*The Role of Disk-Halo Interaction in Galaxy Evolution: Outflow vs Infall?*
*Editor*
*EAS Publications Series, Vol. ?, 2009*

# ARE THERE PHASES IN THE ISM?

Enrique Vázquez-Semadeni[1]

**Abstract.** The interstellar medium (ISM) is subject, on one hand, to heating and cooling processes that tend to segregate it into distinct phases due to thermal instability (TI), and on the other, to turbulence-driving mechanisms that tend to produce strong nonlinear fluctuations in all the thermodynamic variables. In this regime, large-scale turbulent compressions in the stable warm neutral medium (WNM) dominate the clump-formation process rather than the linear developent of TI. Cold clumps formed by this mechanism are still often bounded by sharp density and temperature discontinuities, which however are not contact discontinuities as in the classical 2-phase model, but rather "phase transition fronts", across which there is net mass and momentum flux from the WNM into the clumps. The clumps grow mainly by accretion through their boundaries, are in both thermal and ram pressure balance with their surroundings, and are internally turbulent as well, thus also having significant density fluctuations inside. The temperature and density of the cold and warm gas around the phase transition fronts fluctuate with time and location due to fluctuations in the turbulent pressure. Moreover, shock-compressed diffuse unstable gas can remain in the unstable regime for up to a few Myr before it undergoes a phase transition to the cold phase, and is furthermore constantly replenished by the turbulence. These processes populate the classically forbidden density and temperature ranges. Since gas at all temperatures appears to be present in bi- or tri-stable turbulence, we conclude that the word "phase" applies only locally, surrounding phase transition sites in the gas. Globally, the word "phase" must relax its meaning to simply denote a certain temperature or density range.

## 1 The standard multiphase models

The ISM is almost universally referred to as a "multiphase" medium, a notion first proposed by Pikel'ner (1968) and Field et al. (1969). These authors noted that,

[1] Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Campus Morelia, P.O. Box 3-72, Xangari, Morelia, Michoacán, 58089, México.


DOI: (will be inserted later)

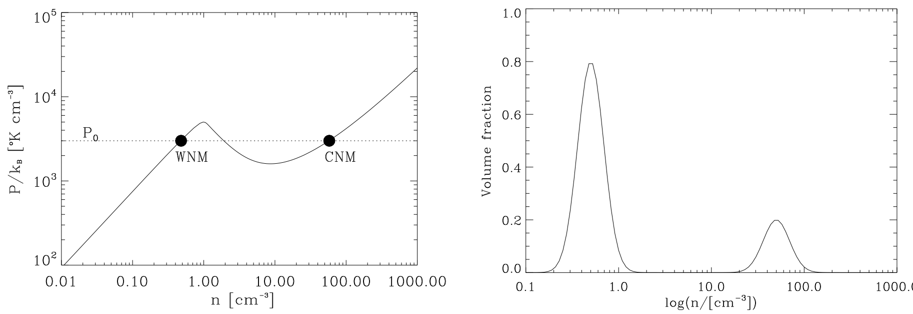


**Fig. 1.** *Left panel:* Thermal pressure corresponding to thermal equilibrium between heating and cooling for the atomic ISM. Figure from Vázquez-Semadeni et al. (2007), using the (errata-free) fit to the cooling function by Koyama & Inutsuka (2002). The horizontal dotted line indicates a mean pressure $P_0$ that allows the medium to spontaneously segregate into a diffuse, warm phase and a cold, dense one, indicated by the heavy dots. *Right panel:* Schematic illustration of the density probability density function (PDF) for the two-phase model. The vertical axis is in arbitrary, non-normalized units, and the relative amplitude of the peaks is meant to simply illustrate the fact that most of the volume is occupied by the WNM.

