

Molecular hydrogen in filaments at high Galactic latitudes

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ABSTRACT

Context. Neutral atomic hydrogen (H I) absorption lines can be used to probe the cold neutral medium (CNM) at high Galactic latitudes. Cold H I with a significant optical depth from the GASKAP-H I survey is found to be located predominantly if not exclusively within filamentary structures that can be identified as caustics with the Hessian operator. Most of these H I filaments (57%) are also observable in the far-infrared (FIR) and trace the orientation of magnetic field lines.

Aims. We considered whether molecular hydrogen (H₂) might also be preferentially associated with CNM filaments.

Methods. We analyzed 241 H₂ absorption lines against stars and determined whether the lines of sight intersected H I or FIR filaments. Using *Far Ultraviolet Spectroscopic Explorer* (FUSE) H₂ data in the velocity range $-50 < v_{\text{LSR}} < 50 \text{ km s}^{-1}$, we traced 65 additional H₂ lines for filamentary H I and FIR structures in velocity and probed the H₂ absorption for coincidences in position and velocity.

Results. For 305 out of 306 positions, the lines of sight with H₂ absorption intersect H I filaments. In 120 cases, there is also evidence for a correlation with dusty FIR filaments. All of the 65 available sight lines with known velocities intersect H I filaments. In 64 cases, the H₂ velocities are consistent with H I filament velocities. For FIR filaments, an agreement is found for only 13 out of 14 H₂ absorption lines.

Conclusions. For the majority of H₂ absorption lines, there is evidence that H₂ is associated with cold H I filaments. Evidence of an association with FIR filaments is less compelling. Confusion along the line of sight limits the detectability of FIR filaments. For a comparable degree of UV excitation in the disk and lower Galactic halo, the formation rate of H₂ appears to be enhanced in H I filaments with increased CNM densities.

Key words. clouds – ISM: structure – (ISM:) dust, extinction – turbulence – magnetic fields

1. Introduction

Neutral atomic hydrogen (H I) gas is one of the most important tracers of the structure and dynamics of the interstellar medium (ISM). Molecular hydrogen (H₂) likewise is the simplest and most abundant molecule, and it provides a link to star formation at different scales. We intend to discuss the properties of the cold neutral medium (CNM), in particular, the transition between the atomic and molecular phase in the diffuse atomic medium. This phase is characterized by typical H I excitation temperatures $30 \lesssim T_{\text{ex}} \lesssim 100 \text{ K}$, densities of $10 \lesssim n_{\text{H}} \lesssim 100 \text{ m}^{-3}$, and dust temperatures of $15 \lesssim T_{\text{d}} \lesssim 20 \text{ K}$. The H I column densities are below $N_{\text{H}} = 10^{21.7} \text{ cm}^{-2}$ and the molecular gas fraction is low, typically $f_{\text{H}_2} = 2n_{\text{H}_2}/n_{\text{H}} \lesssim 0.1$ (Snow & McCall 2006; Wakelam et al. 2017).

Detailed H I observations in this temperature regime demand sensitive optical depth measurements, which are only possible against sufficiently strong continuum background sources. Within the past two decades, 372 unique H I lines of sight, distributed throughout the sky, have been observed by various authors with several instruments. A compilation of these 21 cm H I absorption and emission data, called BIGHICAT, are summarized in the Supplemental Table 1 of McClure-Griffiths et al. (2023). Significant absorption is listed at 306 BIGHICAT positions. Yet another 462 positions became available only recently from the Galactic Australian Square Kilometre Array Pathfinder Pilot Phase II Magellanic Cloud H I foreground observations (GASKAP-H I, Nguyen et al. 2024). They cover an area of 250 square degrees of the Milky Way foreground toward the Magel-

lanic Clouds. In total, 2 714 positions have been observed, resulting in 691 absorption line detections.

The balance of heating and cooling processes in the ISM results in a multiphase medium. The CNM is in pressure balance with a warm neutral medium (WNM) (Wolfire et al. 2003) that dominates most of the observable H I emission. Within the past decade, the evidence mounted that structures on arcminute scales are shaped in a filamentary way and that H I and far-infrared (FIR) emission agree very well (e.g., Clark et al. 2014 and Kalberla et al. 2016). The FIR filaments considered here are always associated with H I. These FIR structures are also associated with cold dust, are stretched out along the magnetic field lines, and have been further investigated by Clark et al. (2019), Peek & Clark (2019), Clark & Hensley (2019), Murray et al. (2020), Kalberla et al. (2020), Kalberla & Haud (2023), and Lei & Clark (2024).

Filaments are defined by their particular topology as caustics that correspond to singularities of gradient maps (e.g., Castiglione & Hayes 2004 or Arnold et al. 1985). As a standard tool for classifying these structures, Kalberla et al. (2021) (hereafter Paper I) have used the Hessian operator, which is based on partial derivatives of the intensity distribution. Filaments can be described in this way as caustics that are associated with cold CNM, an increased CNM fraction, and an enhanced FIR emissivity, and they are understood as coherent H I fibers with local density enhancements in position-velocity space. Kalberla (2024) (hereafter Paper II) has shown that BIGHICAT H I absorption components are exclusively located in filaments with FIR counterparts. Moreover, Kalberla (2025) (hereafter Paper

III) has demonstrated that 57% of the GASKAP-H I absorption components are associated with FIR filaments. All of these 691 CNM clouds with detectable absorption are located in H I filaments. Velocities along H I filaments are observable in projection in the plane of the sky and are affected by turbulent motions with typical dispersions $2.48 < \sigma v_{\text{turb}} < 3.9 \text{ km s}^{-1}$. In a similar way, velocities of embedded small-scale structures in optical depth are affected by turbulence. The derived scale-dependent velocity distribution agrees with the first law by Larson (1979).

