread of each quantity calculated for the ensemble.

4.5. Properties of the Turbulent Cascade

Turbulent fluids are commonly characterized by properties like the Mach number. These can be derived from the velocity dispersions in combination with the size $L$ and average number of H atoms per unit volume $n$ and so again can be considered as
different recastings, not as directly data-driven. They are nevertheless useful in connecting to the literature and understanding numerical simulations. The values of such properties are given in Table 5 for structures in different phases. These are motivated and discussed briefly here.

The turbulent sonic Mach number $\mathcal{M}_s$ of a structure is

$$ \mathcal{M}_s = \sqrt{\frac{3}{\pi}} \frac{\sigma_v}{C_v}. $$

Figure 17 shows the PDFs of $\mathcal{M}_s$. Because $\sigma_v$ is fairly constant, $\mathcal{M}_s$ increases from the warm phase to the cold phase, from a subsonic regime (0.14(2.4)) to a transonic regime (0.75(2.1)). This implies an inverse trend of $\mathcal{M}_s$ with size, as shown in Figure 18.

For properties below involving a mean free path, $\lambda$, we assume $\lambda = 1/n \sigma$ with $\sigma = 1 \times 10^{-15} \text{ cm}^2$ for the hydrogen collision cross section (Lequeux 2012). One such property is the kinematic viscosity,

$$ \nu = \frac{1}{3} \lambda \nu_{th}, $$

where the arithmetic mean speed $\nu_{th} = \sqrt{\frac{8}{\pi \mu} C_v} = \sqrt{\frac{8}{\pi \mu} \sigma_{th}}$.

Another such property is the Knudsen number, $\text{Kn} = \lambda/L$. For an isothermal gas, as assumed here for each individual structure, the ratio of $\mathcal{M}_s$ to the Knudsen number is linked directly to the Reynolds number,

$$ \text{Re} = \sqrt{\frac{\pi}{2}} \frac{\mathcal{M}_s}{\text{Kn}}, $$

which quantifies the relative influence of advection and diffusion in a turbulent fluid. Unlike $\mathcal{M}_s$, $\text{Re}$ is proportional to $n$ through the inverse dependence on $\lambda$. The net dependence on size is shown in the scatter plot of $\text{Re}$ and $L$ in Figure 19. We observe the same trend as for $\mathcal{M}_s$; i.e., $\text{Re}$ increases from large warm structures to small cold structures. The typical values of $\text{Re}$ are of interest too. If the initial perturbations applied to a flow are not too small, turbulence appears at $\text{Re} \sim 2000$ (Reynolds 1883). It therefore seems likely that the turbulence in gas toward CIB is well developed for CNMF, LNMF, and even WNMF, except for four structures with $\text{Re}<1000$ (Figure 19).

Other combinations give characteristic sizes and timescales for structures. The dissipation scale $\eta$, on which the smallest eddies dissipate the turbulent energy into heat through viscosity, is

$$ \eta = L \text{Re}^{-3/4}, $$

and the dissipation timescale $t_\eta$ is

$$ t_\eta = \frac{\eta^2}{\nu}. $$

Note that $\eta$ and $t_\eta$ are also called the Kolmogorov length and timescales. The convective time, also called the large eddy turnover time, is

$$ t_L = t_\eta \text{Re}^{1/2}. $$

The traversal time $\tau_L$ needed for an eddy of size $L$ to traverse the inertial range, in which viscous effects are essentially negligible, down to the Kolmogorov length scale $\eta$ is related to $\text{Re}$ through the relation

$$ \tau_L = \frac{t_L}{1 - \text{Re}^{-1/2}}. $$

For high $\text{Re}$, i.e., fully developed turbulence, $\tau_L \sim t_L$. Finally, combining the dissipation scale and time, the energy transfer

\[11\] For minimal perturbations, the flow can remain laminar up to $\text{Re} \sim 13,000$. 

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**Figure 16.** The PDF of the thermal pressure $P_{th}/k_B$ of structures extracted from WNMF (blue), LNMF (green), and CNMF (red). The total is shown in black.

**Figure 17.** The PDF of the sonic Mach number $\mathcal{M}_s$ of structures extracted from WNMF (blue), LNMF (green), and CNMF (red). The total is shown in black.
CNMF, LNMF, and WNMF are shown in red, green, and blue, respectively. The black dashed line indicates \( M_i = 1 \).

The rate \( \varepsilon \) is

\[
\varepsilon = \frac{\eta^2}{t^3}_n
\]  

(25)

4.6. Scaling Laws between Properties of Extracted Structures

4.6.1. Mass and Density–Size Relations

A scatter plot of H1 mass (proportional to total column density; Equation (11)) and size is shown in Figure 20, color coded by phase. Note the logarithmic scales, such that the slope in this diagram is the power-law exponent of the mass–size relation. Using a bisector estimator of the slopes, the exponents are \( 2.7 \pm 0.2, 2.2 \pm 0.2, \) and \( 2.0 \pm 0.1 \) for WNMF, LNMF, and CNMF, respectively.

Recognizing the uncertainties, we find that the exponent for WNMF is higher than those of LNMF and CNMF. This trend is consistent with the ranking of the exponents found in Section 3 for the power spectra of the column density maps (Figure 8 and Table 3), that for WNMF being steeper.

By definition, \( M \propto n L^3 \). The deviations of the above exponents from 3 show that the average number of H atoms per unit volume \( n \) is not constant even within a single phase. Instead, \( n \) varies inversely with \( L \), with exponents \(-0.3 \pm 0.2, -0.8 \pm 0.2, \) and \(-1.0 \pm 0.1 \) for WNMF, LNMF, and CNMF, respectively. The increase of \( n \) from large to small scales is more pronounced in the unstable and cold phases compared to the warm phase, a result of the thermal condensation.

Finally, we have made an empirical estimate of the typical cooling length scale at which the warm gas is nonlinearly unstable (Audit & Hennebelle 2005). This should be larger than most LNMF and CNMF structures, and so from Figure 11, \( \lambda_{\text{cool}} \sim 15 \) pc, as marked by the vertical black dashed line in Figure 20. This spatial scale is five times higher that the warm phase, a result of the thermal condensation.