due to the net heating and cooling processes to which the ISM is subject, the thermal pressure $P_{\rm eq}$ corresponding to thermal balance between heating and cooling is a non-monotonic function of the density (fig. 1, *left panel*). As is well known, the negative-slope portion of this curve corresponds to a density range that is unstable under the isobaric mode of the thermal instability (TI; Field 1965). Thus, if the ambient pressure lies within the thermally unstable range, such as the pressure $P_0$ shown in Fig. 1 (*left panel*), the medium would tend to naturally segregate into two stable *phases*[1] at the same pressure, but very different densities and temperatures, indicated by the heavy dots in the figure, and which are commonly referred to as the warm and the cold neutral media (respectively, WNM and CNM). This is the well-known "two-phase" model of the ISM. In it, the final state of the instability would be a collection of cold, dense clumps (the CNM) immersed in a warm, diffuse intercloud medium (the WNM), in thermal and pressure equilibrium. The density contrast between the cold clumps and the WNM was expected to be $\sim 100$. The initial sizes of the cloudlets were expected to be small, and larger clouds were assumed to form by merging (coagulation) of smaller cloudlets (e.g., Oort 1954; Field & Saslaw 1965; Kwan 1979). In this scenario, the density and temperature probability density functions (PDFs, or histograms) of the atomic ISM would con-

[1] Thermodynamically, a *phase* is region of space throughout which all physical properties of a material are essentially uniform (e.g., Modell & Reid, 1974). A *phase transition* is a boundary that separates physically distinct phases, which differ in most thermodynamic variables except one (often the pressure).

sist of two Dirac delta functions at the values corresponding to the WNM and the CNM, perhaps braodened by moderate stochastic fluctuations in each phase (Fig. 1, *right panel*).

The two-phase model was later extended by McKee & Ostriker (1977) to include a third, hot phase, produced by supernova (SN) explosions, leading to the famous three-phase model of the ISM. Supernova remnants would start with large pressure excesses over the mean ISM thermal pressure and expand until their pressures equalized with the ambient ISM pressure.

The two- and three-phase models were thus based on the notions of simultaneous thermal balance between heating and cooling, and pressure balance between the phases. Under such conditions, the clumps would be bounded by contact discontinuities, since the pressure gradient between the clumps and the WNM is zero. Interestingly, however, this notion was maintained even in models in which the clumps were assumed to move ballistically through the WNM.

## 2 The controversy

The classical discrete-phase models discussed in the previous section, however, were not easy to reconcile with all observations. Dickey et al. (1977) already noted that the range of spin temperatures in HI gas is very broad, and in fact seemed to peak at temperatures $\sim 300$ K, which correspond to the classically forbidden unstable regime, $300 \lesssim T \lesssim 5000$ K. Since then, significant amounts of gas in this temperature range have been repeatedly found by various groups (e.g., Kalberla et al. 1985; Spitzer & Fitzpatrick 1995; Fitzpatrick & Spitzer 1997; Heiles 2001a; Kanekar et al. 2003), and moreover, a finer subdivision of the ISM "phases" has also been advocated on observational grounds (Heiles 2001b).

On the numerical side, fully dynamic numerical simulations of the turbulent ISM including parameterized heating and cooling, leading to a "soft" effective "equation of state" (EOS)[2] but no TI (Chiang & Bregman 1988; Rosen & Bregman 1995; Vázquez-Semadeni et al. 1995; Passot et al. 1995; Ballesteros-Paredes et al. 1999a, 1999b), suggested that TI might not be an indispensible channel to form cold, dense clouds in a diffuse, warm substrate, since such a configuration was readily obtained in models with a soft EOS, even if they were not thermally unstable.

[2] It can be shown that the condition of thermal balance (heating = cooling), together with the ideal-gas EOS, allows one to write an effective *polytropic* law for the gas of the form $P_{\rm eq} \propto \rho^{\gamma_{\rm e}}$, where $\gamma_{\rm e}$ is the *effective polytropic exponent* (e.g., Vázquez-Semadeni et al. 1995, 1996), and corresponds to the local slope of the curve in Fig. 1. A more detailed perturbation analysis shows that the actual value of $\gamma_{\rm e}$ lies in between the thermal balance value and the adiabatic value, depending on the ratio of the dynamical time to the cooling time (e.g., Elmegreen 1991; Passot et al. 1995). An isothermal flow corresponds to $\gamma_{\rm e} = 1$, while the isobaric mode of TI corresponds to $\gamma_{\rm e} < 0$. Here, we adopt the convention that a "soft" EOS refers to $\gamma_{\rm e} < 1$. The gas is more compressible at smaller $\gamma_{\rm e}$, and in fact, as $\gamma_{\rm e} \Rightarrow 0$, the density jump due to a shock of Mach number $M_{\rm s}$ approaches $e^{M_{\rm s}^2}$ (Vázquez-Semadeni et al. 1996), exemplifying the large compressibility of such regimes.