H₂ is the simplest and most abundant molecule in the ISM, and its formation precedes the formation of other molecules (Wakelam et al. 2017). In the face of the finding that the cold H I is predominantly organized in filaments, we consider here the question whether H₂ as the most significant molecular component in the CNM at high Galactic latitudes might also be distributed in filaments. In Sect. 2 we analyze the available observations. The conclusions are drawn in Sect. 3, and a summary is given in Sect. 4.

2. Observations and data reduction

2.1. Identifying H I and FIR filaments

Filaments are thin, thread-like structures that can numerically be characterized as caustics or local singularities in the data distribution. In the following, we exclusively use the term filaments for structures that satisfy this mathematical classification. Caustics in two-dimensional intensity distributions are uniquely defined (e.g., Arnold et al. 1985 or Castigiano & Hayes 2004). The Hessian matrix is used in elementary calculus to determine the properties of singularities (for a detailed discussion, we refer to Paper II, and we only present a brief summary here).

Caustics in the intensity distribution can be identified as critical points with eigenvalues $\lambda_- < 0$. Hessian eigenvalues and the associated eigenvectors were determined throughout the sky for the HI4PI survey (HI4PI Collaboration et al. 2016) in the velocity range $-50 < v_{\text{LSR}} < 50 \text{ km s}^{-1}$ and simultaneously for the intensity distribution of Planck data at 857 GHz (Planck intermediate results. LVII. 2020). To obtain an identical resolution for the two databases, the FIR data were smoothed and converted into an nside = 1024 HEALPix grid.

The filaments in H I and FIR were derived from the eigenvalue distributions¹. The velocities v_{HI} along an H I filament are the velocities of the local minima of the H I eigenvalues $\lambda_-(v)$ (for examples, see Fig. A.1 of Paper III). All FIR filaments were checked for coincidences with H I filaments. To fit FIR filaments that are aligned with H I structures, the orientation angles of the Hessian eigenvectors were used. The velocity at which the best alignment between H I and FIR orientation angles is found defines the FIR filament velocity v_{FIR} . A tight agreement between FIR and H I filaments was found in narrow velocity intervals of 1 km s^{-1} (see Table 1 in Paper I). The correlation degrades significantly for larger velocity intervals with the implication that the H I that is observed in filaments and is associated with the 857 GHz FIR structures has to be cold. Using GASKAP-H I absorption data observed by (Nguyen et al. 2024), Paper III verified that these filaments contain CNM.

The correlation analysis is significantly complicated by the fact that the line of sight may intersect several filaments. For H I these filaments are separated in velocity, and no confusion affects

the derived parameters. For the FIR, however, the contributions from different filaments (indicated by H I structures) and other background sources cannot be separated. Only the strongest FIR filaments (with low confusion) can be correlated with H I. Paper I considered fiducial eigenvalues $\lambda_- < -1.5 \text{ K deg}^{-2}$ in FIR and $\lambda_- < -50 \text{ K deg}^{-2}$ in H I to ensure a good correlation between H I and FIR filaments. For these parameters, the average velocity uncertainties between H I and associated FIR filaments are 2.6 km s^{-1} . This rms scatter is associated with uncertainties in matching the H I and FIR orientation angles. These differences are within 3° to 4° on average (fitting Voigt functions or Gaussians, respectively). The resulting velocity field along the FIR filaments projected onto the plane of the sky is homogeneous, with typical velocity fluctuations of 3.8 km s^{-1} .

Considering the high-latitude sky with $|b| > 10^\circ$ (or $|b| > 30^\circ$), we found that 30% (18%) of the observed nside=1024 HEALPix positions are covered by FIR filaments and 69% (54%) by H I filaments. Figure 1 shows the covering fractions F_c of filaments within single channels at $|b| > 10^\circ$. The imbalance between the total number of H I and FIR filaments is obvious: About five times more filaments are counted in H I. Line of sight effects severely limit the detection of the FIR filaments. A similar degradation is noticeable in H I when the velocity resolution is decreased (Paper I). The curves shown in Fig. 1 are only estimates because they depend on constraints on the eigenvalues. Fig. A.2 in Paper III indicates that releasing the constraint $\lambda_- < -50 \text{ K deg}^{-2}$ for H I filaments can lead to a detection rate that is higher by 21% when it is applied to GASKAP-H I absorption components.

The global distribution of H I and FIR filaments at high Galactic latitudes shown in Fig. 1 has a dispersion of $8.1 \pm 0.1 \text{ km s}^{-1}$ and $7.9 \pm 0.1 \text{ km s}^{-1}$. All of the filaments have narrow line widths. They represent a population of small-scale CNM clumps that cannot be resolved individually in observations. These distributions therefore represent global probability distributions for the velocity of CNM clumps in the local vicinity.

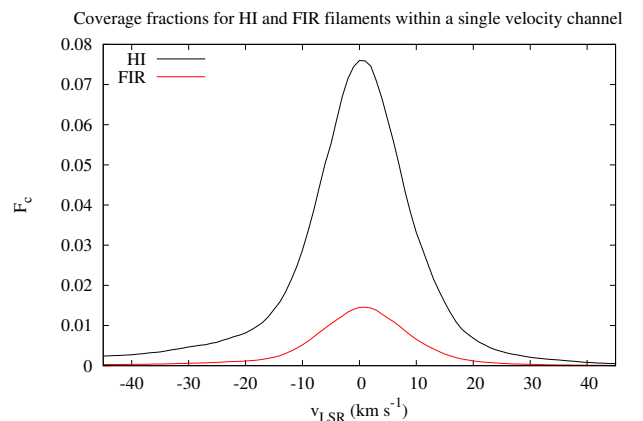


Fig. 1. Average filament coverage fractions F_c for FIR and H I filaments within a single velocity channel at Galactic latitudes $|b| > 10^\circ$.