4.6.2. Turbulent Velocity Dispersion–Size Relation

Figure 21 shows the \( \sigma_v \sim L \) relation, color coded by phase. The two variables are positively correlated, and the Pearson correlation coefficient is 0.27. Although the Pearson coefficient is significantly positive, its value is too low for a reliable determination of the power-law exponent. Given the Mach numbers obtained in Section 4.5, one might expect to see the scaling law of sub/transonic compressible turbulence (Kim & Ryu 2005), close to Kolmogorov’s prediction of incompressible turbulence \( \sigma_v \propto L^{1/3} \) (Kolmogorov 1941). This is illustrated in the top right corner of Figure 21.

4.6.3. Kinematic Viscosity and Energy Transfer Rate–Size Relations

Figure 22 shows the kinematic viscosity as a function of scale. The Pearson correlation coefficient is 0.83 for the ensemble, and a power-law fit using the bisector estimator gives exponent 1.9 \pm 0.1. Noting that \( v \propto T_k^{1/2} n^{-1} \) from Equation (19), this pronounced scaling is seen to be a direct consequence of the phase transition, which lowers the kinetic temperature and increases the average number of H atoms per unit volume of the fluid as the scale decreases.

The Pearson correlation coefficient of the energy transfer rate–size scaling law (not plotted) is \(-0.06 \), showing that no significant trend is observed.

4.6.4. Insights into the Turbulent Cascade

In summary, the physical properties of structures extracted from region F across phases reveal the presence of a sub/transonic turbulent energy cascade. The warm component is the least turbulent phase with \( Re = 0.62 (3.9) \times 10^4 \).

When the fluid undergoes a phase transition, condensed gas with higher \( n \) and lower \( T_k \) appears as smaller structures and filaments (see Figures 6 (left), 7 (left), 11, and 12). This change in the thermodynamic properties of the gas modifies a fundamental property of the turbulence, the kinematic viscosity \( \nu \). The scale dependence of \( \nu \) (Figure 22) increases the relative
strength of the turbulence from large to small scales (see Figure 19 for Re and Figures 17 and 18 for $\mu$). There is a progression from subsonic to transonic turbulence, reaching a state characterized by $\mu = 0.86(2.2)$ in the coldest phase (Table 5).

Despite this change in the statistical properties of the turbulent cascade, a constant energy transfer rate is observed over scales. This favors a scenario where no energy is injected or dissipated along the energy cascade. In other words, this turbulence appears to be self-similar, even if influenced by a phase transition.

The traversal time $\tau_L$ decreases from the warm phase to the cold phase (Table 5). This suggests that velocity fluctuations (and therefore density fluctuations) will last longer in the warm phase than in the cold phase. Note that in each phase, the traversal time and turbulent crossing time $t_{\text{cross}}^c$ are very similar.

5. Thermal Equilibrium and Thermal Instability

The following discussion relates to the interpretation of the thermal properties of the structures in different phases in region F. While it is difficult to demonstrate unequivocally that the colder and denser condensations that are observed have formed simply by a triggered thermal instability, we find multiple pieces of evidence pointing in this direction.

5.1. Thermal Equilibrium

5.1.1. Empirical $T_k-n$ Diagram and Some Caveats

Figure 23 shows the $T_k-n$ diagram for structures extracted from WNMF, LNMF, and CNMF, color coded by phase. There are nine structures from CNMF, with $T_k$ below the horizontal gray dashed line (see Section 4.3.1) and these have large uncertainties.

It is instructive to use this figure for comparisons with thermal equilibrium models, but there are some effects that could compromise the comparison in its detail. First, for each phase, the dispersion in $T_k$ is much smaller than that in $n$. For WNMF, this is expected because the steep temperature dependence of cooling by collisional excitation of $\text{Ly}_\alpha$ constrains the temperature of the warm gas to a narrow range close to $T_k \sim 10^4$ K. However, for the LNMF and CNMF, we would not expect the gas to be so closely isothermal for different structures. The narrowness of the range of $T_k$ found arises at least in part from our spectral decomposition using ROHSA, which, in enabling phase separation, favors a solution with each Gaussian component having a similar Doppler velocity dispersion across the field, as is apparent in Figure 5. The nonthermal component of the dispersion is fairly uniform, so this propagates to the derived uniformity in $T_k$. Therefore, the ensemble for a given phase, LNMF or CNMF, provides a single estimate of the typical temperature for that phase, and any temperature variation with density is lost.

Second, the observed $\sigma_T$ for CNMF, which is quite small, might be biased high by two effects, beam smearing (Section 4.2.1) and the finite spectral resolution of the spectrometer. This bias would propagate such that $T_k$ might then be lower than we have inferred.
Third, as discussed in Section 4.2.1, the limited spatial resolution of the observation is likely to lower the inferred average number of H atoms per unit volume of extracted structures for CNM$_p$. Allowing for these last two effects, the red dots for structures from CNM$_p$ might tend to be shifted down and/or to the right in Figure 23.

5.1.2. Modeling the Thermal State in CIB

We have calculated the thermal state of the gas using the approximation of a static 1D photodissociation association (PDR) model at the location of CIB in the Galactic halo. This is admittedly oversimplified but should be a useful benchmark toward deeper understanding. In particular, we calculated the thermal equilibrium curve $L = 0$ using the chemical network presented in Gong et al. (2017), where $L$ is the net heating and cooling. In the neutral atomic phase of the ISM, heating is dominated by photoelectrons from small dust grains, and cooling is dominated by collisional excitation of Ly$\alpha$ and the fine-structure lines of O I, C II, and C I. The input parameters of this PDR model are the far-UV (FUV) interstellar radiation field strength $\chi$ (in units of the Draine (1978) field strength), the dust abundance $Z_d$ and gas metallicity $Z_g$ (each relative to the value in the solar neighborhood), and the primary cosmic-ray (CR) ionization rate per H atom $\xi_p$.

To choose plausible values of $\chi$ and $\xi_p$, we first evaluated these parameters at the galactocentric radius of CIB, $R_{\text{CIB}} = 11$ kpc, using Table 2 in Wolfire et al. (2003). We then applied the scaling with height $z$ above the Galactic plane using Equation (4) in Wolfire et al. (1995b), assuming $z = 10 \sin(b_{\text{CIB}})$ kpc. In addition, $\chi$ was multiplied by a factor of 0.6 to lower the midplane intensity to the intensity at the surface of the disk, in order to match the FUV optical depth obtained by Tielens & Hollenbach (1985; Wolfire et al. 1995b). This approach led to $\chi \sim 0.2$ and $\xi_p = 6 \times 10^{-17}$ s$^{-1}$. These values anchor ranges that we have explored. We note that an X-ray radiation field that might assume some importance in the Galactic halo is not included in the model. Its potential effects might be mimicked in part by larger values of these two parameters.