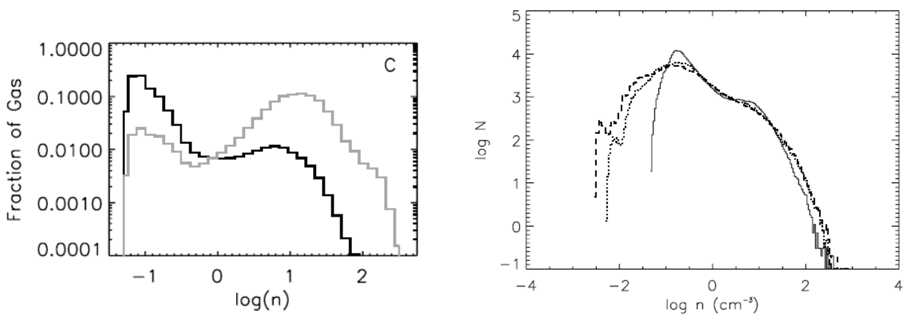


**Fig. 2.** *Left panel* Volume-weighted (*black line*) and mass-weighted (*grey line*) density PDFs from a 3D numerical simulation at $128^3$ resolution of the turbulent atomic ISM driven by the magnetorotational instability, with a three-dimensional velocity dispersion $\sim 2.7$ km s$^{-1}$ (from Piontek & Ostriker 2005). *Right panel:* Density PDFs of three 2D simulations with 2D velocity dispersions $\sim 4.0$ km s$^{-1}$ (*solid line*), $\sim 9.1$ km s$^{-1}$ (*dotted line*), and $\sim 11.4$ km s$^{-1}$ (*dashed line*) (from Gazol et al. 2005).

Moreover, numerical simulations at low resolution including TI (Vázquez-Semadeni et al. 2000), suggested that turbulent mixing could smear the density PDF of the medium, partially or completely erasing the multimodal signature of TI. A follow-up numerical study at higher resolution (Gazol et al. 2001) showed that the temperature PDF, although still bimodal, exhibited sizable amounts of gas mass (up to $\sim 50\%$) in the unstable range between the CNM and the WNM, in good agreement with observational estimates (e.g., Heiles 2001a; Heiles & Troland 2003). More recent numerical models at high resolution confirm these results (e.g., de Avillez & Breitschwerdt 2005; Hennebelle & Audit 2007). These results all seemed to point towards a continuum picture of the ISM (admittedly with large fluctuations in density and temperature), rather than towards a medium composed of various discrete phases. In fact, in an earlier study, Norman & Ferrara (1996), based on an analysis of the multiple scales at which turbulent energy is injected into the ISM, went as far as proposing to extend the notion of a multi-phase ISM to that of a "phase continuum". But this proposal defies the very notion of well-differentiated, nearly uniform *thermodynamic phases*.

However, other numerical studies have advocated precisely the opposite, i.e., that the two-phase model in particular continues to be applicable for the turbulent atomic medium. For example, Piontek & Ostriker (2005) have found that, in three-dimensional (3D) low-resolution ($256^3$) simulations of the atomic ISM driven by the magnetorotational instability (MRI), even the most turbulent cases maintained the bimodal shape of the density and temperature PDFs characteristic of the two-phase model (fig. 2, *left frame*), while Audit & Hennebelle (2005) and Hennebelle & Audit (2007) have pointed out that, in two-dimensional (2D) simulations at very high resolution (up to $10000^2$ grid points) of colliding flows in the WNM, the classical two-phase picture still aplies in the sense that the resulting CNM clouds and the WNM are still separated by stiff thermal fronts, and the two media are in local pressure equilibrium.

## 3 The hybrid regime of thermally bistable turbulence

The apparent controversy probably arises from the fact that the regime of thermally bistable turbulence in the atomic ISM contains features of both the classical, thermal- and pressure-balance two-phase regime, and of a turbulent continuum, and in varying proportions depending on the strength of the turbulence. In this section we first discuss the hybrid nature of this medium, and then we extend the discussion to the full range of interstellar densities and temperatures.