2.2. Stellar H₂ absorption data, and unknown H₂ velocities

Gudennavar et al. (2012) collated absorption line data toward 3008 stars in a unified database of interstellar column densities toward stellar background sources. We used 419 entries for H₂ column densities in their Table 2 from the last published values. In total, 416 of these lines of sight intersect H I filaments, and

¹ For downloads of Hessian eigenvalue spectra and filaments, see https://www.astro.uni-bonn.de/hisurvey/AllSky_gauss/index.php

221 of these also intersect FIR filaments. Sources in the Galactic plane might be affected by confusion, and we therefore restricted our analysis in all cases to positions at latitudes $|b| > 10^\circ$. This sample contains 229 sources, and the lines of sight of 228 sources intersect H I filaments, and 95 lines of sight intersect FIR filaments. We conclude that 99.5% of all detected H₂ lines show evidence for a correlation with H I filaments. For 41.7% of the lines of sight, there is also evidence of a correlation with dusty FIR filaments. We conclude that for the sample considered in this section, the detection rate within the filaments increases by 40% with respect to a random distribution. As discussed in Sect. 2.1, the identification of FIR filaments might be limited by confusion. A low identification rate for FIR filaments implies that most of the FIR filaments are weak, with less significant Hessians. In translucent sight lines, [Rachford et al. \(2002\)](#) and [Rachford et al. \(2009\)](#) observed 12 high-latitude lines of sight. All of them intersected H I, and 8 lines of sight (66.7%) intersected FIR filaments, indicating more prominent and better defined FIR filaments in this case.

2.3. FUSE H₂ absorption data, and known H₂ velocities

The tabulated H₂ data we discussed in the previous subsection do not contain any information on the velocity centroids v_{H_2} of the H₂ components. We discuss H₂ data from the *Far Ultraviolet Spectroscopic Explorer* (FUSE) with known velocities that can be compared with the velocities v_{HI}^{HI} and v_{FIR}^{FIR} of H I and FIR filaments below.

A comprehensive database was provided by [Wakker \(2006\)](#), and we used 65 entries that are available within the velocity range $-50 < v_{LSR} < 50 \text{ km s}^{-1}$.² For each observed line of sight, we first verified whether it was located along a known FIR filament and then derived the velocity difference $\Delta v_{FIR} = v_{H_2} - v_{FIR}^{FIR}$ for the associated FIR filament. Next, we considered H I filaments with the velocity difference $\Delta v_{HI} = v_{H_2} - v_{HI}^{HI}$. For multiple H I filaments, the closest match in velocity was selected. As discussed by [Paper III](#), these velocity differences represent local turbulent velocity deviations between the H₂, which are probed by absorption within a pencil beam, and the FIR filament with a typical width of 9'. This corresponds to 0.63 pc at an assumed filament distance of 250 pc. For the H I absorption discussed by [Paper III](#), dispersions of $\sigma v_{HI}^{HI} = 2.48 \text{ km s}^{-1}$ for the whole H I sample, but $\sigma v_{FIR}^{FIR} = 3.9 \text{ km s}^{-1}$ for FIR filaments was found. We use $\sigma v_{HI}^{HI} = 2.48 \text{ km s}^{-1}$ below as a reference for comparison.

We found that all of the 65 low-velocity H₂ components from the catalog of [Wakker \(2006\)](#) are associated with H I filaments, but only 14 are associated with FIR filaments. The results are displayed in Fig. 2. At the top, we show a comparison of H₂ LSR velocities with the velocities of FIR filaments. The black symbols show a nearly linear relation between H₂ and H I velocities, and the deviations have a dispersion of $\sigma_{HI} = 4 \text{ km s}^{-1}$. At the bottom of Fig. 2, we show histograms of the velocity deviations $v_{H_2} - v_{fil}$. We compare these distributions with the reference distribution of $\sigma \sim 2.48 \text{ km s}^{-1}$, as determined by [Paper III](#). The observed deviations Δv_{HI} (black) are compatible with this reference, except for a few outliers with $|v_{H_2} - v_{HI}^{HI}| \gtrsim 10 \text{ km s}^{-1}$ (4σ with respect to the reference distribution). The velocity deviations Δv_{FIR} (red) are barely compatible with the reference distribution.