Three gas-phase metal abundances, $Z_g = (0.1, 0.3, 0.5)$, were selected ranging over estimated metallicities in complex C (Gibson et al. 2001; Collins et al. 2003, 2007; Tripp et al. 2003). The choice of $Z_d$ is more problematic because no dust has been detected in HVCs to date; we explored two possibilities, dust limited by the metallicity, $Z_d = Z_g$, and a much lower value, $Z_d = 0.01$.

5.1.3. Comparison of Models and Data

The results of our explorations of parameter space are summarized in Figure 23. Any comparisons made with the properties inferred independently from the data (hereafter, data) are subject to the previous caveats.

In the left panel, colored solid and dashed lines show thermal equilibrium curves for varying metallicity and dust abundance, with fixed $\chi = 0.2$ and $\xi_p = 6 \times 10^{-17}$ s$^{-1}$. Solid lines are for different pairs of $Z_g = Z_d = (0.1, 0.3, 0.5)$. The stability of these curves when $Z_g$ and $Z_d$ are decreased simultaneously arises because the photoelectric heating by dust is roughly proportional to $Z_d$ and the gas cooling is roughly proportional to $Z_g$, so that changes in these two processes track each other, and the change in $L$ is small. If the dust abundance $Z_d$ is reduced without changing $Z_g$, the photoelectric heating is reduced, leading to lower temperatures (dashed curves). In each case, the theoretical thermal equilibrium curve $L = 0$ is unable to reproduce the data in WNM$_F$, LNM$_F$, and CNM$_F$ simultaneously. For example, in the case of $Z_g = 0.3$ and $Z_d = 0.01$ (dashed orange curve), the theoretical $L = 0$ curve shows

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12 This factor matches observations at the solar galactocentric radius but could be different at $R_{\text{CIB}}$, e.g., due to the Galactic warp.

13 Further unknown is whether the dust size distribution would be the same as in the diffuse ISM.
rough agreement with the average values in CNMF but does not extend to the higher-density structures seen in the other phases.

In the right panel, solid and dashed lines show thermal equilibrium curves of varying FUV interstellar radiation field strength ($\chi = 0.1$ or 0.01) and CR ionization rate ($\xi_p = 10^{-16}$ or $10^{-17}$ s$^{-1}$) for a fixed metallicity and dust abundance ($Z_g = Z_d = 0.3$). Reducing $\chi$ directly reduces the photoelectric heating. Reducing $\xi_p$ reduces the electron abundance (ionization fraction of the gas), which then also reduces the efficiency of photoelectric heating. Similar to the left panel, no single theoretical thermal equilibrium curve can reproduce the range of data seen in all three phases. The model with $\chi = 0.1$ and $\xi_p = 10^{-17}$ s$^{-1}$ (solid orange curve) passing through the cloud of points for CNMF again fails to reproduce the higher densities seen in the other phases.

5.1.4. Deviation from a Single Thermal Equilibrium Curve

Although general trends relating to phase separation are present in static models with heating and cooling mechanisms in equilibrium, no single thermal equilibrium curve can reproduce the data. There are many failure modes. For example, models that allow a broad range of WNMF densities predict warmer LNMF and CNMF at their inferred densities.

One possible explanation might be local variations in the physical environment ($\chi$ and $\xi_p$) or the gas ($Z_g$ and $Z_d$). However, given the relatively low gas surface density ($N_{H1} \gtrsim 2 \times 10^{20}$ cm$^{-2}$; see Figure 6) and metallicity, significant variations in $\chi$ and $\xi_p$ from shielding are not expected, except perhaps in the densest parts of CNMF that are not well resolved. Local variations of metallicities would require a higher $Z_g$ or lower $Z_d$ in LNMF and CNMF. Plausible local variations of $Z_g$ might arise if the H I observed in CIB is a mixture of the original infalling HVC and the Galactic halo material (F. Heitsch et al. 2021, in preparation). Local variations of $Z_d$ might be produced by mixing with halo material and/or local destruction of dust due to the systematic motions in the encounter.

Alternatively, the gas might just be out of thermal equilibrium. This possibility is implied by the lower thermal pressure in LNMF and CNMF (see Table 5) and supported by the fact that the dynamical timescale (thermal crossing times in Table 5) is comparable to the cooling timescale (see also Section 5.2.2). A related caution (or hint) is the widespread presence of the LNMF phase, which the models suggest is thermally unstable.

5.2. Thermal Instability

In the ISM, the formation and steady-state presence of nongravitational cold condensations has been related to the condensation mode of thermal instability (Field 1965). To assess the relevance of this physical mechanism to the observed phase transition in EN, we evaluated whether perturbations around the mean thermodynamic state of the gas in CIB would allow the condensation mode of thermal instability to develop and then grow freely.

5.2.1. Development of the Condensation Mode

In an idealized nonviscous static fluid in thermal equilibrium, the isobaric criterion for development of the condensation mode of thermal instability can be expressed as

$$\left( \frac{\partial P}{\partial n} \right)_{\mathcal{L}=0} < 0 \quad (26)$$

(Field 1965; Wolfire et al. 1995a). To assess whether this idealized criterion is satisfied in the mean pressure and density range where the phase separation is observed in EN, the properties extracted from WNMF, LNMF, and CNMF are presented in the relevant $P_n/\mathcal{L}_n$ phase diagram in Figure 24, color coded by phase. The mean and spread of the thermal pressure of all structures in CIB are indicated by the blue horizontal dashed line and shaded area. This is lower than in standard models of the solar neighborhood ISM (e.g., Wolfire et al. 1995a; see also the black curves in Figure 24). The data also reveal the relevant density range to consider.

Superimposed on the two panels are model thermal equilibrium curves corresponding to those presented in Figure 23. As in the discussion in Section 5.1, there is no single model that reproduces the data. However, in the average number of H atoms per unit volume range observed in EN, where a number of the plausibly relevant models do intersect with the mean pressure in LNMF and CNMF (green and red points), we can see directly that the curves satisfy Equation (26). On average, from WNMF to LNMF and CNMF, the pressure drops and the density increases, also satisfying Equation (26). Thus, depending on the actual local net cooling of the gas in the CIB conditions, pressure perturbations around the average pressure might plausibly trigger the condensation mode of thermal instability, leading to the phase separation observed.