### *3.1 Multimodality of the density and temperature PDFs*

Some of the most widely used statistical indicators of of compressible turbulent flows are the PDFs of the density, temperature, and thermal pressure. The transition from a discrete-phase PDF for a static, pressure-balance two-phase model, such as that shown in Fig. 1 (*right panel*) to a unimodal PDF, such as that for a single-phase polytropic flow (e.g., Scalo et al. 1998; Passot & Vázquez-Semadeni 1998; Nordlund & Padoan 1999) appears to be continuous, rather than abrupt. For example, Figure 2 (*right panel*) shows density PDFs from three simulations by Gazol et al. (2005) with increasing velocity dispersion. As the latter increases, the bimodality of the PDF is seen to become less pronounced. This indicates the increasing levels of turbulent mixing, which increasingly counteract the segregation of the medium into two discrete phases.

The maintenance of a sizeable fraction of the gas mass in the thermally unstable regime can be understood in terms of a competition between the mixing and the cooling tendencies of the gas (see, e.g., the discussions by Wolfire et al. 2003; Vázquez-Semadeni et al. 2003; Gazol et al. 2005). A compressive turbulent velocity fluctuation is characterized by its crossing time, $\tau_{\rm turb}(L) \equiv L/v(L)$, where $L$ is the size scale of the turbulent motions, and $v(L)$ is the turbulent velocity difference between points separated by a distance $L$. If this time is shorter than the cooling time of the gas, given by $\tau_{\rm c} \approx c_V T/n\Lambda$, where $c_V$ is the specific heat at constant volume, $n$ is the number density, and $\Lambda$ is the cooling rate, the gas tends to respond adiabatically to the compression, and is therefore thrown out of thermal equilibrium between heating and cooling, becoming nonlinearly unstable (Koyama & Inutsuka 2000; Kritsuk & Norman 2002a). Moreover, vortical modes of the turbulence tend to mix the gas also in the turbulent crossing time, fighting condensation.

The cooling time depends only on the local gas conditions, while the turbulent crossing time is scale-dependent, typically following a scaling law $v(L) \sim L^\alpha$, where $\alpha \sim 1/3 - 1/2$, the former value being appropriate for incompressible (Kolmogorov, 1941) turbulence, and the latter being appropriate for highly compressible, Burgers-type (Burgers 1948) turbulence. Such a scaling implies that the velocity dispersion is supersonic at large scales, and subsonic at small scales, the two regimes being separated by the so-called *sonic scale*, $\lambda_s$. Based on observationally reported values of the global velocity dispersion, and on estimates of the scales corresponding to these values, Wolfire et al. (2003) estimated $\lambda_s \sim 200$ pc for the WNM. For this scale, they estimated a ratio of the characteristic times $\Upsilon \equiv (\tau_c/\tau_{\rm turb})_{\lambda=\lambda_s} \sim 1$ for the WNM, suggesting that for this medium, a sizeable fraction of unstable gas should exist, in agreement with numerical simulations with similar parameters (Gazol et al. 2005; fig. 2, *right panel, dotted line*).

In general, it is then natural to expect that the fraction of gas in the thermally unstable regime should increase for decreasing $\upsilon$ (i.e., higher turbulent rms Mach number), as indeed observed through numerical simulations. This causes the density and temperature PDFs of thermally bistable turbulence to transit smoothly from the stricly bimodal shape characteristic of the two-phase model to a unimodal shape, characteristic of a turbulent "phase continuum" (fig. 2, *right panel*).

The above discussion can be extended to the three-phase model. Numerical models of the ISM including SN driving of the turbulence (de Avillez & Breitschwerdt 2005), which include hot gas at temperatures up to $T \sim 10^8$ K, exhibit density and temperature PDFs in which the multi-modality is still present, albeit very mildly in the hydrodynamical case, and barely noticeable in the MHD case. Figure 3 shows the corresponding PDFs for the MHD case, where it can be seen that the density PDF (*left panel*) contains two very subtle peaks at the densities of the "hot" and the "warm" phases (at $n \sim 10^{-2.5}$ cm$^{-3}$ and $n \sim 10^{-1}$ cm$^{-3}$, respectively). The signature of the "cold phase" is barely noticeable as a kink at $n \sim 10^2$ cm$^{-3}$. The temperature PDF (*right panel*) has lost all signatures of multimodality, and only a relatively flat shape from $T \sim 10^2$ K to $T \sim 10^7$ K remains, being indicative that the medium can exist at roughly constant thermal pressure throughout this temperature range.