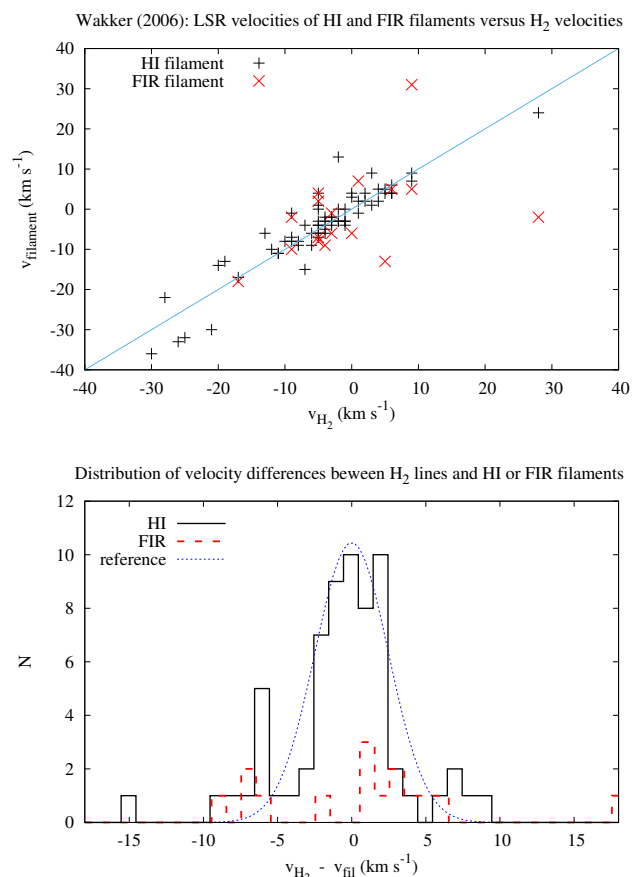


Fig. 2. Comparison of velocities from H₂ absorption and filaments in H I and FIR. Top: Direct comparison between v_{H_2} and filament velocities v_{HI} (black) or v_{FIR} (red) as defined in Sect. 2.1. Bottom: Histogram of the velocity deviations $v_{H_2} - v_{HI}^{HI}$ for H I and FIR filaments. H₂ data are taken from [Wakker \(2006\)](#). The dotted blue curve represents a reference distribution with $\sigma v_{HI}^{HI} = 2.48 \text{ km s}^{-1}$.

An alternative database with 40 FUSE H₂ absorption lines was provided by [Gillmon et al. \(2006\)](#). We processed these data in the same way as the data by [Wakker \(2006\)](#) discussed above. Figure 3 displays the results for 40 absorption lines. The plot at the top shows a good linear relation between H₂ and H I velocities, in this case, with a dispersion of $\sigma_{HI} = 3.6 \text{ km s}^{-1}$. The histogram for $v_{H_2} - v_{fil}$ (bottom) shows a somewhat weird double-peaked structure, but has fewer outliers. The details of the velocity distributions shown in Figs. 2 and 3 might be affected by line blending, or by ambiguities in assigning H I filaments to H₂ absorption structures in a few cases. The general characteristics of the velocity distributions remain unaffected, however.

The 40 sight lines used by [Gillmon et al. \(2006\)](#) are in common with [Wakker \(2006\)](#). The discrepancies between Figs. 2 and 3 can be explained by problems in the FUSE wavelength calibration and different approaches to solving the calibration uncertainties. The FUSE velocity resolution at the full width at half maximum (FWHM) depends on the data binning and typically is 20 km s^{-1} ([Wakker 2006, Sect. 4.2](#)). The velocity centroids were estimated by [Gillmon et al. \(2006, Sect. 2.2\)](#) to be uncertain by 5 km s^{-1} on average. Calibration problems and uncertainties of 2 km s^{-1} for sight lines with a high signal-to-noise ratio (S/N) and simple absorption-line structure up to $6\text{--}8 \text{ km s}^{-1}$ for low

² [Wakker \(2006\)](#) presents measurements of H₂ column densities toward 73 extragalactic targets but discusses predominantly absorption within high and intermediate velocity clouds.

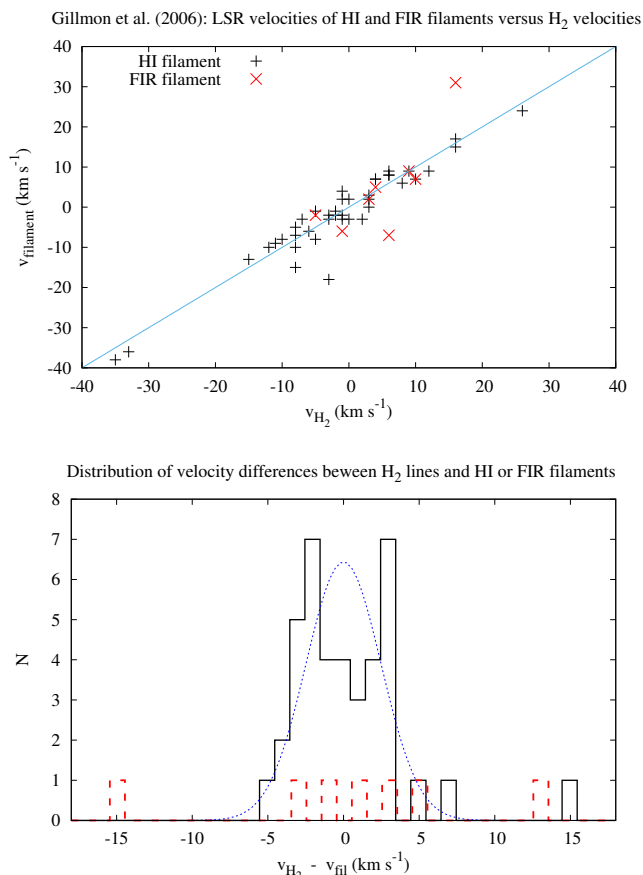


Fig. 3. Comparison of velocities from H₂ absorption and filaments in H I and FIR. Top: Direct comparison between v_{H_2} and filament velocities v_{HI} (black) or v_{FIR} (red) as defined in Sect. 2.1. Bottom: Histogram of the velocity deviations $v_{\text{H}_2} - v_{\text{fil}}^{\text{HI}}$ for H I and FIR filaments. H₂ data are taken from Gillmon et al. (2006). The dotted blue curve represents a reference distribution with $\sigma_{v_{\text{turb}}^{\text{HI}}} = 2.48 \text{ km s}^{-1}$.

