The Dynamical Interstellar Medium: Insights from Numerical Models

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Abstract. Numerical models of the dynamical interstellar medium show that interactions between structures such as supernova remnants and superbubbles are more important than the structures themselves in determining the behavior of the ISM. I review the techniques and conclusions of recent global models, focussing on what they tell us about the formation of star-forming giant molecular clouds.

1. Introduction

The modern picture of the interstellar medium (ISM) as a pervasive medium containing gas at temperatures ranging from hundreds to millions of degrees was first hinted at by Copernicus observations of the far ultraviolet absorption lines of O vi (Jenkins & Meloy 1974, Jenkins 1978). The ambient interstellar radiation field is too soft to photoionize O vi, so it must be thermally ionized by $10^5$ K gas. However, the cooling curve for gas with solar abundances peaks around $10^5$ K, implying that this gas exists in thin, cooling layers at the surface of a reservoir of $10^6$ K gas. This led to models of a thermally regulated, three-phase ISM controlled by the balance between energy input from supernovae and energy dissipation by radiative cooling (Cox & Smith 1974; McKee & Ostriker 1977). A new model is now beginning to emerge, in which dynamical compression rather than thermal conduction determines the thermal state of the gas as well as its structure.

The major question driving this new model is, what determines the star formation rate? The old idea that it might be determined by a balance between supersonic turbulence and self-gravity has come back into favor recently as the idea of magnetostatic support regulated by ambipolar diffusion has run into significant problems: magnetic fields weaker than required (Crutcher 1999); observed cores denser than predicted (Nakano 1998); and the inability of magnetic fields to maintain the observed supersonic motions (Mac Low et al. 1998, Stone, Ostriker, & Gammie 1998). In this paper I argue that numerical models point to supernovae as the main driver of that supersonic turbulence, at least in star-forming regions of the ISM.

As has long been recognized, the odd thing about the observed star formation rate in normal galaxies is how low it is. Typical molecular cloud free-fall times are of order 1 Myr, but there is still plentiful gas available after $10^4$ times that long. Another way to see this is to note that if the $10^{10} M_\odot$ of gas observed
in our galaxy were to collapse on timescales approaching the free-fall time, the star formation rate would be far higher than the observed $1 - 2M_\odot\,\text{yr}^{-1}$.

This has led to the suggestion that molecular clouds are long-lived objects, with lifetimes ranging from 30 Myr (Blitz & Shu 1980) to as long as 100 Myr (Solomon & Sanders 1979, Scoville & Hersh 1979). In addition to the argument from the global star formation rate given above, Blitz & Shu (1980) also point to the extent of the presence of molecular clouds behind spiral arm shocks and the stellar ages then thought to be associated with the clouds as evidence for their lifetime estimate. Recently, however, Ballesteros-Paredes, Hartmann, & Vázquez-Semadeni (1999), have proposed much shorter lifetimes of only 5–7 Myr, based on the lack of post-T Tauri stars with ages in the 5–10 Myr range that are clearly associated with molecular clouds. Individual clouds might be quite short-lived, though cloud-forming regions might last significantly longer, explaining the observed spatial relationships with spiral arms.

2. Simulations

2.1. Questions

Large-scale simulations of the ISM address a number of questions in ways complementary to other methods. First, they can begin to reveal the topology of the different phases of the ISM, distinguishing between scenarios in which the hot gas is confined in isolated bubbles, is distributed in an interconnected tunnel network, or forms a uniform sea surrounding isolated clouds of warm and cold gas. The distribution of cold, neutral gas determines whether ionizing radiation from OB associations in the galactic plane can fully account for the ionization of the Reynolds layer far above it.

Second, the production of star-forming regions appears to be largely determined by large-scale flows in the ISM, influenced by the gravitational potential. Large-scale simulations can thus yield information on the formation and lifetimes of molecular clouds. Related issues can also be addressed, for example, whether supernovae and superbubbles are more important in triggering nearby star formation or in driving turbulence that supports the ISM against gravitational collapse and star formation.

Finally, two other major issues that I will not focus on to the same extent are the production of galactic magnetic fields in a turbulent dynamo, and the vertical flow of the ISM in galactic fountains and winds.