5.2.2. Can the Condensation Mode Grow Freely?

A second criterion, i.e., ensuring that the condensation mode can grow freely, involves dynamical and cooling timescales. When the gas experiences a perturbation (i.e., a compression), condensation is possible if the cooling time of the fluid element is shorter than its dynamical time (Hennebelle & Pérault 1999):

$$\mathcal{T} = t_{cool}/t_{dyn} < 1. \quad (27)$$

The fact that we observe a phase separation implies that $\mathcal{T} < 1$ is satisfied. The presence of LNMF gas further suggests that the phase transition is ongoing.

The dynamical time, the typical thermal crossing time of the warm phase WNMF, is about 2.8 Myr (Table 5). Understanding the balance between timescales requires an assessment of $t_{cool}$ in CIB.

First, we inferred $t_{cool}$ from

$$t_{cool} = \lambda_{cool}/c_{\mathcal{L}}^{\text{WMN}}, \quad (28)$$

where the typical cooling length $\lambda_{cool}$ was estimated in Section 4.6.1 to be about 15 pc. Using $c_{\mathcal{L}}^{\text{WMN}} = 9.6$ km s$^{-1}$, we find $t_{cool} \sim 1.5$ Myr. Compared to the dynamical time, $\mathcal{T} < 1$ is satisfied weakly.

Second, we evaluated the theoretical cooling time for the models presented in Section 5.1. A selection of the curves is shown in Figure 25 as a function of $n$. They correspond to the models with parameters $\chi = 0.2$, $\xi_p = 6 \times 10^{-17}$ s$^{-1}$, $Z_g = 0.01$, and $Z_d = 0.3$ (orange dashed curve as in Figure 23, left) and $\chi = 0.01$.

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14 As noted in Section 5.1.1, the apparent distribution of data points from LNMF and CNMF along the diagonal isothermal lines is a consequence of the phase separation performed with ROESE. Therefore, we can compare the mean pressure and density of LNMF and CNMF but not the values among the data points within each phase.

15 Otherwise, the energy lost by radiation is small when compared to the increase of internal energy, and the process can be considered as adiabatic (i.e., no transfer of heat between the fluid element and its surrounding medium).
\[ \xi_p = 1 \times 10^{-17} \text{ s}^{-1} \] and \( Z_d = Z_g = 0.3 \) (orange solid curve as in Figure 23, right). As discussed above, these models do not reproduce the dispersion observed in the \( T_k - n \) diagram, but they provide examples of consistent models approximating the average thermodynamic state of the gas in CIB and establish the plausibility of thermal instability (Figure 24). For comparison, the black dashed line shows the typical cooling time from Equation (28). The magenta dashed line shows the above estimate of \( t_{\text{dyn}} \) from the mean thermal crossing time of structures from WNMF, which are larger than \( \lambda_{\text{cool}} \). Vertical lines show the mean density of structures from WNMF and LNMF in blue and green, respectively (see Table 5), bounding the range of typical densities where condensation is observed. In that range, these example models have cooling times that are compatible with the Equation (28) estimate and also suggestively close enough to \( t_{\text{dyn}} \) to allow some perturbations to satisfy \( I < 1 \).

6. Origin of Substructure in the Large-scale Context of Complex C

Elongated structures (Figure 12) are a multiscale property of the flow in region F. Structures and filaments are very well correlated across phases and scales (Figures 9 and 10), which indicates that the phase transition is already spatially and anisotropically shaped on large scales. There is no homogeneous warm phase of HI from which the cooler structures condense.

There is some evidence for the importance of thermal instability in the phase transition (Section 5), but thermal equilibrium models are obviously not adequate to describe the complex physical state arising from the interaction of the HVC gas with the Galactic halo. Investigation of the mechanisms that are generated at large scales, lead to the observed thermal condensation, and shape the gas will require numerical simulations.

Simulations in turn need to be set up with appropriate geometries and initial conditions. With observations of just small areas like CIB, this would be challenging, even misleading. For example, the HVC gas in the N1 field has been classified morphologically to be among the substantial subpopulation of compact HVCs that show prominent head-tail structure

Figure 24. Like Figure 23 but for a log10 \( P_{\text{gas}} / k_b T_k \)–log10 \( n \) diagram. The blue horizontal dashed line and surrounding shaded area show the mean and spread of the thermal pressure for the ensemble of structures in region F.

Figure 25. Curves of cooling time vs. \( n \) for thermal equilibrium models with parameters \( \chi = 0.2, \xi_p = 6 \times 10^{-17} \text{ s}^{-1}, Z_d = 0.01, \) and \( Z_g = 0.3 \) (orange dashed curve) and \( \chi = 0.01, \xi_p = 1 \times 10^{-17} \text{ s}^{-1}, \) and \( Z_d = Z_g = 0.3 \) (orange solid curve). The black dashed line shows the typical cooling time in the WNMF from Equation (28). The magenta dashed line shows \( t_{\text{dyn}} \), the mean thermal crossing time of WNMF (Table 5). Vertical lines show the mean density of structures from WNMF and LNMF in blue and green, respectively. (Brüns et al. 2000). However, the observed CNM here occurs in what in that phenomenology is the “tail.” Of more fundamental importance, this gas is not isolated, so it is instructive to consider the context of its place in complex C.

6.1. Large-scale View from EBHIS

This is enabled by the wide sky coverage of the EBHIS data (Kerp et al. 2011; Winkel et al. 2016). Surveyed with the Effelsberg 100 m radio telescope, EBHIS has a spatial resolution comparable to GHIGLS (10′8 and 9′4 beams, respectively). To select only the HVC emission, we used the deviation velocity \( v_{\text{DEV}} \) (Appendix D), which measures the difference between the observed \( v_{\text{LSR}} \) and the predicted velocities of gas throughout a model H1 disk. In complex C and its neighborhood, \( v_{\text{LSR}} \) and \( v_{\text{DEV}} \) are negative. Selecting
\[ v_{\text{DEV}} < -80 \ \text{km s}^{-1} \ (|v_{\text{DEV}}| > 80 \ \text{km s}^{-1}) \] isolates the HVC from the IVC emission (particularly the extended intermediate-velocity arch; Kuntz & Danly 1996) that would be included at smaller deviations.

