The physical and the geometrical properties of simulated cold HI structures

Adriana Gazol and Marco A. Villagran

05/03/2021
Outline

❖ Introduction
❖ Analysis tools
❖ Simulations
❖ Results
❖ Discussion
❖ Conclusions
Introduction

1. What is this paper?

2. Why is this interesting?

3. How is this study carried out?
ISM

- Dense molecular gas
- Diffuse molecular gas
- Cool HI (CNM)
- Warm HI (WNM)
- HII gas
- Coronal gas

T ~ 100 K
n ~ 30 cm$^{-3}$
HI clouds
Observations → Filament network → Preference for local alignment between 2-D n and B projected on the plane of the sky

deference of knowledge → Relationship between the properties of CNM-like structures and B → numerical simulations

theoretical predictions → deficiency of knowledge
Objective of the paper

A detailed **statistical analysis** of the possible connection between the general **physical** properties, the **morphological** properties and the **geometrical** properties of magnetized CNM-like structures!
Analysis tools

- Shape descriptors
- Kernel density estimations
- Directional Statistics
Shape descriptors

Asphericity

\[ A_3 = \frac{1}{6} \sum_k \frac{(m_k - \bar{m})^2}{m^2} \]

Prolatness

\[ m_k : \text{eigenvalues of } M_{ij} = \sum_k \mu^k x_i^k x_j^k \]

\[ \bar{m} = \frac{1}{3} r_g^2 \]

\[ r_g = \sqrt{g_1 + g_2 + g_3} \]
Shape descriptors

Asphericity

\[ A_3 = \frac{1}{6} \sum_k \frac{(m_k - \bar{m})^2}{m^2} \]

Prolatness

\[ S_A = \frac{\Pi_k (m_k - \bar{m})}{\bar{m}^3} \]

\( m_k \): eigenvalues of \( M_{ij} = \sum_k \mu^k x_i^k x_j^k \)

\[ \bar{m} = \frac{1}{3} r_g^2 \]

\[ r_g = \sqrt{g_1 + g_2 + g_3} \]
Shape descriptors

Asphericity

\[ A_3 = \frac{1}{6} \sum_k \frac{(m_k - \bar{m})^2}{m^2} \]

Prolatness

\[ S_A = \frac{\Pi_k (m_k - \bar{m})}{\bar{m}^3} \]

Credit: Tomruen
Directional statistics

They don’t take into consideration the orientation but only the direction \( \theta \in [0, \frac{\pi}{2}] \)

\[
\bar{R} = \left( \bar{C}^2 + \bar{S}^2 \right)^{\frac{1}{2}} \quad \text{measures the concentration of } \theta \text{ values}
\]

\[
\bar{R} \ll 1 \quad \bar{R} \sim 1
\]

\[
\bar{C} = \frac{1}{n} \sum_{j=1}^{n} \cos \theta_j \quad \bar{S} = \frac{1}{n} \sum_{j=1}^{n} \sin \theta_j
\]
Simulations

Data from 5 models

- B00S → 0 μG → HD
- B01S → 0.4 μG
- B05S → 2.1 μG
- B10S → 4.2 μG
- B20S → 8.1 μG

B: initially uniform and // x-axis
Simulations

Each simulation:

- reproduces the thermal conditions of HI gas in the solar neighbourhood
- represents a cubic box with 100 pc by side
- is initially at rest with a uniform density \(2 \, cm^{-3}\) and temperature (1500K)
- is in the thermally unstable regime according to a cooling function (Wolfire et al. 2003)

\(~ 1500\) simulations (300 for each model)
Results

1. Physical properties of clumps → B, n, $\beta_p$, $P_{th}$, $M_{rms}$, $M$, $M_{Arms}$, $M_A$

2. Morphology → $\gamma$, $\beta$, $A_3$, $S_A$

3. Relative alignments → $\theta_B$, $\theta_v$, R, $\theta_{VB}$, $\theta_{VL}$
Results

1. Physical properties of clumps $\rightarrow$ $B, n, \beta_p, P_{th}, M_{\text{rms}}, M, M_{A\text{rms}}, M_A$

2. Morphology $\rightarrow$ $\gamma, \beta, A_3, S_A$

3. Relative alignments $\rightarrow$ $\theta_B, \theta_v, R, \theta_{VB}, \theta_{VL}$
Physical properties of clumps
Physical properties of clumps
Physical properties of clumps

