The Evolving ISM in the Milky Way & Nearby Galaxies

ISM Theory: Gas Phases, Turbulence, and Star Formation

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ABSTRACT

The ISM is a complex and highly dynamic system, and recent numerical modeling efforts have begun to take into account the effects of multiscale, time-dependent processes, generically classified as “turbulence”. Turbulence transforms what would otherwise be a simple two-temperature state for atomic gas into a broader, but still bimodal, distribution; it also affects the relative proportions of gas in each phase – including the molecular phase – by collecting gas in large-scale shocks and by increasing the gas scale height, which determines the midplane pressure. Turbulence has many sources, both from stars and from tapping the rotational energy in galaxies (through magnetic effects and other instabilities). Star formation is strongly affected by turbulence as well, in both “positive” (increased compression in shocks) and “negative” (decreased mean densities from turbulent pressure) ways. In addition to turbulence, “environmental” factors including spiral structure strongly affect the state of the ISM, and the regulation of star formation. I discuss recent advances in modeling, as well as open questions for future theoretical and observational investigations.

Subject headings: galaxies: ISM — ISM: kinematics and dynamics — turbulence — stars: formation — ISM: structure

1. Introduction

The interstellar medium (ISM) is home to the full spectrum of physical processes studied in theoretical astrophysics, and is subject to interactions among these processes that results in a wide array of complex – and beautiful – structures. Through much of the 20th century, studies of ISM concentrated on developing the fundamental theoretical tools to follow radiative and dynamical processes in the ISM, and models focused on characterizing equilibrium

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states and identifying instabilities. In recent years, increased computational power has made it possible to extend ISM modeling into the nonlinear, nonequilibrium, time-dependent domain. Results of these models have greatly enhanced our understanding of many aspects of both the diffuse and dense ISM, as observed by *Spitzer* and other telescopes. While a comprehensive review of the modeling advances is not possible here, I will discuss three main topics that have been the subject of recent investigations in the theoretical community:

- Phases and phase transitions in the ISM
- Driving ISM turbulence
- Regulation of star formation

In addition to discussing some of the progress in these areas, I will highlight problems, issues, and questions that remain outstanding. As this contribution is intended primarily as a record of a review talk given at the *4th Spitzer* conference rather than a traditional review paper, I adopt an informal format and approach.

2. Phases and phase transitions in the ISM

The gas in the ISM can be divided into three main components:

- **Ionized gas**: consisting of *warm ionized gas*, which is heated and ionized by stellar UV, is diffuse in form, and includes the "Reynolds Layer" at high latitude in the Milky Way; and *hot ionized gas*, which is heated by spernova shocks, and is in part organized into bubbles and chimneys from correlated supernovae.

- **Atomic gas**: consisting of *warm atomic gas*, which is diffuse and fills much of the volume near the Galactic midplan, and *cold atomic gas*, which is organized into dense clouds, sheets, and filaments of size $L \sim 1 - 10\,\mathrm{pc}$. Atomic gas is the primary gas component by mass in the outer parts of spiral galaxies.

- **Molecular gas**: which is observed in the Milky Way as structured into giant molecular clouds (GMCs, with masses $\sim 10^5 - 10^6\,M_\odot$), and dark clouds ($M \lesssim 10^4\,M_\odot$), with sizes $L \sim 20 - 50\,\mathrm{pc}$ and typical volume-averaged density $n \sim 100\,\mathrm{cm}^{-3}$, and containing dense clumps and cores with $n = 10^3 - 10^6\,\mathrm{cm}^{-3}$. In external spirals (and the Milky Way), GMCs are organized into larger-scale superclouds and giant molecular associations, which include atomic envelopes. Molecular gas is concentrated in the spiral arms in the outer parts of galaxies, while it makes up the primary component by mass in the inner parts of galaxies (including both diffuse and self-gravitating molecular clouds).