Figure 26 shows a map of the column density \( N_{\text{HI}} \) of the selected HVC emission in an orthographic projection centered on \((l, b) = (90^\circ, 45^\circ)\), close to CIB at \((l, b) = (84^\circ.5, 44^\circ.3)\), indicated by the white arrow. The column density is dominated by complex C and its neighbors, complexes A and M. Most of the emission from the Galactic plane has been removed by the \( v_{\text{DEV}} \) cut, but some emission from the Milky Way extraplanar gas is still visible at \(|b| < 30^\circ\) (Marasco & Fraternali 2011). The relative prominence of this non-HVC emission is suppressed by imaging \( N_{\text{HI}} / \csc b \) here. Also suppressed is the faint extension of complex C to lower \( l \) and \( b \).\textsuperscript{16}

As mentioned in Section 2.1 and discussed below, CIB straddles a projected edge of the main body of complex C. Beyond this edge, \( N_{\text{HI}} \) is very low, about 2 orders of magnitude less than the brighter features in N1.

Figure 27 maps the centroid velocity (in GSR) of the same selected gas with the same orthographic projection. The centroid velocity can be calculated for low column densities too, leading to a more frothy appearance compared to

\textsuperscript{16} This has been called the “tail” of complex C (Hsu et al. 2011; see Section 6.3).
Figure 26. A velocity gradient on large scales is seen across complex C, going from about 50 km s$^{-1}$ at lower longitudes to about $-50$ km s$^{-1}$ in the prominent emission adjacent to complexes A and M.

A connection in PPV space between complexes C and A, reflected in Figures 26 and 27, was reported by Encrenaz et al. (1971), but its faint emission led Wakker & van Woerden (1991) to catalog them as two distinct entities. In addition to their subsolar metallicities (Kunth et al. 1994; Wakker et al. 1996; Gibson et al. 2001; Wakker 2001; Collins et al. 2003, 2007; Tripp et al. 2003), their distance estimates of $D_C = 10 \pm 2.5$ kpc (Thom et al. 2008) and $D_A \approx 8$–10 kpc (Wakker et al. 1996; Ryans et al. 1997a; van Woerden et al. 1999; Wakker et al. 2003; Barger et al. 2012, for the high-latitude part of complex A) also support that they could be physically associated.

Curiously, a similar PPV connection apparently links complexes C and M. However, complex M has a higher, possibly supersolar metallicity (Yao et al. 2011), and current estimates place complex M at $D_M \leq 4$ kpc (Danly et al. 1993; Ryans et al. 1997b; Yao et al. 2011), together suggesting that these two complexes are not in fact physically related. Ryans et al. (1997b) suggested that complex M is a part of the intermediate-velocity arch.

Clearly, modeling the connections would require further investigation, notably the determination of the 3D orientation of complex C and its neighbors (Heitsch et al. 2016). A locus of velocities and distances might also constrain the “orbits” of

Figure 27. Orthographic projection of the centroid velocity field of the HVC gas in Figure 26. Note that the velocity is shown in the GSR. The centroid velocity can be calculated even at low $N_{\text{H I}}$, but the gray background corresponds to a mask with $N_{\text{H I}} < 0.5 \times 10^{19}$ cm$^{-2}$. The white box shows the coverage selected from EN.
the gas complexes (e.g., Lockman et al. 2008, for the Smith Cloud) and possible related galactic progenitors.

6.2. The Edge of Complex C

Focusing now on the edge of the main body of complex C probed by the EN data, Figures 26 and 27 show the presence of quasiperiodic scalloping and fingerlike structures, of which, importantly, CIB is a part. See also the top right panel of Figure 31 in Appendix E for a zoomed view. Note that we deliberately use the terminology “edge” to describe what appears in the column density map. This edge corresponds to the projection of the 3D “boundary” between complex C and its surrounding environment, which seems devoid of H I and could be warm/hot ionized gas of the Galactic halo or complex C itself (Tuft et al. 1998; Haffner et al. 2003; Fox et al. 2004).

These quasiperiodic fingerlike structures that stick out beyond the edge strongly resemble the effects expected from hydrodynamic instabilities, i.e., Kelvin–Helmholtz (KH) or Rayleigh–Taylor (RT) instabilities (Chandrasekhar 1961). Differentiating between these two possibilities is challenging, requiring the 3D velocity field of both the HVC gas at this edge and that of the adjacent Galactic halo gas (or the unseen ionized component of complex C). In a simplified model, motion parallel to the boundary in a static halo would favor an interpretation in terms of KH instabilities. On the other hand, a relative velocity perpendicular to the boundary would favor an interpretation as RT instabilities.

A further clue is that other substructure with a similar orientation appears projected against the eastern body of complex C (see, e.g., the zoom in Figure 31, top left), suggesting a complex boundary and interaction in 3D. Interestingly, similar periodic scalloping and fingerlike structures are also seen in complexes A and M (see zooms in Figure 31, bottom, in Appendix E), again suggesting interaction with warm/hot ionized material. Hydrodynamic instabilities are also relevant in producing the structure seen in intermediate-velocity clouds like the Draco Nebula (Miville-Deschênes et al. 2017). All of these merit further study.

In recent work, Barger et al. (2020) presented a qualitative study of the hydrodynamic instabilities observed in complex A using archival GBT data contained in the GHIGLS NCPL mosaic plus new targeted data. We had seen similar structures using the EBHS data (see Figure 26 and the zoom in Figure 31, bottom left). The GBT data reach a spatial resolution of 9′/1 and a sensitivity of 75 mK per 0.8 km s\(^{-1}\) channel, not unlike EBHS. Barger et al. (2020) compared their GBT data to the spatial resolution and sensitivity of the HI4PI survey (16′/2 beam, 43 mK per 1.29 km s\(^{-1}\) channel), concluding that targeted observations of HVCs at the higher resolution were needed to resolve hydrodynamic instabilities. However, HI4PI is a combination of EBHS (10′/8 beam) and the Galactic All-Sky Survey (GASS, 16′/1 beam; McClure-Griffiths et al. 2009; Kalberla et al. 2010; Kalberla & Haud 2015), and for HI4PI, the EBHS data had to be degraded to the resolution of GASS to produce an all-sky survey. Therefore, one should use EBHS data where available.

Whatever the origin of these large-scale instabilities, they are arguably related to the phase transition found in the EN data. The nature of WN\(_M\) and LN\(_M\) (see the upper and middle left panels of Figure 6) can now be revisited in this large-scale context. This warm/lukewarm arch follows the local orientation of the edge. Very little CNM is observed along this arch, suggesting that cold structures are preferentially formed along fingers and not in the gas connecting them to the main body. A multiphase analysis using data along the entire edge together with simulations will be useful for understanding the complex details of the connections between scales and the role that instabilities play in the phase transition.

