A Search for Kinematic Inflow Signatures in Simulated Molecular Clouds

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Abstract

The relatively poor understanding of the very beginnings of star formation is extremely detrimental to our understanding of the Universe we inhabit. In this study, we present preliminary results from a kinematical analysis of simulated molecular gas clouds as a method of unraveling the secrets behind the birth of stars. Using TIGRESS 3-dimensional simulations of solar neighborhood-type regions of the interstellar medium, we focus on a close investigation of the kinematic structure and evolution of molecular clouds and their surrounding neutral halos.

We will expand upon our established methodology of 3-dimensional molecular cloud isolation and kinematic analysis via moment one calculation and subsequent statistical methods to a larger sample of gas clouds. Through tracking these clouds across millions of years of evolution we will identify important kinematic signatures that can be searched for in observational data. We will also apply our analysis to understand molecular clouds in as many different interstellar environments, from areas with extensive high-density interacting structures to isolated molecular clouds that may only interact with their neutral hydrogen halos. We find that the velocity offset between the cold neutral medium and the molecular gas is centered very closely to zero across the entire process of star formation. These had a much smaller range than the observational data but confirm that the CNM follows the molecular gas very closely and are kinematically associated with each other.

1. Introduction

The interstellar medium (ISM) consists mainly of atomic hydrogen (HI), molecular hydrogen (H_2), and small traces of various heavier elements, molecules, and dust particles. The HI typically exists in galaxies in the form of three phases (Draine 2011). These are: the stable warm neutral medium (WNM) with temperatures above 5000 K, the stable cold neutral medium (CNM) with temperatures less than 250 K, and the thermally unstable middle state, unstable neutral medium (UNM) with temperatures between 250 and 5000 K (Draine 2011). Outside of these standard phases, HI is ionized at temperatures commonly set greater than or equal to 10,000 K. Given enough time, this dense gas becomes massive enough to self-gravitate, form dense molecular clouds (MCs), and eventually collapse to form protostars. However, the exact mechanics and processes of the formation of these over dense regions of the ISM are not well understood.

This study focuses on understanding how molecular clouds (MC) form from their HI halos, with an emphasis on the physical conditions similar to those of the Solar neighborhood. The HI halos around MCs likely consist largely of material left over from the formation of these clouds or as a product of the photodissociation of molecular gas from nearby stars (Stanimirovic et al. 2014). Therefore, HI halos around MCs play an extremely important role in shielding H_2 and other molecules from dissociating radiation, allowing for these molecules to accumulate (Stanimirovic et al. 2014). This transition from HI to H_2 is also believed to be a major bottleneck event in the early processes of star formation (Lee et al. 2018). H_2 region formation is likely to begin at points of interaction or collision between atomic clouds (Stanimirovic et al. 2014).

In this study we use numerical simulations, the TIGRESS (Kim et al. 2017), to investigate kinematic signatures of atomic and molecular gas and develop a greater understanding of the formation processes of molecular clouds. As the CNM phase of the ISM is believed to be the most crucial for the formation of molecular clouds (Lee et al. 2018), we search for kinematic offsets between CNM and molecular gas. Systematic kinematic offsets are expected if the CNM inflows into molecular clouds.

This study is part of the project entitled "Earliest stages of Star formation Probed by Observations of InterstellaR absorption (ESPOIR)". ESPOIR, French for "hope", is a large observational project with the Very Large Array (VLA) to examine properties of the CNM around the Perseus molecular cloud (PI: Min-Young Lee). This survey aims to accomplish two main goals, first to spatially measure the properties of the CNM in unprecedented detail, and second, to confront theoretical ISM models with vastly improved observational statistics (Lee et al. 2018). All observations have been completed and are now being processed. After developing a methodology for studying the kinematic properties of HI TIGRESS simulated data, we will apply the same methodology on ESPOIR data.

2. TIGRESS Simulation Data

This study uses the Three-phase Interstellar medium in Galaxies Resolving Evolution with Star formation and Supernova feedback (TIGRESS) simulation that tracks structures across a ½ kpc^3 area modeling the solar neighborhood. Thus far, we have employed the R8 simulation with two pc resolution. TIGRESS provides density, temperature, and velocity data in three dimensions that can be analyzed as is or compressed into Position-Position-Velocity (PPV) cubes to mimic observational data. TIGRESS simulations are implemented through Athena Magnetohydrodynamic (MHD) code and are specifically designed to both temporally and spatially resolve critical structures in the ISM (Kim and Ostriker 2017). The version implemented in this study is timestamped at million-year intervals so that the evolution of atomic-to-molecular clouds and beyond can be easily observed. The simulations are specifically designed to track features such as gravitational collapse and ongoing accretion of gas that leads to star formation clusters, supernova explosions (SNe) that drive turbulence in the ISM leading to star formation, the evolution of such SN remnants, and large-scale galactic differential rotation (Kim and Ostriker 2017). Importantly, the simulation we have implemented thus far is metallicity invariant, however similar simulations with metallicity variance and post-processed chemistry were made public following recent data releases (Kim and Ostriker 2017). Because no real-time chemistry data is available in TIGRESS, density, and temperature thresholds are our only tools to separate HI from molecular gas.