Atomic Gas

The steady-state thermodynamics of optically-thin atomic gas subject to the then-known heating and cooling processes was analyzed by Field et al. (1969), who found that there are three possible equilibria. These are the warm phase, at temperature $\sim 10^4\,\mathrm{K}$, the intermediate-temperature phase ($T \sim 200 - 5000\,\mathrm{K}$), and a cold phase ($T \lesssim 200\,\mathrm{K}$). The warm and cold phases are thermally-stable, whereas the intermediate-temperature phase is subject to thermal instability, in that small perturbations about the equilibrium will result in increasing heating or cooling so as to depart from the equilibrium (Field 1965). Thus, in radiative and dynamical equilibrium (where the latter implies a common pressure for all gas), only a warm atomic phase (heated primarily by the photoelectric effect on small grains, and cooled by Lyα, C II, and O I lines, and by electron recombination), and a cold atomic phase (also heated primarily heated by the photoelectric effect, and cooled mainly by CII 158 μm emission), would be expected to be present in the ISM (Wolfire et al. 1995).

Time-dependent numerical simulations indeed show that gas at density within the thermally-unstable range rapidly separates into two phases, consisting of cold clouds and a warm intercloud medium (e.g. Piontek & Ostriker 2004; Koyama & Inutsuka 2004; Brandenburg et al. 2007). At the same time, the gas tends to cool so that the overall pressure decreases towards the minimum pressure at which two phases are possible. Thus, the "classical" two-phase description of the atomic ISM would hold to an excellent approximation, if the ISM were quiescent. In fact, many processes stir turbulence and other time-dependent motions in the ISM, and these time-dependent effects lead to departures from the classical two-phase equilibrium state. For a dynamic medium, in addition to the radiative heating and cooling terms, there are shock heating, heating from dissipation of magnetic energy, and PdV heating or cooling associated with contraction or expansion. Numerical studies of gas distributions as a function of density and temperature have been performed by a number of groups, considering different sources of turbulence (e.g. Piontek & Ostriker 2005; Audit & Hennebelle 2005; Gazol et al. 2005; Joung & Mac Low 2006). Overall, these studies show that although the density and temperature PDFs broaden, a quasi-two-phase state persists for atomic gas, because turbulent timescales are typically at least as large as the radiative cooling timescales. Turbulence also alters the relative proportions of gas in the warm and cold phases. These numerical results are in general agreement with observations of the atomic medium in 21 cm emission and absorption, which indicate the presence of out-of-equilibrium gas (Heiles & Troland 2003).

Molecular Gas

Cold atomic gas can become molecular when both the density n (which governs the rate of molecular formation) and the column density N (which determines the degree of dust shielding and self-shielding) are sufficiently large (e.g. Draine & Bertoldi 1996). Recent numerical simulations adopting an approximate self-shielding approach have shown that H_2 forms rapidly in turbulent gas, because supersonic shocks produce strong local compressions in which cooling and molecule formation are both accelerated compared to the rates at the same volume-averaged density (Glover & Mac Low 2007). The mean observed column densities of GMCs in the Milky Way of $N_H \approx 1.5\times10^{22}\,\mathrm{cm}^{-2}$ (Solomon et al. 1987) exceed the typical column density at which CO approaches becomes abundant, $N_{H_2} = 2-3\times10^{21}\,\mathrm{cm}^{-2}$ (van Dishoeck & Black 1988). Up to densities of $\sim 10^5\,\mathrm{cm}^{-3}$, CO lines provide the main coolants of cold molecular gas (e.g. Neufeld et al. 1995).