6.3. Comparison with Structures in the “Tail” of Complex C

Hsu et al. (2011) analyzed the physical properties of 79 structures located in what they called the tail\(^{17}\) of complex C at (l, b) \(\sim (32^\circ, 18^\circ)\) using 4′ resolution data from the GALFA-HI survey ( Peek et al. 2011, 2018). Assuming the same distance of 10 kpc (Thom et al. 2008), the masses deduced for these structures spanned \(10^{1.1} - 10^{4.8}\) M\(_\odot\), and the sizes were \(10^{1.2} - 10^{2.6}\) pc. The typical line widths of 20–30 km s\(^{-1}\) were characteristic of warm gas.

Unlike in CIB, where cold structures of both smaller mass and size are found using EN data (~2 M\(_\odot\) and ~3 pc, respectively), thermal condensation does not seem to be occurring in this part of the complex. The lower spatial resolution relative to DHIGLS seems unlikely to explain this difference. The CNM structures are identified in CIB using GHIGLS N1 data at 9′/4 resolution (Appendix A), so GALFA-HI data at 4′ resolution ought to have revealed similar cold structures if they were present.

Hsu et al. (2011) suggested that this lack of multiphase structure could be related to the low metallicity of complex C (Section 5.1.2), which would increase the cooling time so that it is long compared to the typical lifetime of a structure; if that lifetime is a proxy for the typical dynamical time, then the condensation mode of thermal instability cannot grow freely (Section 5.2.2).

At least for the conditions found in CIB above, where the phase transition is observed, cooling does seem to be sufficiently rapid. Perhaps the metallicity is even lower in the tail, for example, due to a higher mixing ratio of the original HVC gas with a (perhaps counterintuitively) lower-metallicity Galactic halo gas (Heitsch et al. 2021, in preparation). Alternatively, perhaps because of some details of the interaction, there is a shorter dynamical time for these structures in the tail preventing the condensation mode from growing freely.

The actual situation is undoubtedly complex, and, as we began in the introduction of Section 6, we conclude by emphasizing the importance of simulations and understanding the basic geometry and environmental context of the underlying interaction.

7. Summary

Our novel study of the multiphase and multiscale properties of the concentration CIB of HVC complex C is based on high spatial resolution H I spectra from DHIGLS. ROHSA was used to decompose the spectra and produce maps of the column density, centroid velocity, and velocity dispersion of the multiphase gas. In one of two physical regions, region F, the three thermal phases, WN\(_M\), LN\(_M\), and CNM\(_F\), are well correlated, associated with the thermal phase transition. Multiscale properties of phases within each region have been quantified by a power spectrum analysis. We used dendrograms

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\(^{17}\) Here this nomenclature is used in the context of the morphology at large angular scales, not of substructures. It should not necessarily suggest a direction of motion for the complex.
to perform a hierarchical segmentation of the column density maps of the phases and analyzed the physical properties of the ensembles of structures. As a benchmark of the physical environment at the location of the condensation CIB, we used a series of PDR models that compute the chemical and thermal properties of the gas in different environments. Building on this, we evaluated whether perturbations around the mean thermodynamic state of the gas allow the condensation mode of thermal instability to develop and grow freely. Finally, we investigated the large-scale context of CIB within complex C using HI data from EBHIS.

We conclude that there is an ongoing phase transition in region F, located along a pronounced edge of complex C. The thermal condensation proceeds from large to small scales, and the cold phase has more small-scale structure.

1. Values corresponding to the mean and spread of the logarithmic PDFs of the average density and kinetic temperature of structures in the HI phases are 0.41 (1.9) cm\(^{-3}\) and 9.5 (1.0) \times 10^3 \ K (WNM\(_F\)). 1.4 (1.8) cm\(^{-3}\) and 0.90 (1.2) \times 10^3 \ K (LNMF\(_F\)), and 1.3 (1.9) cm\(^{-3}\) and 0.20(2.1) \times 10^3 \ K (CNMF\(_F\)). Corresponding values for the mass are 296 (3.4), 18 (2.3), and 12 (1.9) M\(_\odot\), and for the size, 28 (1.6), 7.3 (1.4), and 6.4 (1.4) pc.

2. The angular power spectrum of the WNM\(_F\) column density map is significantly steeper than for LNM\(_F\) and CNMF\(_F\). The same trend is observed in the slopes of the mass–size relation of the structures.

The turbulent energy cascade in the CIB gas is well described by compressible sub/transonic turbulence.

1. From the warm phase to the cold phase, both the turbulent Reynolds number and the Mach number increase.

2. Nevertheless, a constant energy transfer rate is observed over scales, suggesting that energy is neither injected nor dissipated along the energy cascade.

Our simplified modeling of the thermal state in CIB supports the plausible relevance of the condensation mode of thermal instability.

1. There could be local variations of the gas properties of the physical environment (Z\(r\), Z\(p\), \(\chi\), and \(\xi\)) and/or deviation from thermal and dynamical equilibrium.

2. Nevertheless, the mean thermodynamic properties of the gas across different phases are suggestive of the development of the condensation mode of thermal instability.

3. The typical scale at which the gas is unstable is about 15 pc, corresponding to a typical cooling time of about 1.5 Myr. This is suggestively low enough compared to the mean thermal crossing time in WNM\(_F\) (2.8 Myr) to allow the thermal condensation initiated by some perturbations to grow freely.

Clues to the triggering of the thermal instability require a large-scale context. The large-scale view of complex C suggests that the prominent protrusion in region F, extending from the edge of the complex as the condensation CIB, is the result of a hydrodynamic instability (KH or RT) at the interface. Other similar “fingers” are observed along the edge in complex C and other complexes. Understanding the complex and intricate connections between scales and the role that these instabilities play in this phase transition will require further investigation through comparison between observations and numerical simulations.

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Software: matplotlib (Hunter 2007); NumPy (van der Walt et al. 2011); Astropy,\(^{18}\) a community-developed core Python package for astronomy (Astropy Collaboration et al. 2013, 2018); astrodendro,\(^{19}\) a Python package to compute dendrograms of astronomical data; the HEALPix package (Górski et al. 2005); and galpy\(^{20}\) (Bovy 2015).