S/N data were reported by Wakker (2006, Sect. 2.2)³ (for details, we refer to the extended discussions in that paper). We derived average velocity discrepancies with a dispersion of 5.7 km s^{-1} from an intercomparison of the two datasets that were used to derive Figs. 2 and 3. Typical 21 cm emission lines in cold H I filaments have dispersions of $\sim 1.3 \text{ km s}^{-1}$ (e.g., Clark et al. 2014 and Kalberla et al. 2016). Filaments, using the Hessian operator, were determined on a velocity grid with a resolution of 1 km s^{-1} (Paper I).

All of the velocity uncertainties discussed above were compared with observed turbulent velocity fluctuations for the CNM of about $\sigma_v = 2.48 \text{ km s}^{-1}$ on arcminute scales in the plane of the sky and within a single-dish beam (Paper III). For prominent FIR filaments, the observed dispersion can be up to 3.9 km s^{-1} . According to the first law by Larson (1979), turbulent motions cause scale-dependent velocity fluctuations in the ISM. The velocity dispersion increases with distance l as $\sigma_v(l) \propto l^q$. For supersonic turbulence, the exponent q is expected to be in the range $1/3 \lesssim q \lesssim 1/2$; $q = 0.5$ applies to the molecular cloud regime (Heyer et al. 2009) and also to the CNM. The relation of line width to size was verified for H I absorption components over distances from $7''$ to $10''$ (Paper III, Fig. 4).

To gain a deeper insight into the properties of the H₂ distribution, we plot in Fig. 4 the H₂ fraction $\log f_{\text{H}_2}$ derived by Gillmon et al. (2006) as a function of $v_{\text{H}_2} - v_{\text{fil}}$. Figure 5 alternatively shows the relation between H₂ column densities and $v_{\text{H}_2} - v_{\text{fil}}$ derived by Wakker (2006). As noted before by Gillmon et al. (2006), $\log N_{\text{H}_2} \sim 17$ appears to separate two populations of H₂ absorbers. A similar gap exists in Fig. 4 at $\log f_{\text{H}_2} \sim -3$. Adopting turbulent velocity fluctuations with $\sigma_{\text{turb}} = 2.48 \text{ km s}^{-1}$ as a reference, we considered $|v_{\text{H}_2} - v_{\text{fil}}| \geq 10 \text{ km s}^{-1}$ as misidentifications and excluded these positions from the discussion. Because of the low number statistics for FIR filaments, we also excluded FIR filaments. With these restrictions, the scatter $|v_{\text{H}_2} - v_{\text{fil}}|$ increases in Fig 5 for $\log N_{\text{H}_2} \lesssim 17$ by a factor of two with respect to $\log N_{\text{H}_2} \geq 17$. The average dispersion is 3.6 km s^{-1} and in the range $2.48 < \sigma_{v_{\text{turb}}} < 3.9 \text{ km s}^{-1}$, observed for H I absorption discussed by Paper III. Turbulence is also observable in the distribution of the metal lines. Comparing H₂ velocities with the velocities of metal lines, Wakker (2006) derived from his Table 2 a compatible dispersion of 3.9 km s^{-1} with peak deviations up to $\pm 9 \text{ km s}^{-1}$. For the wavelength calibration problems discussed by Wakker (2006, Sect. 2.2 and 4.2), it is plausible that the center velocities of sight lines with a low column density have significantly increased uncertainties. These uncertainties also explain the differences in the dispersions that are visible in Figs. 2 and 3. The extended wings in Figs. 2 are caused by sources with low H₂ column densities, which explains the high uncertainties in the velocity centroids. In the light of these problems, we conclude that the observed scatter in $v_{\text{H}_2} - v_{\text{HI}}$ and $v_{\text{H}_2} - v_{\text{FIR}}$ is significantly affected by observational uncertainties, but is still consistent with the turbulent velocity field shown in Fig. 4 of Paper III.

3. Discussion

The ISM is dominated by a multiphase medium (Wolfire et al. 2003) with a diffuse WNM and a clumpy CNM in pressure equilibrium. Large-scale H I surveys such as HI4PI (HI4PI Collaboration et al. 2016) or GALFA-H I (Peek et al. 2018) have led to the picture that a major part of the cold ISM is organized in filamentary structures that are aligned with the magnetic field lines (e.g., Clark et al. 2014 and Kalberla et al. 2016). These structures are detectable with the Hessian operator as caustics. Based on this classification, filaments can rigorously be characterized in the FIR with a coherent velocity field and in H I with an extended network of H I fibers at distinct velocities (Paper II). H I and FIR filaments are both exposed to a turbulent external medium, which leads to characteristic velocity fluctuations along and within the filaments.

A detailed analysis of the CNM in filaments became available with the GASKAP-H I absorption line survey, which covers nine adjacent fields of with over 25 square-degrees in the direction to the Magellanic clouds (Nguyen et al. 2024). The analysis of 691 absorption components in 462 lines of sight has led to major improvements in the understanding of the physical properties of the CNM. It was subsequently found that all H I absorption line components are associated with filamentary structures in H I and/or FIR (Paper III), suggesting that a major part of the CNM is located in filaments. The GASKAP-H I components have a mean column density of $N_{\text{HI}} = 1.8 \cdot 10^{20} \text{ cm}^{-2}$ and a mean spin temperature of $T_s = 50 \text{ K}$, and in pressure equilibrium with the WNM with $\log(p/k) = 3.58$ (Jenkins & Tripp 2011), a mean volume density $n_{\text{HI}} = 76 \text{ cm}^{-3}$ can be derived. The question arises whether these conditions support a transition from H I to H₂. If this is the case, we expect that H₂ might also share the filamentary nature of the CNM.

³ Gillmon et al. (2006) required S/R > 4, after binning 8 pixels at most.