3. Methods

The first step in our analysis is to isolate clouds using a visualization package Glue and Python in tandem. Plotting HI and H_2 column density maps in Python allows us to visually isolate MCs in the x and z dimensions. Exporting these 2-dimensional areas as fits file then allows us to visually select the appropriate y-coordinates to roughly select the physical boundaries of MCs and their HI halos. After this visualization, we apply these 3-dimensional bounds in Python to only select data that are spatially correlated with the desired MC.

To mimic observational data, we then implement the random selection of lines of sight (LOS) surrounding MCs in the TIGRESS simulation. This was initially done by specifying a region of the simulation in x and z-dimension restrictions. Then a selection cut was applied searching for LOSs that contained any gas with a density value greater than 50 H atoms cm^{-3}. Any gas exceeding this 50 mol threshold was considered molecular (H2) and compiled into a list of LOSs that can be used as a tool to randomly select observational data from.

From this further reduced pool of LOSs, we can then examine density and velocity profiles in manners similar to those used observationally. One significant advantage of using simulated MCs as opposed to observational data is the ease with which we can separate the flavors of the ISM. We isolate the CNM by applying a density cut of fewer than 50 mols and a temperature of less than or equal to 250 K. We group the UNM and WNM (WUNM) with a density cut of fewer

than 50 mols and a temperature threshold strictly greater than 250K.

For the selected CNM and molecular portions of simulated MCs, we calculate the density-weighted mean velocity (so called moment one) and compare results between molecular and atomic gas. These mass-weighted velocity calculations allow us to analyze how different phases interact spatially and kinematically in and around MCs.

Particularly interesting is the moment one offset between the CNM and molecular gas (CNM-Mol). It is suspected because of the increased density of the CNM commonly observed in and around gas structures could correspond to actively accreting MCs or the formation of new molecular structures.

The most challenging problem encountered thus far in this study has been the issue of accurately isolating MCs and their surrounding HI halos in three-dimensional space. By using Python3-integrated 3D visualization tools such as Glue and applying accurate thresholds, we have a uniform set of simulated clouds but future refinements to cloud isolation process may involve more sophisticated approaches, such as Dendrogram analysis.

Representative velocities of MCs allow for the analysis of not only the motion of these clouds through space but the respective motion of their HI halos as well. Through analysis of these velocity structures, it is possible to discern gas inflow onto molecular clouds. We calculate this through statistical analysis. We assume clouds with a relatively narrow molecular gas velocity distribution, i.e. standard deviations less than or equal to about 7.5 km s^{-1} although this can also be dependent on the spatial structure of these MCs. Another important note is the difference in molecular gas terminology. Observationally, CO is used as a proxy for the formation of H_2 gas while in TIGRESS due to the limited ability of real-time chemistry data, and for simplicity's sake, we hold any gas above our molecular threshold to be H_2 (Glover and Low 2011).

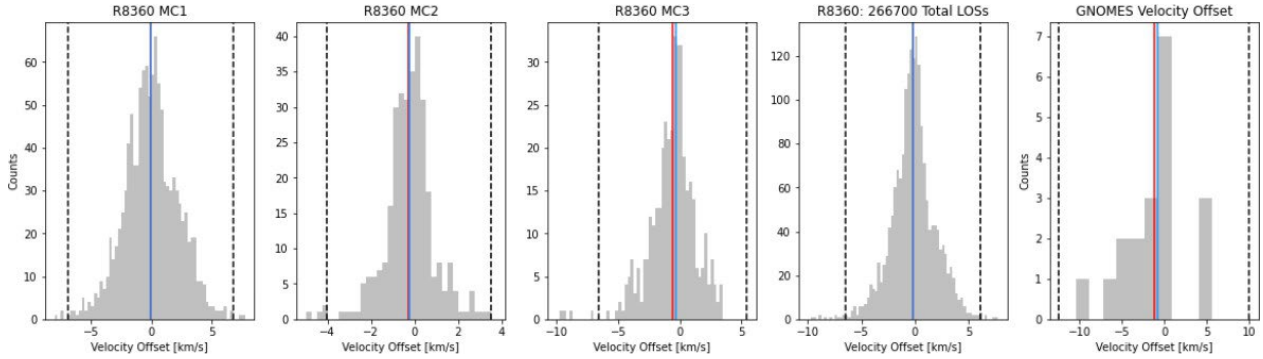

Figure 1. These histograms are representative of snapshot 360 in the R8 TIGRESS simulation. The blue vertical lines correspond to the median value while the red vertical lines correspond to the mean. Plots where only the blue is shown is due to python overplotting the two lines. The black dashed lines correspond to the three sigma levels.