We conclude that in these SN-driven simulations, the density and temperature PDFs are nearly flat over a wide range, and the multimodal signature of truly distinct thermodynamic phases has been nearly lost, with the unstable regimes being as populated as the stable ones. In this case, the usage of the term "multiphase" must be understood to mean "multi-temperature", and the term "phase" to simply mean a range of temperatures or densities.

### *3.2 Clump structure in thermally bistable turbulence*

In view of the fact that the temperature PDFs of the turbulent ISM become populated in the unstable ranges, the finding of Audit & Hennebelle (2005) that sharp discontinuities and thermal pressure balance continue to hold at the boundaries of clumps is particularly intriguing, and we now turn to how these two features can be reconciled.

A key issue in this problem is the fact that in a supersonically turbulent medium, the compressive part of the velocity field works to produce density enhancements (the "clumps"; von Weizsäcker 1951; Sasao 1973; Elmegreen 1993; Ballesteros-Paredes et al. 1999a). Moreover, moderate (transonic) turbulent com-

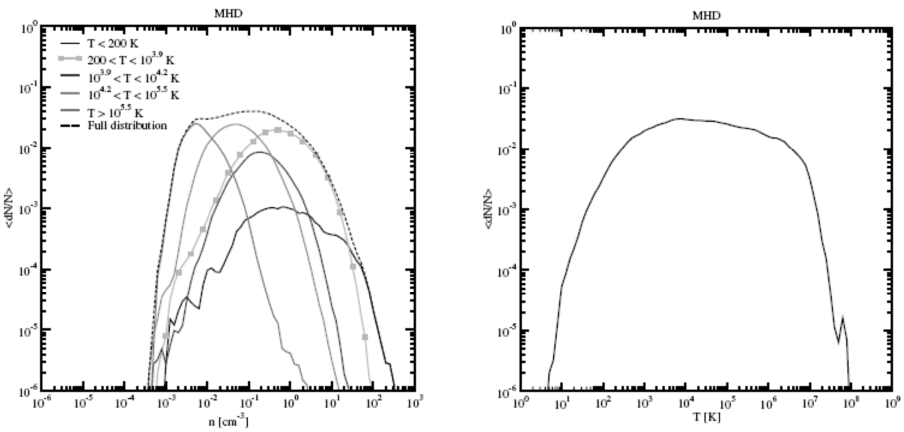


**Fig. 3.** Density (*left panel*) and temperature (*right panel*) PDFs from numerical simulations of the SN-driven turbulent ISM by de Avillez & Breitschwerdt (2005). The density PDF shows a barely noticeable multimodality, with subtle peaks at the "hot-phase" ($n \sim 10^{-2.5}$ cm$^{-3}$) and "warm-phase" ($n \sim 10^{-1}$ cm$^{-3}$) densities. The signature of the "cold phase" is barely noticeable as a kink at $n \sim 10^2$ cm$^{-3}$. The temperature PDF has lost all signatures of multimodality.

pressions in the WNM (which is close to the thermally unstable range) can nonlinearly trigger the development of TI (Hennebelle & Pérault 1999; Koyama & Inutsuka 2000, 2002), and thus produce density enhancements of factors $\sim 100\times$ above the WNM's mean density through compressions that would only cause density enhancements of just a factor of a few in an isothermal flow.

This process has been quantified by Vázquez-Semadeni et al. (2006), who presented analytical solutions of the plane-parallel problem of a WNM flow colliding against a wall (which represents the opposite colliding stream) at transonic velocities, finding the physical conditions in the resulting compressed layer of CNM as a function of the sonic Mach number of the inflow. In this problem, an outer, outwardly-traveling shock is formed, immediately behind which the (still warm) medium has been heated and pressurized, and thus thrown away from cooling-heating balance. Approximately one cooling time downstream from the shock (fig. 4, *left panel*), the medium begins to be able to cool, and eventually undergoes a *sudden* phase transition to the CNM. This occurs at a "phase transition", or "condensation" front, which constitutes the boundary of the dense cloud.

