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Modeling the Dynamics of the Interstellar Medium

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Stars and star clusters are the fundamental visible building blocks of galaxies. They form by gravitational collapse in regions of high density in the complex multi-phase interstellar medium. The process of stellar birth is controlled by the intricate interplay between the self-gravity of the star-forming gas and various opposing agents, such as supersonic turbulence, magnetic fields, radiation pressure, and gas pressure. We approach the problem employing high-resolution multi-physics multi-scale simulations. We report some recent results from our research activities making use of the high-performance computing infrastructure in Baden-Württemberg.

1 Introduction

Understanding the formation of stars together with their subsequent evolution and identifying the physical processes that govern the dynamics of the interstellar medium (ISM) are central research themes in astronomy and astrophysics. Knowledge of stellar birth is a prerequisite for deeper insights into the assembly of planets and planetary systems and for the search for our own origins. Stars and star clusters are fundamental building blocks of the galaxies we observe. Understanding the formation and evolution of galaxies, their chemical enrichment history, and their observational properties throughout the cosmic ages are key research areas in extragalactic astronomy and cosmology that also depend on a deep understanding of ISM physics.

Dynamical processes in the ISM are the central engine of galaxy evolution, and determine where and at what rate stars form. There are close links between large-scale phenomena, such as spiral arms or tidal perturbations, and the local process of star birth. Conversely, the energy and momentum input from stars is an important driver of ISM dynamics and turbulence. Stellar radiation and winds as well as supernova explosions determine the chemical and thermal state of the ISM, which in turn affects subsequent star formation. The dynamical evolution of the ISM is governed by the complex interplay between matter and radiation, turbulent motions, magnetic fields, self-gravity, and local variations in the chemical composition.

Shedding light on the fundamental physical processes that control the formation and evolution of stars and galaxies at different cosmic epochs and identifying and characterizing the various feedback loops that link these together are research activities at the Center for Astronomy in Heidelberg (ZAH) and the Heidelberg Institute for Theoretical Studies (HITS). Here, we report some recent findings that make use of the high-performance computing infrastructure in Baden-Württemberg as well as national supercomputing facilities.

2 Numerical Approach

The formation of stars and the dynamics of the ISM can only be understood by considering self-gravity, turbulence, magnetic fields, the coupling between matter and radiation, chemical reactions, stellar feedback, cosmic rays, as well as the galactic environment consistently and simultaneously. This lies at the very forefront of computational astrophysics, and only recently have researchers begun to truly face this complexity through the development of sophisticated computer codes capable of simulating these processes self-consistently.

In this proceedings I focus on an investigation by Rowan Smith and collaborators [13], in which we use the moving mesh code Arepo developed by Volker Springel and his group at the Heidelberg Institute for Theoretical Studies [14]. Arepo solves the hydrodynamical equations on an unstructured mesh defined by the Voronoi tessellation of a set of mesh-generating points. These points can be kept static or can move with the local gas flow. In the latter case, the method becomes similar to a mesh-based Lagrangian scheme, but one which avoids the severe mesh distortions that have hampered the application of previous mesh-based Lagrangian schemes to complex three-dimensional gas flows. With moving mesh points, the scheme naturally adapts its spatial resolution to account for local accumulation of gas, in a similar fashion to the widely-used smoothed particle hydrodynamics (SPH) approach. However, unlike SPH, the fact that the method is mesh-based allows modern high-order shock-capturing schemes to be used, allowing strong shocks and other discontinuities to be treated more accurately than in SPH (see e.g. [1], [12] for examples of flows treated more accurately by Arepo than by SPH). The Arepo mesh can be refined or de-refined simply by adding or subtracting mesh points, allowing the study of problems with an extremely large dynamical range of densities and length scales. Together, these properties make Arepo a superb tool for modeling the formation of dense molecular gas in spiral galaxies.