After satisfactorily calculating the representative velocity of the MC we can subtract this value from the velocity of the surrounding HI gas, essentially measuring all neutral hydrogen motion with respect to the motion of the MC. This is an extremely insightful method of displaying the

relative motion between MCs and their HI halos, allowing us to visualize where inflow may be occurring or track other interesting kinematic events throughout the region of interest.

4. Preliminary Results and Discussion

In Figure 1 we show the difference of the density-weighted mean cloud velocity (moment one) between the CNM and the molecular gas for the sample of selected simulated clouds. As we have calculated these velocity offsets for each spatial pixel in a given cloud, we plot all pixel values as histograms. Figure 1 shows that both the mean and the median of the velocity offset are centered around zero for nearly all clouds and for all timestamps in the TIGRESS simulation. This suggests that in simulated clouds the CNM and molecular gas are kinematically coupled and we do find evidence for large offsets which would be indicative of gas inflows or outflows.

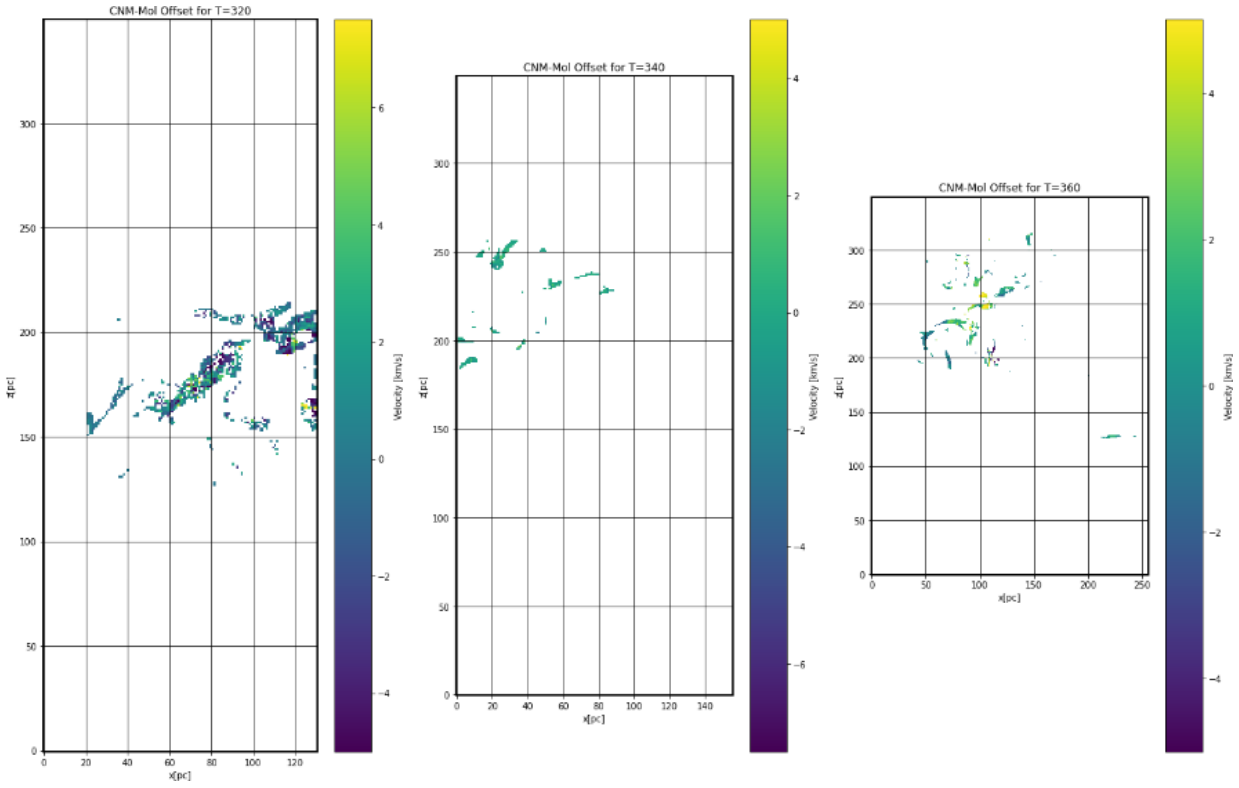

Figure 2 This figure contains the moment one maps for three timestamps of the TIGRESS simulation. The map corresponding to T=320 corresponds to a snapshot before the star formation peak, T=340 is near the star formation peak, and T=360 is post star formation peak.