How are molecular clouds formed? To make the transition from predominantly-atomic to predominantly-molecular gas, it is necessary to have both sufficient volume density and sufficient column density. Possible mechanisms include pairwise coagulation of cold atomic clouds, shock compression in a converging flow, and compression by galactic vertical gravity or gas self-gravity. Cloud coagulation (Kwan 1979) is generally too slow to reach the sizes and masses of observed GMCs, and for realistic shock durations in the diffuse ISM, the total column of observed dense gas accumulated would be smaller than the typical GMC column density by an order of magnitude, although the column would be sufficient to form molecules and create dark clouds (McKee & Ostriker 2007). Galactic vertical gravity increases n at the midplane, and is greatest where the total column of gas is large; conditions are therefore favorable for molecule formation in the inner parts of galaxies where the vertical gravity from stars and gas are both large. Further from the centers of galaxies, gas self-gravity can increase both n and N together, eventually creating a massive molecular cloud. It is important to note that molecular gas and self-gravitating gas are not necessarily synonymous (Elmegreen 1993): self-gravitating atomic clouds can become molecular as n and N increase, whereas diffuse gas that is molecular (being sufficiently self-shielded and at high density) can become self-gravitating. Favorable conditions for molecule formation are also found in spiral arms, where shocks and the gravitational potential of the arm together sharply increase n and the gas surface density Σ_g. Of course, a parcel of gas that makes a transition from the atomic to the molecular phase can be recyled back into atomic gas, either by photoevaporation when massive stars create an HII region, or if a massive GMC is broken up dynamically and dispersed into non-self-shielding pieces (e.g. Krumholz et al. 2006).

Consistent with expectations, spiral arms and the inner parts of galaxies are indeed observed to be the most molecule-dominated regions. In particular, Blitz & Rosolowsky (2006) find that the ratio of molecular to atomic gas, $\Sigma(H_2)/\Sigma(HI)$ increases approximately linearly with a quantity $P_{BR} = \sqrt{2G\rho_*}c_{eff}\Sigma_g$ that represents the hydrostatic pressure in an isothermal layer where the gravity is dominated by the stellar disk. Numerical simulations that follow the dynamical evolution of the ISM, including self-gravity and feedback from star formation, are in general agreement with the observed empirical increase of $\Sigma(H_2)/\Sigma(HI)$ with ρ_* and Σ_g (Koyama & Ostriker 2008, in preparation), although with a slightly different interpretation. The models show that the mass-weighted pressure and mean (volume-weighted) midplane pressure typically differ by about an order of magnitude (so that there is no unique hydrostatic pressure), with P_{BR} lying in between the two to track the overall change in pressure as environmental conditions vary. The timescale for self-gravitating clouds to form also decreases with increasing gas and stellar surface density, and the dense gas in the models is always found to be collected into self-gravitating structures. Thus, an interpretation of the empirical relation between $\Sigma(H_2)/\Sigma(HI)$ and P_{BR} is that in denser environments, self-gravitating clouds re-form again rapidly (with exchange between neighbors) after they are dispersed by star-formation, such that at any given time most of the gas is collected in self-gravitating clouds. Interestingly, the ratio $\Sigma(H_2)/\Sigma(HI)$ is much higher than observed values at a given value of Σ_g in models that exclude star formation (Koyama & Ostriker 2008, in preparation), indicating that turbulent feedback is essential in setting the fraction of gas in each phase real galaxies.

3. Driving ISM turbulence

As has become more and more clear in recent years, turbulence has many important effects in the interstellar medium. Consequences of turbulence include alterating the proportions of gas in different phases (see section 2), increasing the vertical scale height of gas (e.g. Koyama & Ostriker 2008, in preparation), and affecting the rate and character of star formation (see section 4). Given the importance of turbulence, it is essential to understand how it is created. In the traditional view (e.g. Spitzer 1978), the primary driver of turbulence is supernovae. By balancing energy gains from expanding supernova-driven shells with losses from cloud collisions, the typical velocity dispersion obtained for diffuse ISM gas would be ~ 7 km s^{-1}, consistent with observations. Using numerical simulations that model supernova effects, de Avillez & Breitschwerdt (2005) found atomic gas velocity dispersions of 6-20 km s^{-1} for Solar-neighborhood models, while Dib et al. (2006) found quite low velocity dispersions when star formation rates are reduced. Given the observed lack of correlation between turbulence and star formation (in comparisons of arm/interarm and inner/outer galaxy regions; see Dickey et al. 1990; van Zee & Bryant 1999; Petric & Rupen 2007), this suggests that sources other than star formation must contribute to turbulent driving. This conclusion is further supported by the evidence that outer disks contain cold gas (de Blok & Walter 2006) that would be strongly gravitationally unstable (producing higher-than-observed star formation rates) if the gas were not turbulent. Contributing non-stellar sources of turbulence include the magnetorotational instability, swing amplification at surface densities too low for gravitational runaway, non-steady spiral shocks, and other processes (including Parker instabilities and effects induced by cosmic rays).