Appendix A

Decomposition of the N1 Field from GHIGLS

As summarized in Section 2.3.1, to evaluate the impact of the spatial resolution, we performed a decomposition of N1 HVC spectra from the GHIGLS survey using \(N = 6\) and all hyperparameters equal to those used for the decomposition of the GHIGLS/N1 data. In this case, ROHSA also converges toward four components (Table 1). We applied the same procedure as for the DHIGLS/EN data to find the unstable and cold gas associated with regions F and A.

Figure 28 shows column density maps of the six phase components encoding the HVC in CIB (N1). Although at lower resolution here, the phase structure as seen for the DHIGLS/EN data in Figure 6 can be recognized. Importantly, the phase separation in region F shows evidence for cold gas (CNMF\(_F\)), albeit at a somewhat higher velocity dispersion because of beam smearing (see Section 2.3.1, Table 1). On the other hand, the small amount of emission modeled in CNMF\(_A\) using EN data is not present using N1 data (see lower right panel in Figure 28).

Appendix B

Segmentation of \(N_{\text{H}1}\) Maps Using Dendrograms

Using astrodendro,\(^{21}\) we obtained a segmentation via hierarchical clustering in maps of \(N_{\text{H}1}\) from EN data for WNM\(_F\), LNM\(_F\), and CNMF\(_F\) and for WNM\(_A\), LNM\(_A\), and CNMF\(_A\). To suppress noise, maps of WNM\(_F\) and WNM\(_A\) were convolved first to 4/4, four times the native spatial resolution of EN data. For the six phases, Figure 29 shows the structures obtained overlaid on the respective parent \(N_{\text{H}1}\) map.

Table 6 summarizes the values of the three user-selected parameters. For each LNM and CNM phase, these are the same: \(\text{min}_{\text{value}}\), the threshold in \(N_{\text{H}1}\) below which data are ignored, set at twice the sensitivity limit (see Table 2); \(\text{min}_{\text{delta}}\), the minimum height in \(N_{\text{H}1}\) required for a structure to be retained, set at the detection limit; and \(\text{min}_{\text{pix}}\), the minimum number of pixels required for an independent structure, set at 16 pixels (∼1.2 times the size of the synthesized beam). Due to

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\(^{18}\) http://www.astropy.org

\(^{19}\) http://www.dendrograms.org/

\(^{20}\) http://github.com/jobovy/galpy
Figure 28. Column density maps of the six HVC phase components from ROHSA from N1 data, to be compared with the higher-resolution Figure 6 from EN data. Left: WNMF (top), LNMF (middle), which is actually quite warm (Table 1), and CNMF (bottom). Right: WNMA (top), LNMA (middle), and CNMA (bottom). Note that the color bars have different scales. Coordinates (not shown here) are the same as in Figure 2 (left). White circles indicate the positions of the six spectra shown in Figure 4.
Figure 29. Structures extracted in the three HVC phases in each of two regions identified in CIB from EN using astrodendro. These are shown over the parent map of $N_{\text{H}}I$ as red contours over a blue color map (rather than that in Figure 6) to highlight the clustering results. The corresponding ellipses are superimposed in green. Left: WNMF (top), LNMF (middle), and CNMF (bottom). Right: WNM$_A$ (top), LNM$_A$ (middle), and CNM$_A$ (bottom). The black mark on the color bars shows the sensitivity limits (3σ) tabulated in Table 2. For WNM$_F$ and WNM$_A$, this has not been corrected for the convolution applied to suppress noise. Coordinates (not shown here) are the same as in Figure 2 (left).
the convolution applied to WNM_F and WNM_A, lowering the sensitivity limits from those tabulated in Table 2, both min_value and min_delta were chosen manually to ensure a consistent visual clustering of the data. On finding the resulting clustering, the original WNM maps were used to infer the properties of the structures.

The convolution applied to WNM_F and WNM_A to lower the noise increases the size of the smallest structure that could be extracted. Although our methodology provides a realistic segmentation of the WNM maps, smaller warm structures (\(<15\) pc) might be missed. However, such structures would be smaller than the larger unstable (LNM) structures extracted, and their origin would more likely be attributed to turbulent cascade rather than thermal condensation.

### Appendix C

#### Properties of Structures from Segmentation of \(N_{\text{H}_1}\) Maps in Environment A

Table 5 in Section 4.1 summarizes the results from the dendrogram analysis for region F. Here, for completeness and comparison, Table 7 provides a summary for region A.

|        | min_value \(10^{19}\) cm\(^{-2}\) | min_delta \(10^{19}\) cm\(^{-2}\) | min_apex |
|--------|----------------------------------|----------------------------------|----------|
| WNM_F  | 0.5                              | 0.5                              | 16       |
| LNM_F  | \(2 \times N_{\text{H}_1}^{\text{lim}}\) | \(N_{\text{H}_1}^{\text{lim}}\)   | 16       |
| CNM_F  | \(2 \times N_{\text{H}_1}^{\text{lim}}\) | \(N_{\text{H}_1}^{\text{lim}}\)   | 16       |

|        | min_value \(10^{19}\) cm\(^{-2}\) | min_delta \(10^{19}\) cm\(^{-2}\) | min_apex |
|--------|----------------------------------|----------------------------------|----------|
| WNM_A  | 1                                | 0.5                              | 16       |
| LNM_A  | \(2 \times N_{\text{H}_1}^{\text{lim}}\) | \(N_{\text{H}_1}^{\text{lim}}\)   | 16       |
| CNM_A  | \(2 \times N_{\text{H}_1}^{\text{lim}}\) | \(N_{\text{H}_1}^{\text{lim}}\)   | 16       |