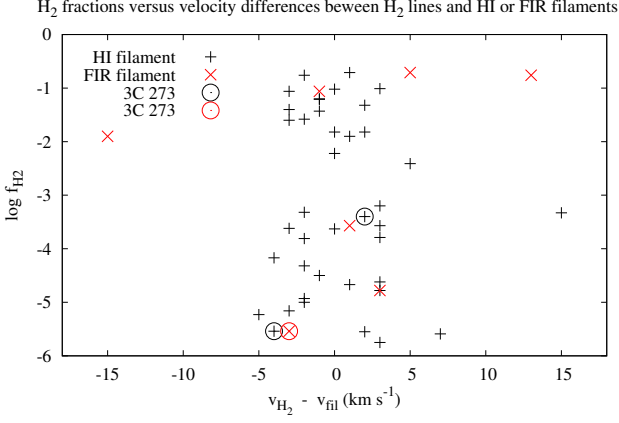


Fig. 4. H_2 fraction $\log f_{H_2}$ derived by [Gillmon et al. \(2006\)](#) vs. observed velocity deviations $v_{H_2} - v_{fil}$. The filament velocities are v_{HI} (black) or v_{FIR} (red), as defined in Sect. 2.1.

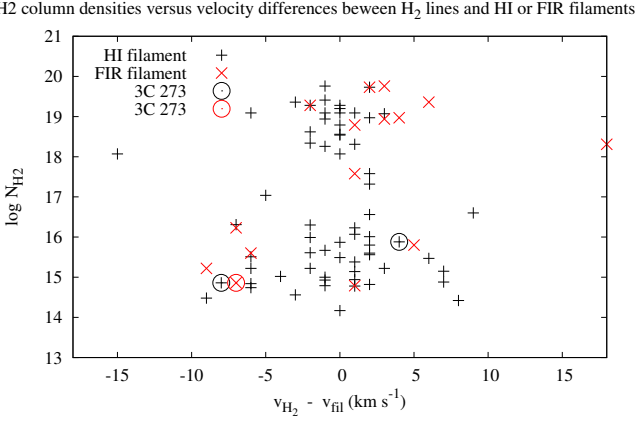


Fig. 5. H_2 column densities $\log N_{H_2}$ derived by [Wakker \(2006\)](#) vs. observed velocity deviations $v_{H_2} - v_{fil}$. The filament velocities are v_{HI} (black) or v_{FIR} (red), as defined in Sect. 2.1.

Analyzing published H_2 absorption data, we found that 305 out of 306 lines of sight are located along $H I$ filaments in total. A subset of 64 absorption lines has known H_2 center velocities. These components, again with a single exception, can also be assigned to $H I$ filaments in velocity.⁴ The observed deviations $v_{H_2} - v_{HI}$ are consistent with the turbulent velocity fluctuations from the GASKAP- $H I$ data ([Paper III](#)). Assuming that the H_2 formation is supported in presence of CNM with parameters as observed by GASKAP- $H I$, we conclude that the observable H_2 may predominantly be located in cold $H I$ filaments.

This inference is indirect and needs $H I$ absorption data for verification. These observations are missing, except for a single case. Only for the source 3C273 (QSO B1226+0219) can a link between H_2 , $H I$, and dust be established. The line of sight to 3C273 intersects an FIR filament with a dust temperature of $T_d = 17.978 \pm 0.013$ K ([Shull & Panopoulou 2024](#)). Filaments are observed for $H I$ at $v_{HI} = -1$ km s⁻¹ and for the FIR at $v_{FIR} = -2$ km s⁻¹ (see Fig. 6).

⁴ For seven sources observed by [Wakker \(2006\)](#) no significant H_2 lines could be detected. Velocities determined from metal lines were found in four of these cases to be consistent with $H I$ filament velocities, however. For a single source, no caustic was found, and two cases remained without conclusive absorption lines.

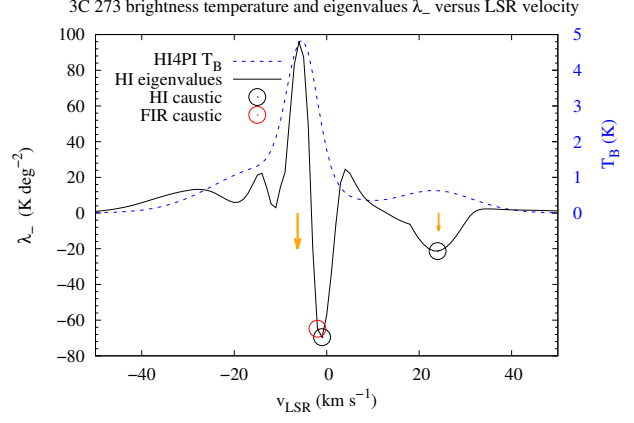


Fig. 6. HI4PI brightness temperatures (blue) at the position of 3C 273 and associated eigenvalues λ_- (black). $H I$ caustics exist at $v_{LSR} = -1$ and $+24$ km s⁻¹. The FIR caustic is at $v_{LSR} = -2$ km s⁻¹. The arrows sketch absorption components observed by [Murray et al. \(2018\)](#) and [Heiles & Troland \(2003\)](#) at $v_{LSR} = -6.3$ and $v_{LSR} = 24.2$ km s⁻¹.