The magnetorotational instability (MRI) is a generalization of the instability analyzed by Balbus & Hawley (1991), which feeds off the interaction between sheared rotation and magnetic fields threading the disk at different radii. Sellwood & Balbus (1999) pointed out that MRI may contribute to the driving of turbulence in galaxies, and this process has been studied using numerical simuations in a series of papers that take into account the detailed structure and thermodynamics of the ISM (Piontek & Ostriker 2004, 2005, 2007). The MRI is different in galaxies from accretion disks because of the bistable cooling curve of atomic gas. As a consequence, the thermal pressure is set by heating and cooling, and typically lies between the minimum value of P for a cold medium to be present, and the maximum value of P for a warm medium to be present. The mean density, on the other hand, is not simply proportional to the pressure (as would be true in an isothermal medium), but is set by the "loading" of cold gas: $\langle n \rangle = (P/kT_{warm})(1 + M_{cold}/M_{warm})$, where $T_{warm} \sim 10^4\,\mathrm{K}$. Piontek & Ostriker (2005) found that for two-phase ISM gas, the saturation level of the magnetic pressure, $B^2/(8\pi)$, is independent of $\langle n \rangle$, and is typically twice the level of thermal pressure. For the same models, the turbulent velocity dispersion varies with mean density as $\sigma_v = 3\,\mathrm{kms}^{-1}\langle n \rangle^{-0.77}$, which suggests that turbulence levels could be quite high in outer galaxies where the mean density is low. Indeed, the stratified-disk simulations of Piontek & Ostriker (2007) found $\sigma_v = 5$ km s^{-1}and 20% cold gas in outer disk models with $\Sigma_g = 6$ $M_\odot$ pc^{-2}and a total midplane (stellar + dark matter) density of 0.003 $M_\odot$ pc^{-3}.

The swing amplifier (Goldreich & Lynden-Bell 1965; Toomre 1981), in situations of sufficiently low Toomre parameter $Q \equiv \kappa c_s/(\pi G \Sigma_g)$, can result in nonlinear runaway and formation of massive ($\gtrsim 10^7\,M_\odot$) self-gravitating clouds (Kim & Ostriker 2001; Kim et al. 2002, 2003; Kim & Ostriker 2007; Li et al. 2005a,b). On the other hand, when Q is larger than the critical value, fragmentation does not occur, but instead large-amplitude density and velocity fluctuations can be driven, with typical values $\approx$ 4km s^{-1}when Q approaches $Q_{crit} \approx 1.5$ (Kim & Ostriker 2007). The large-scale turbulence produced by sub-threshold swing amplification will cascade to smaller scales, and contribute to maintaining turbulence in the outer parts of disks.