\[ \beta_p = \frac{P_{th}}{P_b} \]
Physical properties of clumps
Physical properties of clumps

\[ M_{rms} = \langle \frac{v_{rms}}{c_s} \rangle \quad v_{rms} = |v - \bar{v}| \]

\[ M = \langle \frac{v}{c_s} \rangle \]
Physical properties of clumps

\[ M_{rms} = \langle \frac{v_{rms}}{c_s} \rangle \quad \nu_{rms} = |v - \bar{v}| \]

\[ M = \langle \frac{v}{c_s} \rangle \]

\[ M_{Arms} = \langle \frac{v_{rms}}{v_A} \rangle \quad M_A = \langle \frac{v}{v_A} \rangle \]
Results

1. Physical properties of clumps $\rightarrow$ $B, n, \beta_p, P_{th}, M_{rms}, M, M_{A_{rms}}, M_A$

2. Morphology $\rightarrow$ $\gamma, \beta, A_3, S_A$

3. Relative alignments $\rightarrow$ $\theta_B, \theta_v, R, \theta_{VB}, \theta_{VL}$
Morphology

\[ \gamma = \frac{\text{smallest semi-axes}}{\text{largest semi-axes}} \]
Morphology

\[ \beta = \frac{\text{intermediate semi-axes}}{\text{largest semi-axes}} \]
Morphology

- Spherical
- Oblate
- Filamentary
- Prolate
Morphology
Results

1. Physical properties of clumps $\rightarrow$ $B$, $n$, $\beta_p$, $P_{th}$, $M_{rms}$, $M$, $M_{Arms}$, $M_A$

2. Morphology $\rightarrow$ $\gamma$, $\beta$, $A_3$, $S_A$

3. Relative alignments $\rightarrow$ $\theta_B$, $\theta_V$, $R$, $\theta_{VB}$, $\theta_{VL}$
Relative alignments

$$\bar{R} = \left( \bar{C}^2 + \bar{S}^2 \right)^{\frac{1}{2}}$$
Relative alignments

\( \theta_B \): largest principal axis of the clump and magnetic field

\( \theta_V \): largest principal axis of the clump and velocity
Relative alignments

\( \theta_{VL} \): largest principal axis of the clump and internal velocity

\( \theta_{VB} \): velocity and magnetic field
Discussion

1. Internal motions and magnetic field intensity
2. Pressure balance
3. Effects of the magnetic field on morphology
4. Magnetic field alignments
Discussion

1. Internal motions and magnetic field intensity
2. Pressure balance
3. Effects of the magnetic field on morphology
4. Magnetic field alignments
1. Internal motions and magnetic field intensity
1. Internal motions and magnetic field intensity

Clumps as a whole move supersonically while their internally movements are barely transonic
1. Internal motions and magnetic field intensity

Clumps as a whole move supersonically while their internally movements are barely transonic.

Accordance with previous numerical works (e.g. Heitsch et al. 2005; Hennebelle et al. 2007; Saury et al. 2014)
Discussion

1. Internal motions and magnetic field intensity
2. Pressure balance
3. Effects of the magnetic field on morphology
4. Magnetic field alignments
2. Pressure balance
2. Pressure balance

- $\beta_p \rightarrow$ not all the clumps magnetically dominated
2. Pressure balance

- $\beta_p \rightarrow$ not all the clumps magnetically dominated
- Bulk distributions $\rightarrow$ super-Alfvénic
2. Pressure balance

- $\beta_p \rightarrow$ not all the clumps magnetically dominated
- Bulk distributions $\rightarrow$ super-Alfvénic
- Internal velocity distributions $\rightarrow$ sub-Alfvénic or trans-Alfvénic (except for the low $B_0$ model)
2. Pressure balance

- $\beta_p \to$ not all the clumps magnetically dominated
- Bulk distributions $\to$ super-Alfvénic
- Internal velocity distributions $\to$ sub-Alfvénic or trans-Alfvénic (except for the low $B_0$ model)
- Observations consistent with the distributions including only internal motions
Discussion