In addition, an $H I$ filament lies at $v_{HI} = 24$ km s⁻¹. We discuss this structure first. A corresponding H_2 absorption was observed by [Gillmon et al. \(2006\)](#) at $v_{LSR} = 26$ km s⁻¹ and by [Wakker \(2006\)](#) at $v_{LSR} = 28$ km s⁻¹⁵. The $H I$ absorption with $\tau = 0.002$ is too weak for us to measure a significant spin temperature, but [Heiles & Troland \(2003\)](#) determined with the Arecibo telescope an upper limit of 87 K for the excitation temperature at this velocity. For a local equilibrium pressure of $\log(p/k) = 3.58$ ([Jenkins & Tripp 2011](#)), we estimated the density to be $n_{CNM} \lesssim 44$ cm⁻³. This is evidence that H_2 at the velocity $24 \lesssim v_{LSR} \lesssim 28$ km s⁻¹ is associated with an $H I$ filament at $v_{LSR} = 24$ km s⁻¹.

Particular cold $H I$ was observed at $v_{LSR} = -6.3$ km s⁻¹. [Heiles & Troland \(2003\)](#) determined a spin temperature of $T_s = 44.4$ K, and [Murray et al. \(2018\)](#) reported $T_s = 17$ K. In pressure equilibrium, the density is $86 \lesssim n_{CNM} \lesssim 223$ cm⁻³. This component is associated with $H I$ gas at $v_{LSR} = -5.5$ km s⁻¹ ([Heiles & Troland 2003](#)) or $v_{LSR} = -5.8$ km s⁻¹ ([Murray et al. 2018](#)), belonging to the unstable neutral medium (UNM) with a spin temperature of 651 K or 455 K, respectively. As discussed by [Heiles & Troland \(2003, Sect. 4.5.2\)](#), overlapping opacity components cause considerable uncertainties in the Gaussian fit parameters. The $H I$ velocity of $v_{LSR} = -6.3$ km s⁻¹ is well defined and agrees with the H_2 absorption observed at $v_{H_2} = -5$ km s⁻¹ by ([Gillmon et al. 2006](#)), but differs significantly from $v_{H_2} = -9$ km s⁻¹ derived by [Wakker \(2006, Sect. 4.2\)](#) in presence of considerable uncertainties in the H_2 velocity calibration. The observations by [Heiles & Troland \(2003\)](#) indicated CNM column densities of $N_{HI} = 4 \cdot 10^{18}$ cm⁻² with associated column densities of $N_{HI} = 46 \cdot 10^{18}$ cm⁻² for the UNM. [Murray et al. \(2018\)](#) determined for the CNM $N_{HI} = 2 \cdot 10^{18}$ cm⁻², and for the UNM, $N_{HI} = 29 \cdot 10^{18}$ cm⁻². Despite the observational uncertainties, we conclude that the structures observed in FIR, H_2 and $H I$ are related. 3C273 is one of the strongest continuum sources, allowing high S/N detections in $H I$ and H_2 absorption. The velocity deviations $v_{H_2} - v_{HI}$ are within the uncertainties that are consistent with the turbulent velocity field from GASKAP- $H I$ ([Paper III](#)). The filaments are indicated in Fig. 5.

Consistent with previous GASKAP- $H I$ results, our current analysis leads to detection rates close to 100% for absorption

⁵ In his Table 4 a velocity $v_{LSR} = 25$ km s⁻¹ is given.

lines associated with H I filaments. We compare this with expectations for a random filament distribution. The joint probability P to detect absorption along a filament depends on F_c , the average filament coverage per channel, as shown in Fig. 1, on the filament velocity v_{fil} , and further, on the expected turbulent velocity dispersion σ_{turb} along the filament,

$$P = \int F_c(v) \frac{1}{\sqrt{2\pi\sigma_{\text{turb}}^2}} \exp\left(-\frac{(v-v_{\text{fil}})^2}{2\sigma_{\text{turb}}^2}\right) dv. \quad (1)$$

Using $\sigma_{\text{turb}}^{\text{HI}} = 2.48 \text{ km s}^{-1}$ and $\sigma_{\text{turb}}^{\text{FIR}} = 3.9 \text{ km s}^{-1}$ we derived for H I filaments an expected probability of $P_{\text{HI}} = 0.112 \pm 0.033$ and $P_{\text{FIR}} = 0.0085 \pm 0.0037$ for FIR filaments. For reference, we compared these results with GASKAP-H I absorption observations (Nguyen et al. 2024). In this case, we derived probabilities of $P_{\text{HI}} = 0.126 \pm 0.013$ for H I and $P_{\text{FIR}} = 0.0112 \pm 0.0014$ for the FIR filaments discussed by Paper III. In summary, compared to a random distribution, the observed detection rate for H₂ or H I absorption associated with H I filaments is higher by a factor of eight to nine and even higher than 20 for FIR filaments.

The derived overdensity suggests that the cold and dense regions that give rise to detectable absorption lines in H₂ and H I are located within H I filaments. The detection rate R for FIR filaments, however, is affected by systematical environmental fluctuations. For GASKAP-H I data in the direction of two prominent FIR filaments, a rate of $R = 0.57$ was found (Paper III). For stellar H₂ lines, which are distributed throughout the high-latitude sky, we obtained $R = 0.43$. This might be representative for the high-latitude sky. For the *FUSE* absorption observations lines against AGN, we only obtained $R = 0.26$. A sample in the direction of translucent sight lines yields $R = 0.66$, however. The margin in R can be explained by selection effects. We considered the two extreme cases. The sample studied by Wakker (2006) is in directions with low extinction ($R = 0.26$), while translucent sight lines ($R = 0.66$) contain significant amounts of dust. These regions can provide sufficient protection from interstellar radiation, which would support an increased H₂ content. Photodissociation is assumed to be generally the dominant H₂ removal mechanism (Wakelam et al. 2017), and less dissociation is expected for translucent sight lines. Dissociation is also minimized for condensed structures with high density. We therefore rejected the ideas that absorption lines and filaments might be caused by an observational accumulation from numerous separate volume elements along the line of sight by a velocity-crowding effect (Yuen et al. 2024).