The chemical evolution of the gas in our simulations is modeled using a highly simplified hydrogen-carbon-oxygen chemical network designed to follow the formation and destruction of the two main molecular species in the ISM, H_2 and CO [7, 8, 11]. Full details of this network can be found in [5], with some additional discussion in [10]. We account for the photodissociation of H_2 and CO by the interstellar radiation field (ISRF), which we assume to have a similar strength and spectrum to the values measured in the solar neighborhood [4]. The attenuation of this radiation field in dense gas owing to molecular self-shielding and dust absorption is treated using the TreeCol algorithm developed by Clark and colleagues [3]. This algorithm computes approximate discretized maps of the dust extinction and molecular column densities surrounding each mesh cell with the help of information stored in an oct-tree structure. These maps then allow us to calculate the amount by which the ISRF is attenuated in each mesh cell, and hence also the amount by which the H_2 and CO photodissociation rates are reduced compared to their values in optically thin gas. At the same time as modelling the chemistry, we also model the thermal evolution of the gas due to radiative and chemical heating and cooling, using a simplified but accurate cooling function [6, 5].

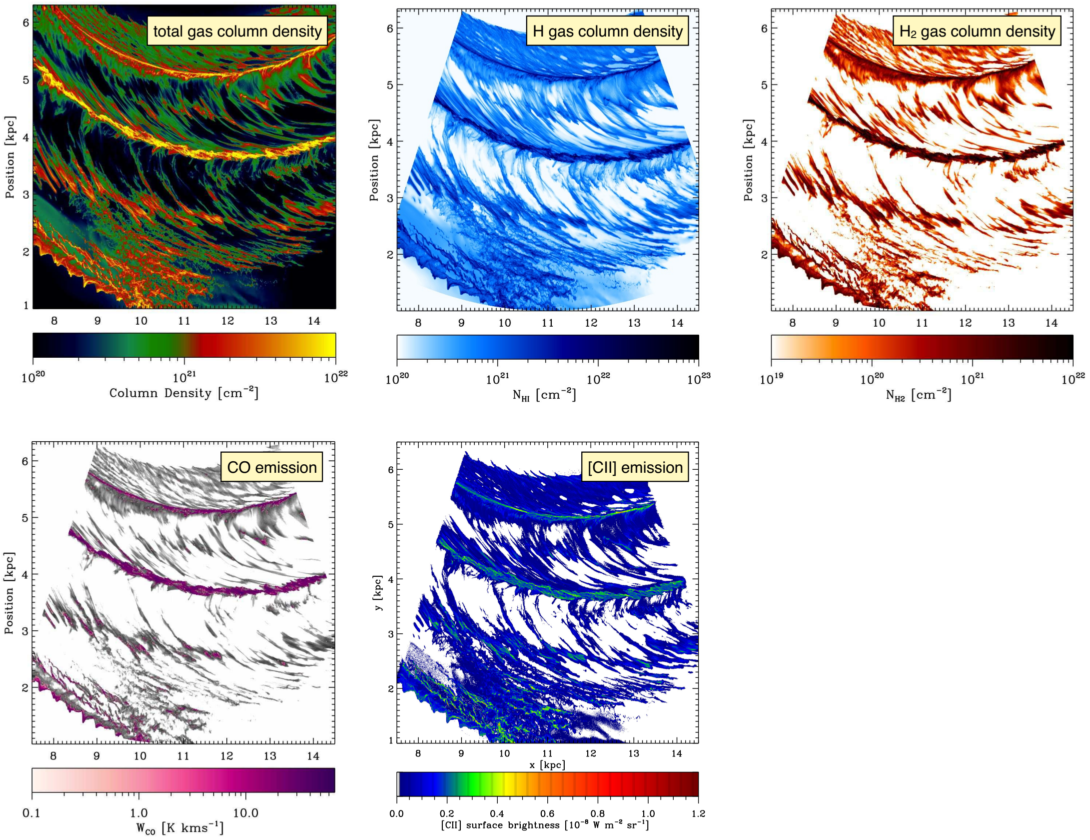

Figure 1: Map of the column densities and emission from various important chemical species in a selected region of the disk of a Milky Way type galaxy from the simulation of Smith et al. [13]. The *top left* shows the total column density of the gas. The *top middle* depicts the column density of atomic hydrogen, and the *top right* illustrates the distribution of molecular hydrogen. As molecular hydrogen itself does not emit under typical Milky Way conditions, observers often resort to studying the emission of carbon bearing species. At the *bottom left* we therefore show the emission of carbon monoxide (purple) superimposed on the column density of molecular hydrogen (in grey). The *bottom middle* image provides an impression of the fine structure emission of singly ionized carbon, the [CII] line; for more details, see Glover & Smith [9]. Note that all maps exhibit a wide range of morphologies, including dense spiral arms, filamentary spurs, and diffuse inter-arm regions.

3 Selected Results

By mass, the ISM consists of around 70% hydrogen, 28% helium, and 2% heavier elements (referred to generically as "metals"). However, because helium is chemically inert, it is common to distinguish the different phases of the ISM by the chemical state of hydrogen in each phase. For example, ionized bubbles are called HII regions, while atomic gas is often termed HI gas, in both cases referring to the spectroscopic notation. Dark clouds are sufficiently dense and well-shielded against the dissociating effects of interstellar ultraviolet radiation to allow H_2 and CO to survive for millions of years. They are therefore called molecular clouds. These are the regions that give birth to new generations of stars, and so they are the focus of most current studies of the star formation process.