In the inner parts of disks, where spiral structure is strong, another contributor to turbulence comes from the complex dynamics within spiral arms. The response of gas to a given spiral pattern is stronger than that of the stars, and in particular because gas enters the arm supersonically (except near corotation), it typically undergoes a shock (Roberts 1969). This shock front is generally curved in the radial-vertical plane, so that gas entering horizontally will be redirected vertically. Vertical motions are also induced by the enhanced gravity downstream from the arm, where gas collects. As the vertical oscillation time is generally non-commensurate with the arm-to-arm crossing time, the spiral shock front cannot maintain a steady configuration: it flaps horizontally, which then drives further vertical motions. These motions, with "eddy scale" comparable to the disk scale height, then cascade into smaller-scale turbulence. The tubulence so driven is supersonic for a shock strengths similar to the observed values (based on arm/interarm surface density contrasts) (Kim et al. 2006). Since gas is concentrated into the arms in galaxies with strong spiral structure, this process may be very important for driving observed turbulence.

Thus, it appears that in addition to supernovae, many other processes may contribute to observed turbulence levels. In the future, important directions for theoretical research include: (1) understanding interactions among the various processes that contribute to turbulence; (2) thoroughly studying parameter dependence, to determine whether some processes dominate in specific regions (e.g. outer galaxies, spiral arms, galactic centers), and how the character of turbulence (e.g. amplitude, directional variation, and power spectrum) depends on ISM phase; and (3) obtaining observational discriminants that aid in discriminating among models (e.g. ratios of radial to vertical velocity dispersion, which differ for turbulence that taps differential rotation and tubulence driven by star formation), and testing observational proxies for turbulence when the velocities cannot be directly measured (e.g. scale height for edge-on galaxies).

4. Regulation of star formation

Star formation is inherently a complex process that is regulated by processes at scales from kpc to sub-pc. It is therefore convenient to break down this regulation, where possible, into different stages. In the simplest breakdown of this kind, one can separate star formation into two stages: (1) creation of self-gravitating GMCs out of diffuse gas, at a rate $\Sigma_{diffuse}/t_{diffuse}$; and (2) conversion of a fraction ϵ_{GMC} of the gas in a GMC into stars, over the lifetime t_{GMC} of the GMC. Assuming that all star formation takes place in GMCs and the total surface density of GMCs is Σ_{GMC}, and that a steady state is reached, then the overall star formation rate can be expressed as:

$$\Sigma_{SFR} = \epsilon_{GMC} \frac{\Sigma_{diffuse}}{t_{diffuse}} = \epsilon_{GMC} \frac{\Sigma_{GMC}}{t_{GMC}} = \epsilon_{GMC} \frac{\Sigma_g}{t_{diffuse} + t_{GMC}}, \tag{1}$$

where $\Sigma_g = \Sigma_{GMC} + \Sigma_{diffuse}$ is the total gas surface density (McKee & Ostriker 2007). More generally, one could replace $\Sigma_{GMC} \rightarrow \Sigma_{bound}$, $t_{GMC} \rightarrow t_{bound}$, and $\epsilon_{GMC} \rightarrow \epsilon$, if star formation occurs with efficiency ϵ within bound structures having lifetimes t_{bound}. This allows for the case where essentially all of the gas is molecular, and stars form within massive, bound clumps. In many situations, substructures within turbulent systems will have shorter lifetimes than their formation times, because dynamical times decrease at smaller scales and for higher densities (e.g. Elmegreen 2002, 2007).

In the case where spiral stucture is strong and the duration of the diffuse stage is the interarm period, $t_{diffuse} \sim t_{orb}/2 \ll t_{GMC}$ for a two-armed spiral well inside corotation, the azimuthally-averaged star formation rate will then be $\Sigma_{SFR} \approx 2\epsilon_{GMC}\Sigma_g/t_{orb}$ (cf. Wyse & Silk 1989). This is consistent with galaxy-averaged observations for $\epsilon_{GMC} \approx 0.05$ (Kennicutt 1998). Taking the point of view that gas content regulates star formation in potentially nonlinear ways, Schmidt (1959) investigated the possibility of star formation laws of the form $\rho_{SFR} = a\rho_g^n$ and $\Sigma_{SFR} = S\Sigma_g^N$. There is significant observational evidence relating star formation rates to gas content via "orbital" and Schmidt-type laws (Kennicutt 1989, 1998; Wong & Blitz 2002; Murgia et al. 2002; Boissier et al. 2003; Kennicutt et al. 2007). Empirical Schmidt-law indices are typically $N = 1 - 2$, although questions remain regarding the differences between star formation laws based on total gas content vs. molecular gas content.