The main distinction between this process and the classical two-phase model is twofold. First, there exists a continuous flux of mass across the boundary, and thus the cloud is "confined" by the sum of the thermal and ram pressures of the WNM inflow. We have placed quotes around the word "confined" because the cloud is growing as it accretes mass from, and is changing shape and sometimes being dispersed by, the turbulent WNM surrounding it, rather than being truly confined in place. Second, since the WNM has been heated by the shock, the process is equivalent to one with a higher heating rate than the pure background due to photoelectric heating from the diffuse UV background, an effect whose net result is to shift the equilibrium pressure-density curve to higher values of both variables (see, e.g., fig. 7 of Wolfire et al. 1995). In a turbulent medium, in which there is a distribution of shock strengths (e.g., Smith et al. 2000a,b), the equilibrium values of the density and temperature of the WNM and CNM vary from one location to another, thus populating classically forbidden density and temperature ranges in the PDFs, while locally maintaining the two-phase structure (Audit & Hennebelle 2005; Hennebelle & Audit 2007).

A recent study by Banerjee et al. (2009) has focused on the clump structure within this framework, using the adaptive-mesh refinement code FLASH (Fryxell et al. 2000) to simulate the formation of dense clouds from transonic compressive motions in the WNM. The study includes self-gravity and a weak (supercritical) magnetic field. They have found that the clumps are indeed formed dynamically by the turbulent compressions, being the densest regions in a network of sheets and filaments. Figure 4 (*right panel*) shows a cross section of the central 8 parsecs of a simulation having a full extent of 256 pc, and a mean field $\langle B \rangle = 1\ \mu$G permpendicular to the image. The density field is seen to exhibit sharp jumps of up to factos of $\sim 100\times$, although a significant fraction of the volume surrounding the clump is in the classically unstable regime (colored *green* and *light blue*). In addition, the central parts of the clump are seen to reach densities of up to $n \sim 3000$ cm$^{-3}$. This is $\sim 8$ times larger than the thermal equilibrium density,[3] suggesting that turbulent motions within the clump must be responsible for the additional density enhancement by a factor of $\sim 8$.

The clumps in this regime are thus seen to exhibit features of both turbulence-induced clumps, such as a centrally-peaked density profile, amorphous shapes, and a turbulent internal velocity field, which induces significant density fluctuations, while they retain features of the two-phase model, such as sharp discontinuities at their boundaries. These boundaries, however, are not contact discontinuities, which by definition do not involve any mass flux across them, but rather phase transition fronts, across which mass continually flows in from the WNM, leading them to grow in mass and size, possibly being able to eventually render them gravitationally unstable. The clumps are not truly confined, since they move around, form part of larger filaments and sheets, and grow in mass and size, being part of the global turbulent flow, although they can be at much higher densities by virtue of the thermal bistability of the flow.

Finally, it is worth noting that the simulations of Banerjee et al. (2009) employed a very mildly supersonic inflow speed. It is quite likely that higher inflow

[3] The simulation has a mean density of 1 cm$^{-3}$, uses a cooling curve leading to the $P_{\rm eq} - n$ curve shown in Fig. 1 (*left panel*) and starts with colliding streams that have a Mach number (with respect to the WNM) of 1.22. With the applied cooling curve, the temperatures of the warm and cold gas are respectively $\sim 3000$ K and $\sim 20$ K. Thus, the implied pressure-balance density of the cold gas, including the ram pressure of the inflows, is $n \sim 375$ cm$^{-3}$.

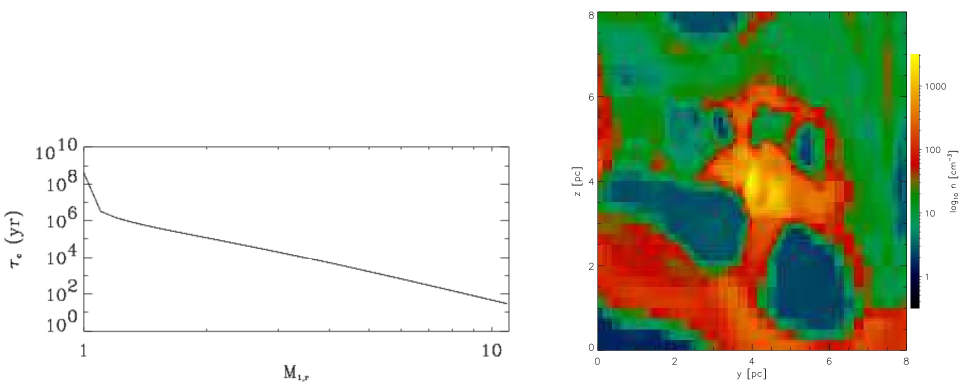


**Fig. 4.** *Left panel:* Cooling time $\tau_c$ for WNM gas after having been shocked and compressed, as a function of the Mach number of the compression (from Vázquez-Semadeni et al. 2006). After approximately $1\tau_c$, the shocked WNM undergoes a phase transition to the cold phase. *Right panel:*Density cross section of a the central 8 parsecs of a simulation by Banerjee et al. (2009). The full extent of the numerical box is 256 pc.

speeds may lead to a blurring of the sharp clump boundaries.