2.2. Objects vs. Interactions

Traditionally, numerical simulations of the ISM focussed on specific objects, such as supernova remnants, stellar wind bubbles, superbubbles, shocked clouds, or bow shocks produced by fast-moving stars or stellar jets. Such simulations have proved useful, but are limited by the lack of interactions with surrounding structures.

Observations of the ISM are structured at all scales. A frequent problem encountered by observers is distinguishing objects such as superbubbles from the structured background. The background structure is often as important in defining the final nature of an object as more traditional considerations such as
the central energy source or cooling physics. The interactions between “objects” such as supernova remnants or superbubbles becomes as important as the objects themselves. The random supersonic flows generated by these interactions in turn determines whether regions will be supported against gravitational collapse, or be compressed and cooled, starting a process of collapse leading to molecular cloud and star formation.

2.3. Models

In the last five years, a significant number of global models have been computed. They are distinguished by the different physical processes included, and by the different numerical techniques used.

The most important distinction appears to be the driving mechanism for the modeled interstellar turbulence. The most abstract model for the driving is simply a uniform, Gaussian field, which has both the advantage and disadvantage of being very general, but not reproducing the specifics of particular real drivers. Three real drivers have also been used in various models: stellar ionization heating, rotational shear, and supernovae. The last appears to be the most realistic, although the other two add important physics when used in addition to the supernovae.

The dimensionality and coverage of the simulation are also very important. Two-dimensional simulations overstate the difficulty of hot gas escaping from the plane and cannot be used fruitfully to explore questions of magnetic field generation, but have yielded fundamental insights into the turbulent ISM. Three-dimensional models have been done in both local and global modes, either focussing on a particular region of a disk (typically around 1 kpc²) or attempting to encompass the entire disk.

Three main technical issues differentiate the models. First is the numerical diffusivity of the method used. Smoothed particle hydrodynamics (SPH) tends to be the most diffusive method due to the need to average over a fairly large number of particles to derive the flow quantities. Spectral methods are excellent for smooth flows, but handle shocks and other abrupt features in flows poorly. Grid-based methods have a numerical diffusivity determined by a combination of the order of the method, the advection technique used (e.g. second-order Van Leer, piecewise parabolic method (PPM), or total variation diminishing (TVD) methods), and the technique used for handling shocks.

The second main issue is the shock handling technique itself. Artificial viscosity can be used with particle, spectral, and grid methods to resolve shocks over several resolution lengths. Exact or linearized Riemann solvers resolve shocks more accurately and in fewer zones. They compute the flow at the edge of each zone by solving for the combination of shocks and compression or rarefaction waves that results from the breakup of the discontinuity at each zone boundary.

The third issue is the structure of the grid in those methods using one. The simplest grids are fixed, Eulerian grids, with periodic boundary conditions in the case of local simulations. Ratioed fixed grids that focus resolution toward a region of interest such as the galactic plane or the galactic center are the next step. SPH models effectively use an unstructured Lagrangian grid that follows the flow, with the advantage of high resolution in dense regions, but the corresponding disadvantage of low resolution in more rarefied regions. Adaptive
mesh refinement focuses resolution into regions of interest regardless of density, at the cost of significant additional programming complexity.

3. Results

The outlines of a coherent picture of the interstellar medium is emerging from the numerical models, one that places a greater emphasis on dynamical interactions and less on equilibrium structures than previous analytically constructed pictures.

In the absence of supernova heating and the presence of normal interstellar cooling, the gas cools rapidly, forming dense clouds scattered through the disk of the galaxy that interact with each other, surrounded by a thicker disk of warm $10^4$ K gas, but without hot, $10^6$ K, X-ray emitting gas. An example of this solution is seen in the global SPH computations by Gerritsen & Icke (1997).

The global, two-dimensional PPM computations of Wada & Norman (1999) add the element of driving from galactic shear. Starting with a Toomre stable disk, they find that the gas rapidly cools and collapses into a filamentary network of clouds that are cold enough to be Toomre unstable. Although occasional cloud collisions generate small amounts of $10^5$ K gas, the interesting conclusion can be drawn from these computations that the Toomre stability criterion must be applied to a medium whose velocity dispersion is maintained by some mechanism other than ionization heating.