One would like to observe molecular clouds by observing the emission from the H_2 molecules, since H_2 is the main constituent of the clouds. Unfortunately, H_2 is a very light molecule with widely-spaced energy levels, and its first accessible radiative transition lies around 500 K above its ground state. Since most of the molecular gas has a temperature of less than 50 K, the result is that transitions in H_2 are rarely excited. For this reason, observers focus instead on emission at radio and sub-millimeter wavelengths from dust grains or from heavy molecules such as CO that tend to be found in the same locations as H_2. The outer layers of molecular clouds are also often studied using the fine structure line of singly ionized carbon (C^+).

Because we employ a time-dependent chemical network that runs alongside the hydrodynamics in every computational cell and that is updated at every timestep in the simulation, we can produce synthetic maps of various chemical species. Figure 1 provides examples of this approach. In the top row we show the column densities of the total gas, of atomic hydrogen, and of molecular hydrogen. The bottom row illustrates the emission from CO and C^+. Further details of these emission maps can be found in [13] and [9], respectively.

Figure 2 focuses on the most important tracer of molecular gas, the emission from CO, and provides zoom-ins into different regions. Visual inspection of the images reveals that a significant fraction of molecular hydrogen is not well traced by CO. This is the so-called CO-dark H_2 gas. One obvious hiding place of this gas is in dark envelopes surrounding CO-bright molecular clouds. This has been investigated in the past [15] using static one-dimensional radiative transfer calculations with highly detailed chemical networks (PDR codes, where PDR stands for photodissociation region). In the three-dimensional simulations of ISM dynamics presented here we also find CO-dark H_2 in the immediate vicinity of CO-bright clouds. But in addition, these calculations show that a significant amount of CO-dark H_2 is located in extended filaments with lengths of tens to hundreds of parsecs. They are typically located in the inter-arm regions of the disk and inclined to the main spiral arms.

These filaments are created when denser gas clumps are sheared out by the differential rotation of the disk following their passage through the spiral arm [2]. Their highly elongated geometry makes the filaments more susceptible to photodissociation since it is easier for radiation to penetrate the cloud along the short axes of the filament. Compared to a spherical cloud a filamentary one has a greater surface to volume ratio which increases the difficulty of achieving a sufficient column density of gas to shield the CO. Many of the longer filaments in our calculation do have CO-bright regions close to their centers, but some remain CO-dark throughout. Measurements of the ends of these structures using UV line absorption would characterize them as diffuse molecular clouds with high H_2 fractions but little or no CO, whereas the central regions would be easily visible in CO emission and would be characterized as dense molecular clouds. However, in reality, both "clouds" are part of the same extended structure.