## 4 Discussion and conclusions

So, are there phases in the turbulent ISM, then? The answer appears to be more complicated than a simple "yes" or "no". At present, numerical and analytic work suggests that, locally, yes, there exist clearly defined *thermodynamic* cold and warm phases at each side of a phase transition front but, because of the turbulent fluctuations in the pressure and the heating rate, the densities and temperatures of these *locally stable* phases differ in general from one location to another, and moreover vary in time as the local ram pressure varies, causing a constant flux of gas among the phases, similarly to the effect of a temporal variation of the background UV radiation field (Kritsuk & Norman 2002b). Moreover, shocks traversing the warm neutral gas leave it in an *unstable* regime, from which it cools down to CNM conditions in roughly one cooling time, which may amount to up to a few Myr, depending on the strength of the shock (fig. 4, *left panel*). These processes populate the entire range of values of density and temperature between those of the classical cold and warm phases, creating a continuous distribution. Although the details of the corresponding gap between the classical warm and hot phases have not been investigated in the case of a SN-driven turbulent ISM, it is conceivable that similar phenomena occur, since the density and temperature PDFs in simulations of this medium are equally densely populated. In this situation, no clear dividing line exists between the hot, warm and cold gas, and the word phase is best understood as a range of density and temperature values, while the true, distinct thermodynamic phases continue to exist locally as a consequence of the accelerating nature of the cooling in thermally unstable gas as it becomes denser, causing *sudden transitions* to the cold phase.

Much work remains to be done in this field. In particular, studies of the local structure of the gas similar to those that have been performed for the atomic (warm and cold) ISM, are now necessary in the context of the SN-driven ISM, in order to assess the nature of the transition gas between the classical warm and hot phases.

The author is glad to acknowledge vivid and fruitful discussions with Patrick Hennebelle over several years, and thanks him for a critical reading of this manuscript. This research has been funded in part by CONACYT grant U47366-F.

## References

Audit, E. & Hennebelle, P. 2004, A&A 433, 1

Ballesteros-Paredes, J., Hartmann, L. & Vázquez-Semadeni, E. 1999b, ApJ 527, 285

Ballesteros-Paredes, J., Vázquez-Semadeni, E., & Scalo, J. 1999a, ApJ, 515, 286

Banerjee, R., Vázquez-Semadeni, E., Hennebelle, P. & Klessen, R.S. 2009, MNRAS, submitted (arXiv:0808.0986)

Burgers,, J.M. 1948, Adv. in Appl. Mech. 1, 171

Chiang, W.-H., & Bregman, J.N. 1988, ApJ, 328, 427

de Avillez, M. A., & Breitschwerdt, D. 2005, A&A, 436, 585

Dickey, J.M., Salpeter, E.E., & Terzian, Y. 1977, ApJ, 211, L77

Elmegreen, B.G. 1991, in The Physics of Star Formation and Early Stellar Evolution, ed. C.J. Lada and N.D. Kylafis (Dordrecht:Kluwer), 35

Elmegreen, B. G. 1993, ApJ 419, L29

Field, G. B., 1965, ApJ 142, 531

Field, G. B., Goldsmith, D. W., & Habing, H. J. 1969, ApJ, 155, L149

Field, G.B. & Saslaw, W.C. 1965, ApJ, 142, 568

Fitzpatrick, E. L. & Spitzer, L. 1997, ApJ, 475, 623

Fryxell B., Olson K., Ricker P., Timmes F. X., Zingale M., Lamb D. Q., MacNeice P., Rosner R., Truran J. W., Tufo H., 2000, ApJS, 131, 273

Gazol, A., Vázquez-Semadeni, E., Sánchez-Salcedo, F. J.& Scalo, J. M. 2001, ApJ, 557, 121