Figure 2 shows the spatial distribution of the CNM—molecular gas velocity offsets calculated for a single simulated cloud several snapshots corresponding to before, during, and after the star formation rate peak in the R8 simulation. We can see in the initial snapshot for T=320, there are many lines of sight (LOSs) that contain molecular gas while the snapshot near the star formation

peak (T=340) contains much clumpier gas. The gas likely becomes clumpier because of the increased dissociating radiation from star formation destroys clouds. This trend persists in the T=360 snapshot. Also, important to note is that the velocity offsets do not vary greatly with time or across regions of space. This is shown in these plots as well as the histograms in Figure 1 as a bulk of the offsets are contained within a very small range of values centered around zero km s^{-1}.

One of the most important goals of this study is to ensure that our analysis of the TIGRESS simulation produces results that are easily comparable to observational data. Figure 3 is a centroid velocity offset plot mapping the CO-HI first moment offsets across the Perseus MC. This figure shows the CO-HI velocity offsets of 19 radio continuum sources taken during a GNOMES survey. These are the red or white filled circles seen throughout the plot. They are overlaid on a dust map taken from a Planck survey.

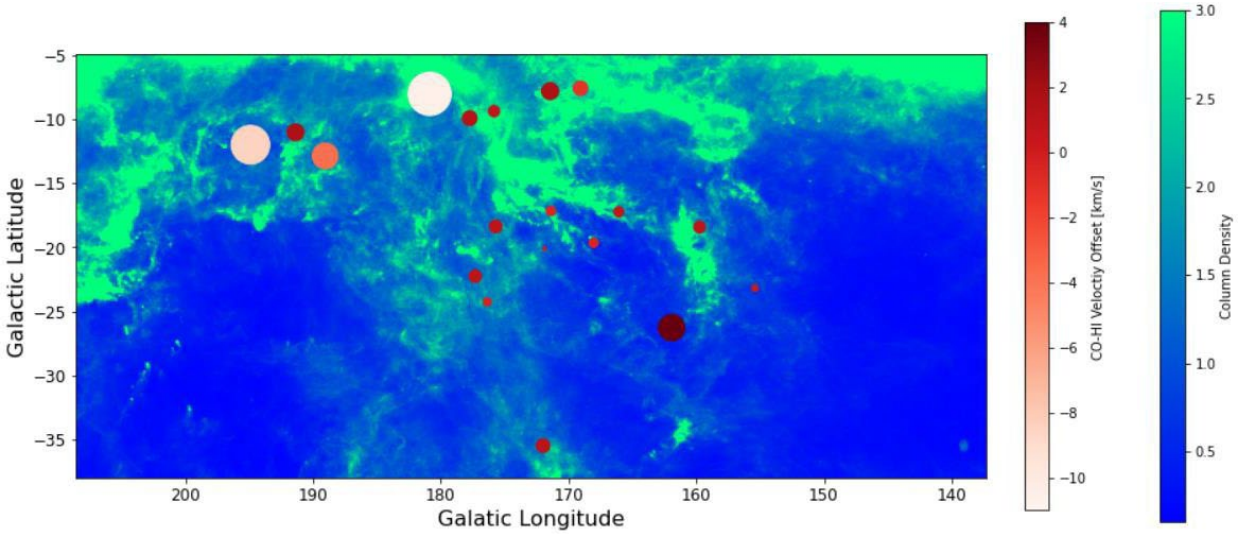

Figure 3 This is a spatial map of CO-HI moment one velocity offsets in the Perseus MC. The background is a dust image taken by a Planck survey (Planck Collaboration et al. 2013) and the points correspond to GNOMES spectra (Stanimirovic et al 2014).

Observationally, CO-HI offsets range from -10 km s^{-1} to about 4 km s^{-1}. This is wider than what we typically see in simulated molecular clouds. The bulk of the calculated CNM-molecular offsets are found between -5 and 5 km s^{-1}. This is such a tight distribution that the three sigma levels frequently only range to plus or minus 5 km s^{-1}.

4. Conclusions

The main conclusion we drew from this preliminary study are that the velocity offsets between the CNM and molecular gas are much lower in the simulation than in the observational data. We find this is very consistent throughout all snapshots of the simulation and the various cloud environments that we have picked. We also find that there are some features of the ISM cloud cycle that appear to be somewhat related to the star formation rate, such as the degree of

clumpiness or the standard deviation of the velocity offsets. However, as said before these velocity offsets are very consistently centered around zero and have overall very small standard deviations. Future direction in this research will consist of publishing our these, and more findings in an extensive paper. We will continue to flush out current issues and go into greater depth in our analysis of the kinematic association of the CNM and molecular gas in the ISM.

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