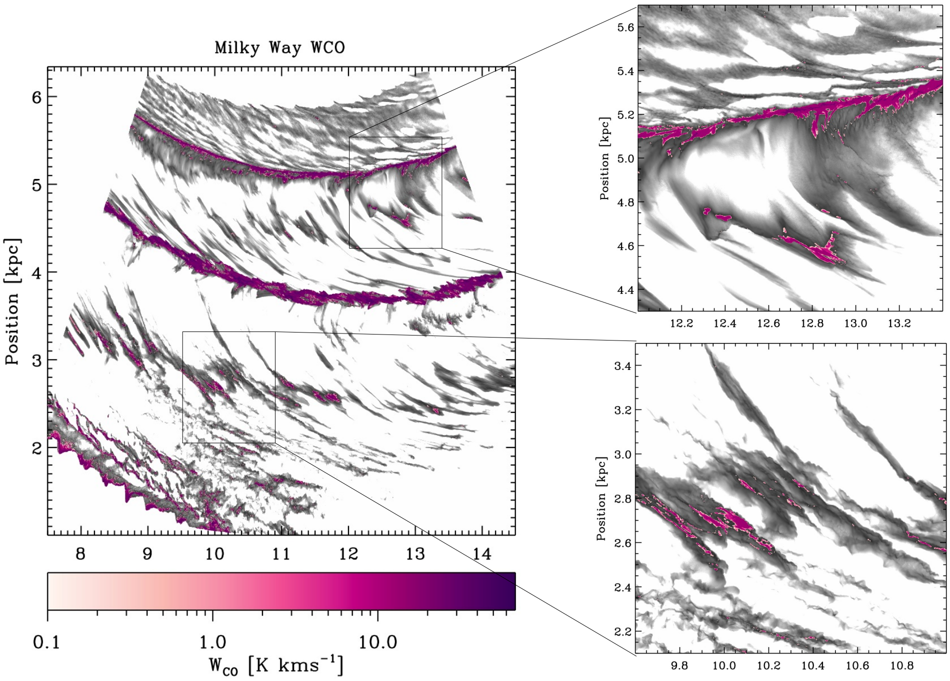

Figure 2: Comparison of H_2 column density and CO integrated intensity for selected regions. The images demonstrate that a significant fraction of molecular hydrogen is not well traced by CO. This is the so-called CO-dark H_2 gas.

4 Summary

In this contribution, we have discussed numerical simulations of Smith and collaborators [13], in which we model a significant portion of the disk of a Milky Way like galaxy with a version of the AREPO moving mesh code [14] that includes a self-consistent treatment of the chemistry of the interstellar medium. In the most highly refined portion of our simulation we reach a mass resolution of only four solar masses. This approach enables us to resolve substructure within the disk sufficiently accurately to match the observed transition from atomic to molecular hydrogen gas without having to resort to some ad-hoc subgrid-scale model to represent unresolved density fluctuations. We can, for example, determine the fraction of CO-dark H_2 gas with unprecedented precision and compare the simulation value with the results from current measurements. Other applications include the prediction of [CII] emission for observational campaigns with SOFIA[1], which is a high-altitude airplane equipped with a 2.5 meter telescope, or the calculations of synthetic HI emission maps that help improve our astrophysical interpretation of data from 21 cm surveys of the plane of our Milky Way or of external galaxies (such as THOR and THINGS, lead by researchers at the Max Planck Institute for Astronomy in Heidelberg)[2].

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[1] SOFIA – Stratospheric Observatory for Infrared Astronomy: `https://www.nasa.gov/mission_pages/SOFIA/index.html`

[2] THOR – The HI/OH/Recombination Line Survey of the Inner Milky Way: `http://www2.mpia-hd.mpg.de/thor/Overview.html`, THINGS – The HI Nearby Galaxy Survey: `http://www.mpia.de/THINGS/Overview.html`

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