Gazol, A., Vázquez-Semadeni, E. & Kim, J. 2005, ApJ, 630, 911

Heiles, C. 2001, ApJ, 551, L105

Heiles, C. 2001, in Galactic Structure, Stars and the Interstellar Medium, ASP Conference Series, Vol. 231, ed. C. E. Woodward, M. D. Bicay, and J. M. Shull (San Francisco: Astronomical Society of the Pacific), 294

Heiles, C. & Troland, T. 2003, ApJ, 586, 1067

Hennebelle, P., & Pérault, M. 1999, A&A, 351, 309

Hennebelle, P., & Audit, A&A, 465, 431

Kalberla, P. M. W., Schwarz, U. J., Goss, W. M. 1985, A&A, 144, 27

Kanekar, N., Subrahmanyan, R., Chengalur, J. N., & Safouris, V. 2003, MNRAS, 346, L57

Koyama, H. & Inutsuka, S.-I. 2000, ApJ, 532, 980

Koyama, H. & Inutsuka, S.-I. 2002, ApJ, 564, L97

Kritsuk,, A., & Norman, M.L. 2002a, ApJ, 569, L127

Kritsuk,, A., & Norman, M.L. 2002b, ApJ, 580, L51

Kwan, J. 1979, ApJ, 229, 567

McKee, C.F. & Ostriker, J.P. 1977, ApJ, 218, 148

Modell, M., & Reid, R.C. 1974, Thermodynamics and Its Applications (Englewood Cliffs, NJ: Prentice-Hall)

Nordlund, Å., & Padoan, P. 1999, in Interstellar Turbulence, eds. J. Franco and A. Carramiñana (Cambridge: Cambridge University Press), p. 218

Norman, C.A. & Ferrara, A. 1996, ApJ, 467, 280

Oort, J.H. 1954, Bull. Astr. Inst. Netherlands, 12, 177, no. 455

Passot, T., Vázquez-Semadeni, E. & Pouquet, A. 1995, ApJ, 455, 536

Passot, T., & Vazquez-Semadeni, E. 1998, Phys. Rev. E 1999, 58, 4501

Pikel'ner, S.B. 1968, Sov. Astron. 11, 737

Piontek, R.A. & Ostriker, E.C. 2005, ApJ, 629, 849

Rosen, A. & Bregman, J.N. 1995, ApJ 440, 634

Sánchez-Salcedo, F. J., Vázquez-Semadeni, E., & Gazol, A. 2002, ApJ, 577, 768

Sasao, T. 1973, PASJ, 25, 1

Scalo, J., Vázquez-Semadeni, E., Chappell, D., & Passot, T. 1998, ApJ, 504, 835

Smith, M.D., Mac Low, M.-M., & Zuev, J.M. 2000a, A&A, 356, 287

Smith, M.D., Mac Low, M.-M., & Heitsch, F. 2000b, A&A, 362, 333

Spitzer, L. & Fitzpatrick E. L. 1995, ApJ, 445, 196

Vázquez-Semadeni, E., Gazol, A., Sánchez-Salcedo, F. J., and Passot, T. 2003, in Turbulence and Magnetic Fields in Astrophysics, ed. T. Passot & E. Falgarone, Lecture Notes in Physics, 614, 213

Vázquez-Semadeni, E., Gazol, A., & Scalo, J. 2000, ApJ, 540, 271

Vázquez-Semadeni, E., Gómez, G. C., Jappsen, A. K., Ballesteros-Paredes, J., González, R. F., & Klessen, R. S. 2007, ApJ, 657, 870

Vázquez-Semadeni E., Passot T., & Pouquet A., 1995, ApJ, 441, 702

Vázquez-Semadeni E., Passot T., & Pouquet A., 1996, ApJ, 473, 881

Vázquez-Semadeni, E., Ryu, D., Passot, T., González, R. F., & Gazol, A., 2006, ApJ, 643, 245

von Weizsäcker, C.F. 1951, ApJ, 114, 165

Wolfire, M.G.,Hollenbach, D., McKee, C.F., Tielens, A.G.G.M., Bakes, E.L.O. 1995, ApJ, 443, 152

Wolfire, M.G., McKee, C.F., Hollenbach, D., & Tielens, A.G.G.M. 2003, 587, 278