1. Internal motions and magnetic field intensity
2. Pressure balance
3. Effects of the magnetic field on morphology
4. Magnetic field alignments
3. Effects of the magnetic field on morphology
3. Effects of the magnetic field on morphology

- Most of the clumps are filament-like structures
3. Effects of the magnetic field on morphology

- Most of the clumps are filament-like structures
- The probability of having more aspherical clumps increases for models with $B_0 \neq 0$
3. Effects of the magnetic field on morphology

- Most of the clumps are filament-like structures
- The probability of having more aspherical clumps increases for models with $B_0 \neq 0$
- High probability of forming highly prolate clumps for magnetized models and low probability of having oblate structures
3. Effects of the magnetic field on morphology

- Most of the clumps are filament-like structures
- The probability of having more aspherical clumps increases for models with $B_0 \neq 0$
- High probability of forming highly prolate clumps for magnetized models and low probability of having oblate structures
- Large difference between magnetized and non-magnetized clumps

Magnetic fields are heavily relevant to the structure of the neutral clumps of the ISM.
3. Effects of the magnetic field on morphology

- Most of the clumps are filament-like structures
- The probability of having more aspherical clumps increases for models with $B_0 \neq 0$
- High probability of forming highly prolate clumps for magnetized models and low probability of having oblate structures
- Large difference between magnetized and non-magnetized clumps
- Magnetic fields are heavily relevant to the structure of the neutral clumps of the ISM
- Accordance with previous works (Hennebelle 2013; Xu et al. 2019)
3. Effects of the magnetic field on morphology

- HI filaments → edge-on shells or sheets originated by shock-waves resulting from supernova explosions (Kalberla et al. 2016, 2017a)
3. Effects of the magnetic field on morphology

- HI filaments → edge-on shells or sheets originated by shock-waves resulting from supernova explosions (Kalberla et al. 2016, 2017a)
- These models cannot evaluate the presence of CNM sheets
Discussion

1. Internal motions and magnetic field intensity
2. Pressure balance
3. Effects of the magnetic field on morphology
4. Magnetic field alignments
4. Magnetic field alignments
4. Magnetic field alignments

- As $B_0$ increases the clumps are preferentially perpendicular to magnetic field.
4. Magnetic field alignments

- As $B_0$ increases the clumps are preferentially perpendicular to magnetic field.
- $\bar{\theta}_{VL} \rightarrow \pi/2$ : compression facilitates the accumulation of material in directions almost perpendicular to the flow.
4. Magnetic field alignments

- As $B_0$ increases, the clumps are preferentially perpendicular to the magnetic field.
- $\bar{\theta}_{VL} \rightarrow \pi/2$: compression facilitates the accumulation of material in directions almost perpendicular to the flow.
- $\bar{\theta}_{VB}$ wider as $B_0$ increases: the internal motions in the clumps of this sample are not preferentially along the magnetic field lines.
Conclusions
Conclusions

- Study of the cold clumps formed via thermal instability in HD and MHD simulations of the atomic interstellar medium
Conclusions

- Study of the cold clumps formed via thermal instability in HD and MHD simulations of the atomic interstellar medium
- The morphology of HD is different to MHD
Conclusions

- Study of the cold clumps formed via thermal instability in HD and MHD simulations of the atomic interstellar medium
- The morphology of HD is different to MHD
- Predominantly filament-like structures and tendency to prolate structures for MHD with respect to HD
Conclusions

- Study of the cold clumps formed via thermal instability in HD and MHD simulations of the atomic interstellar medium
- The morphology of HD is different to MHD
- Predominantly filament-like structures and tendency to prolate structures for MHD with respect to HD
- Preferred angles for $\theta_B : [\pi/4, \pi/2]$
Conclusions

- Study of the cold clumps formed via thermal instability in HD and MHD simulations of the atomic interstellar medium
- The morphology of HD is different to MHD
- Predominantly filament-like structures and tendency to prolate structures for MHD with respect to HD
- Preferred angles for $\theta_B : [\pi/4, \pi/2]$
- Asphericity and prolatness: a different way to characterize the morphological properties of density structures
Thank you for your attention!