Figure 30 shows the orientation of the dendrogram structures found for region A. In contrast to Figure 13 for region F, where the preferred orientation was \(+63^\circ\), here the preferred orientation is almost orthogonal, \(-43^\circ\). The latter is interestingly similar to the orientation of the edge defined in Section 2.1 \((-60^\circ)\) and the arc of gas in WNM_A (Section 2.4).
Table 7
Properties of Structures in Region A

| Symbol       | WNM_A | LNM_A | CNM_A | Total_A | Units     |
|--------------|-------|-------|-------|---------|-----------|
| N_th         | 26    | 48    | 1     | 75      | pc        |
| Mass         | 2.4   | 0.41  | 3.2   | 1.5     | M_⊙       |
| Average number of H atoms per unit volume | 0.41 (1.9) | 1.21 (2.0) | 1.1 (1.0) | 0.84 (2.3) | cm⁻³      |
| Thermodynamic |       |       |       |         |           |
| Doppler velocity dispersion | 9.8 (1.0) | 3.1 (1.1) | 2.1 (1.0) | 4.6 (1.8) | km s⁻¹    |
| Turbulent velocity dispersion | 0.81 (2.5) | 0.60 (2.0) | 1.5 (1.0) | 0.67 (2.2) | km s⁻¹    |
| Thermal velocity dispersion | 9.7 (1.0) | 2.9 (1.1) | 1.4 (1.0) | 4.4 (1.8) | km s⁻¹    |
| Kinetic temperature | 11 (1.0) | 1.0 (1.2) | 0.24 (1.0) | 2.4 (3.2) | 10⁷ K     |
| Sound speed | 11 (1.0) | 3.2 (1.1) | 1.6 (1.0) | 4.8 (1.8) | km s⁻¹    |
| Thermal crossing time | 2.4 (1.5) | 2.2 (1.6) | 5.1 (1.0) | 2.3 (1.6) | Myr       |
| Turbulent crossing time | 32 (2.1) | 12 (1.8) | 5.1 (1.0) | 17 (2.2) | Myr       |
| Thermal pressure | 4.8 (1.9) | 1.3 (1.9) | 0.3 (1.0) | 2.0 (2.5) | 10⁸ K cm⁻³ |
| Turbulent pressure | 0.1 (6.7) | 0.2 (3.8) | 1.0 (1.0) | 0.1 (4.9) | 10⁸ K cm⁻³ |
| Total pressure | 5.6 (1.9) | 1.7 (1.9) | 1.3 (1.0) | 2.6 (2.3) | 10⁸ K cm⁻³ |

Turbulent Cascade
Turbulent sonic Mach number | 0.13 (2.5) | 0.32 (2.0) | 1.7 (1.0) | 0.24 (2.5) |           |
Mean free path | 0.78 (1.9) | 0.27 (2.0) | 0.30 (1.1) | 0.39 (2.3) | 10⁻⁵ pc   |
Kinematic molecular viscosity | 1.1 (1.9) | 0.11 (2.0) | 0.06 (1.0) | 0.24 (3.6) | 10⁴ cm⁻¹ s⁻¹ |
Knudsen number | 3.0 (1.6) | 3.7 (1.5) | 3.7 (1.0) | 3.4 (1.6) | 10⁻³       |
Reynolds number | 0.56 (3.4) | 1.1 (2.4) | 5.8 (1.0) | 0.89 (2.9) | 10⁸       |
Dissipation scale | 4.1 (2.2) | 0.68 (2.0) | 0.21 (1.0) | 1.2 (3.1) | 10⁻⁴ pc   |
Dissipation time | 4.7 (3.8) | 1.3 (2.6) | 0.24 (1.0) | 2.0 (3.6) | 10⁻⁴ Myr  |
Convective time | 35 (2.1) | 13 (1.8) | 6 (1.0) | 18 (2.2) | Myr       |
Travers time | 36 (2.1) | 13 (1.8) | 6 (1.0) | 18 (2.3) | Myr       |
Energy transfer rate | 0.25 (12) | 0.35 (6) | 5.3 (1) | 0.32 (8) | 10⁻⁵ L⊙ M⁻¹ |

Note. Values correspond to the mean and spread from the logarithmic PDF.

Appendix D
Deviation Velocity

The deviation velocity for a given line of sight measures the difference between the observed \( v_{\text{LSR}} \) and the predicted velocities of H I gas throughout a differentially rotating model Galactic disk (Wakker 1991). It can be used to identify gas in the halo that does not share the motion expected from the disk.

To evaluate the model, we used the rotation curve \( v(R) \) at galactocentric radius \( R \) from the galpy “MWPotential2014” (Bovy 2015) in

\[
v_{\text{LSR, model}} = \left( \frac{R}{R_0} v(R) - v(R_0) \right) \sin l \cos b. \tag{D1}\]

We adopted the simple model of the H I disk from Wakker (2004), which has a radius \( R_{\text{max}} = 26 \) kpc and flared edges \( \pm z_{\text{max}} \) in the vertical direction, given by

\[
z_{\text{max}} = z_1 (R < R_0) \quad \text{and} \quad z_{\text{max}} = z_1 + (z_2 - z_1) \times \left( \frac{R/R_0 - 1}{4} \right) (R > R_0), \tag{D2}\]

where \( z_1 \) and \( z_2 \) are 1 and 3 kpc, respectively. At any distance \( d \) along the line of sight,

\[
R = \sqrt{R_0^2 + (d \cos b)^2} - 2R_0(d \cos b) \cos l \sin z = d \sin b. \tag{D3}\]

For any direction \((l, b)\), \( v_{\text{LSR, model}} \) can be evaluated using Equations (D1)–(D3) over the range of \( d \) inside the model H I disk \((R < R_{\text{max}} \quad \text{and} \quad |z| < z_{\text{max}}) \) to find the minimum and maximum, \( v_{\text{min, model}} \) and \( v_{\text{max, model}} \), respectively. The deviation velocity is defined as

\[
v_{\text{DEV}} = v_{\text{LSR}} - v_{\text{min, model}} \quad (v_{\text{LSR}} < 0) \quad \text{and} \quad v_{\text{DEV}} = v_{\text{LSR}} - v_{\text{max, model}} \quad (v_{\text{LSR}} > 0). \tag{D4}\]

Appendix E
Quasiperiodic Scalloping and Fingerlike Structures in Complexes C, A, and M

In support of the discussion in Section 6.2, Figure 31 shows \( N_{\text{HI}} \) maps of the selected HVC emission from EBHIS for areas dominated by complex C and its neighbors, complexes A and M. The relative positions of the panels on the sky can be judged by using the coordinates on the axes, reference to Figure 26 (albeit in a different projection), and the caption. These zoomed views highlight quasiperiodic scalloping and fingerlike structures not only at obvious projected edges but also against the main body of gas, presumably because of projection of the complex boundary in 3D.
Figure 31. Zoomed images from Figure 26 highlighting quasiperiodic scalloping and fingerlike structures in $N_{\text{H}}$ toward complex C and its neighbors. The apparent orientation of the features depends on the projection in the different maps. Top left: emission toward the eastern end of complex C. Top right: main body of complex C with its pronounced upper edge containing CIB. The white box shows the coverage selected from the EN data. Bottom left: complex A and its bridge to complex C in the image above. Bottom right: western part of complex M, adjacent to upper east end of complex C in projection.

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