The case of H₂, which might be produced in structures that are much denser than the clouds on average, was considered by Valdivia et al. (2016). These authors performed high-resolution magnetohydrodynamical (MHD) colliding-flow simulations to study the H₂ formation of multiphase molecular clouds. As a result of a combination of thermal pressure, ram pressure, and gravity, the clouds produced at the converging point of HI streams were highly inhomogeneous. These authors demonstrated in their Fig. 13 that the derived molecular fractions as function of total hydrogen column density compare well with observations by Gillmon et al. (2006) and Rachford et al. (2002, 2009). Their Fig. B.1 shows that the total shielding coefficient for H₂ at column densities $\log N_{\text{H}_2} \lesssim 20$ is little affected by an absence of shielding by dust. The translucent sight lines observed by Rachford et al. (2002, 2009) have $\log N_{\text{H}_2} \gtrsim 20$; shielding is expected to be strong. Thus, environmental conditions might explain our finding that the detection rate R for H₂ absorption in FIR filaments is higher in translucent regions.

The MHD colliding-flow simulations by Valdivia et al. (2016, Figs. 8 and 9) showed that H₂ can be formed quickly, within two or three million years for typical volume densities and spin temperatures as observed in the GASKAP-H I sample. Compressible forcing leads to the formation of clumps that are significantly denser than for solenoidal turbulent forcing (Miccic et al. 2012). For 3C273, which lies in direction of radio loops I and IV (Panopoulou et al. 2021) at a distance of $\sim 112 \text{ pc}$, there is some evidence that the observed H I distribution might be affected by shocks from supernova events. In comparison to the CNM, ten times more UNM is observed. Most of the cold H I is therefore probably in transition from the WNM to the CNM.

Processes that lead to an H I to H₂ transition for turbulent forcing under various conditions were studied with MHD simulations by Bellomi et al. (2020). In this case, the observed correlation between the H I and H₂ column density (Bellomi et al. 2020, Fig. 3) is reproduced well for H₂, which is built up in CNM structures between ~ 3 and $\sim 10 \text{ pc}$. H₂ for fractions $\log f_{\text{H}_2} \lesssim -3$ and column densities $\log N_{\text{H}_2} \lesssim 17$ are built up from diffuse low-density components along the line of sight, while dense small-scale clumps cause high H₂ column densities (Bellomi et al. 2020, Fig. 7). The locations of the 3C273 data within Figs. 4 and 5 are indicated in both cases in the lower parts of the plots. This regime, based on the model by Bellomi et al. (2020), is expected to be occupied by diffuse low-density components ($n \lesssim 8 \text{ cm}^{-3}$). The observed CNM densities for 3C273 ($n_{\text{CNM}} \gtrsim 86 \text{ cm}^{-3}$) exceed the model distribution significantly. Likewise the mean densities from the GASKAP-H I sample ($n_{\text{CNM}} \sim 76 \text{ cm}^{-3}$) do not fit the model in Fig. 7 of Bellomi et al. (2020). We conclude that a model for turbulent forcing without additional compressible contributions is not supported by H I absorption observations so far.

4. Summary and conclusions

Recent sensitive H I absorption observations (Nguyen et al. 2024) have shown that the location of CNM in the plane of the sky is predominantly along H I filaments (Paper III), as observed with large single-dish telescopes throughout the sky. A fraction of these filaments can also be traced in the FIR. The turbulent velocity distribution is characteristic for the 3D distribution along the filaments, which is consistent with the first law by Larson (1979). Inspired by these results, we investigated whether the observed H₂ distribution is also consistent with the H I results.

We found that most of the known H₂ absorption lines are located along H I filaments. Only for a few of these data were velocity centroids determined as well, and H I absorption data are available for only a single source. This is clearly an observational deficit that limits the credibility of the data analysis. Additional deficits are caused by problems in the wavelength or velocity calibration of the *FUSE* observations. Wakker (2006) and Gillmon et al. (2006) provided different solutions with an average velocity discrepancy of 5.7 km s^{-1} . These data need to be considered with care. In 64 out of 65 lines of sight are the H₂ velocities with derived turbulent velocity fluctuations still consistent with the H I filament velocities discussed by Paper III, however.

High-sensitivity H I absorption lines are available in the direction to 3C273, which is one of the strongest radio sources. These lines confirm the expectation that H₂ is correlated with the CNM along filaments in position and velocity. H₂ formation is expected to be enhanced in the presence of cold and dense H I (e.g. Valdivia et al. 2016). We are confident that these results can be generalized, and we expect that H₂ with increased densities

predominantly exists within CNM filaments. Additional H I observations at positions with known H₂ absorbers are encouraged.

The formation of H₂ in the gas phase is not very relevant to interstellar environments (Vidali 2013; Valdivia et al. 2016). The preference of H₂ to accumulate in H I filaments only implies that the CNM in filaments provides perfect conditions to support H₂ formation. These conditions are given by cold H I associated with cold dust (Nguyen et al. 2024, Fig. 17) that has settled in H I filaments. The direct observational evidence for H₂ in FIR filaments is affected by sensitivity limitations (see, e.g., Fig. 4 of Kalberla et al. (2016)). Only the most prominent FIR filaments are easily observable. Assuming, on the other hand, an increased formation rate for H₂ in regions with cold H I at high Galactic latitudes leads to filamentary structures on large scales (Kalberla et al. 2016, Fig. 11), without the need to invoke a sophisticated Hessian analysis (see also Skalidis et al. 2024).

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