From the theoretical point of view, it is important to determine what Schmidt-type empirical laws imply about underlying physical processes, and whether it is possible to derive them from fundamental considerations of star formation. Schmidt laws can be recast in the form $t_{SF} = \Sigma_g/\Sigma_{SFR} \propto \Sigma_g^{-(N-1)}$, so that $N = 1$ corresponds to a fixed star formation time independent of environment within a galaxy, whereas $N > 1$ implies that the star formation time decreases as the gas surface density increases. Theoretically, important questions are how t_{SF} should depend on the gaseous surface density (local, azimuthally-averaged, or globally-averaged), and what other environmental parameters (such as a velocity dispersion) must be intoduced in order to convert a Schmidt-type law to a dimensionally-correct formula for t_{SF} (potentially also yielding tighter empirical relations). By comparison to the generalization of equation (1), $t_{SF} = (t_{diffuse} + t_{bound})/\epsilon$. If the timescale in the diffuse phase far exceeds the lifetime of individual bound clouds or clumps, then $\Sigma_g \approx \Sigma_{diffuse}$ and $t_{SF} \approx t_{diffuse}/\epsilon$, whereas in the opposite limit of long-lived bound entities, $\Sigma_g \approx \Sigma_{bound}$ and $t_{SF} \approx t_{bound}/\epsilon$. If, further, the lifetimes of bound structures are determined by internal processes (namely, energetic feedback from star formation), then in the latter case t_{SF} would be a constant, independent of environment, which would yield a Schmidt index $N = 1$.

For the situation where diffuse gas dominates, the controlling timescale is the interval required to gather gas into self-gravitating structures. A characteristic timescale for formation of bound structures is $t_{grav} \sim (G\rho)^{-1/2}$. For a gas layer in hydrostatic equilibrium in its own self-gravity, $\rho = \Sigma/2H \rightarrow \pi G\Sigma^2/(2\sigma_v^2)$, where σ_v is the vertical velocity dispersion. In this situation, the expected scaling of star formation time with the properties of the gas layer is $t_{SF} \propto \epsilon^{-1}(G\Sigma/H)^{-1/2} \propto \sigma_v(\epsilon G\Sigma)^{-1}$. Agreement with a Schmidt law would therefore require that $H^{1/2}/\epsilon \propto \Sigma^{3/2-N}$ or $\sigma_v/\epsilon \propto \Sigma^{2-N}$. To test these ideas in simulations, it is essential that the vertical structure of the disk be well resolved and that turbulence be incorporated self-consistently in the models, so that the disk thickness is appropriate for a given surface denisty. To test these ideas observationally, it is necessary to measure the thickness and/or vertical velocity dispersion of the star-forming gas layer.

5. Open Issues

While recent years have begun to see a change in the conception of the ISM, from a quasi-static equilibrium to a highly dynamic system, many issues on both the theoretical and observational side remain unresolved. For example, the consequence of the multi-scale nature of turbulence is still very much under investigation: small-scale turbulent velocities and magnetic fields tend discourage star formation by contributing to the effective pressure, while turbulent large-scale velocities encourage star formation by concentrating gas locally into dense clumps/cores that can rapidly collapse, and turbulent large-scale magnetic fields help in removing angular momentum and limiting the centrifugal support of contracting systems. The net result of opposite tendencies at different scales is still not understood, and indeed it is unclear whether there is a clean separation of scales. A related set of questions concerns whether and/or where star formation may be self-regulated, with velocity dispersions responding to the star formation rate and altering the phase state – and gravitational susceptibility – of the ISM. Over the next several years, we can expect continued progress in understanding these and other questions.

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