At the same time, it has become clear that dense interstellar clouds can be formed by turbulent compression. The local, 2D, MHD, spectral models of Passot, Vázquez-Semadeni, & Pouquet (1995) show that this can be a dominant mechanism for structure formation in the warm and cold ISM even in the presence of magnetic fields. Hennebelle & Pérault (1999, 2000) have explored the interplay of compression and thermal condensation due to conduction in detail with 1D, adaptive mesh models with and without magnetic fields, showing that compression will cause collapse on far shorter timescales than thermal condensation under typical ISM conditions. As thermal condensation is the dominant mechanism for cold cloud formation in analytic equilibrium models such as those of McKee & Ostriker (1977), this is an important conclusion.

Using supernovae as the main driving mechanism produces hot gas with moderate filling factor in the disk of galaxies with parameters similar to those of the Milky Way, and much larger filling factor above the plane. Local, 2D models done with a second-order, Van Leer algorithm on a ratioed grid by Rosen & Bregman (1995) established that such driving alone could lead to the formation of a network of cold clouds and hot gas, along with a flow of hot gas out of the disk. Use of adaptive mesh refinement with a Riemann solver allowed Avillez (1999) to perform 3D models extending 10 kpc into the upper halo. He finds that hot gas is not trapped in the disk as occurred in the 2D models. Ballesteros-Paredes, Avillez, & Mac Low (2000) show that instead, isolated, cold, dense clouds with masses and sizes typical of giant molecular clouds form in and close to the disk. Column density distributions of cool and cold gas from these models strongly resemble observations of H $^1$, for example by Kim, Stavely-Smith & Bessell (1999).
These models either lack self-gravity, or, in the case of Passot et al. (1995) lack the resolution for self-gravity to become significant. However, isothermal, uniformly-driven models provide some insight into whether supernova-driven turbulence could support the gas against gravitational collapse. Klessen, Heitsch, & Mac Low (2000) show that supersonic turbulence can globally support a thermally Jeans unstable region, but local collapse will still occur due to the density enhancements caused by shock waves in the supersonic turbulence, except in the case of extremely strong turbulence. In fact, it appears that a signpost of global turbulent support under molecular cloud conditions is isolated star formation, while lack of turbulent support leads to efficient runaway star formation (Klessen, Burkert, & Bate 1998, Klessen & Burkert 2000a, 2000b). Heitsch, Mac Low, & Klessen (2000) show that magnetic fields add small-scale structure, and slow local collapse, but do not prevent it.

Applying the insights gained from these models to the interstellar case, it appears that the supernova-driven turbulence may naturally create regions that are gravitationally-bound, but then may drive enough turbulence within them to reduce their star-formation rate to the low levels observed in typical molecular clouds, probably with the help of interstellar magnetic fields. Observations of molecular clouds appear to show that they have self-similar structure to scales of as much as tens of pc (e.g. Stutzki et al. 1998), which Mac Low & Ossenkopf (2000) find to be most readily explained by driving of the turbulence from even larger scales, again consistent with large-scale driving by supernovae.

Korpi et al. (1999) use a 3D, fixed grid, local, MHD code to model the evolution of the magnetic field in shearing, supernova-driven turbulence. Korpi (1999) measures the stress terms in the flow to find preliminary evidence for the operation of a dynamo, with roughly the strength predicted by Ferrière (1996, 1998) from semi-analytic models of superbubble expansion.

All the supernova-driven models find a flow of hot gas from the plane into the halo. Avillez & Mac Low (2000) point out that much of this gas does not flow through chimneys directly into the halo, but rather rises buoyantly into the Lockman and Reynolds layers, not necessarily reaching the hot halo. A true fountain flow only appears above 1 kpc (Avillez 2000). One consequence of this is that even fairly active normal galaxies, such as the Milky Way or NGC 891, do not drive strong winds into the surrounding intergalactic medium. Kinetic energy feedback from galaxy formation will only come from starburst galaxies (Mac Low & Ferrara 1999, Silich & Tenorio-Tagle 1998, Suchkov et al. 1994, 1996).

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