Triggered Star Formation in a Turbulent ISM
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Dynamical evolution of a supernova driven turbulent interstellar medium

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Abstract. It is shown that a number of key observations of the Galactic ISM can be understood, if it is treated as a highly compressible and turbulent medium, energized predominantly by supernova explosions (and stellar winds). We have performed extensive numerical high resolution 3D hydrodynamical and magnetohydrodynamical simulations with adaptive mesh refinement over sufficiently long time scales to erase memory effects of the initial setup. Our results show, in good agreement with observations, that (i) volume filling factors of the hot medium are modest (typically below 20%), (ii) global pressure is far from uniform due to supersonic (and to some extent super-Alfvénic) turbulence, (iii) a significant fraction of the mass ($\sim 60\%$) in the warm neutral medium is in the thermally unstable regime ($500 < T < 5000$ K), (iv) the average number density of Ovi in absorption is $1.81 \times 10^{-8}\,\mathrm{cm}^{-3}$, in excellent agreement with Copernicus and FUSE data, and its distribution is rather clumpy, consistent with its measured dispersion with distance.

Keywords. ISM: general, ISM: evolution, ISM: structure,ISM: magnetic fields, hydrodynamics, MHD, turbulence

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1. Introduction

Low resolution observations of the interstellar medium (ISM) at various wavelengths reveal a rather smooth spatial distribution of the gas and magnetic fields, and distinctive gas phases can be discerned. Theoretical studies during the last three decades have culminated in a widely accepted multiphase "standard model" (e.g. McKee & Ostriker 1977 (MO-model), McKee 1990), in which the gas is distributed into three phases in global pressure equilibrium, a cold and warm neutral phase (CNM and WNM, respectively), a warm ionized (WIM) and a hot intercloud (HIM) medium. There is global mass balance by evaporation and condensation, and energy balance between supernova (SN) energy injection and radiative cooling. One of its testable predictions is a large volume filling factor of the HIM ($f_h \geqslant 0.5$) for the Galaxy. Observations, however, also in external galaxies ($f_h \sim 0.1$, e.g. Brinks & Bajaja 1986), point to much lower values. This discrepancy can be removed if one allows for a fountain flow due to the break-out of superbubbles into the galactic halo (so-called chimney model, Norman & Ikeuchi 1989) as well as buoyant outflow from supernova remnants (SNRs). Ovi absorption line column densities, which were pivotal in establishing the HIM in the first place, are thought to arise in conductive interfaces, yielding systematically too large values by an order of magnitude, when compared to Copernicus observations (Jenkins & Meloy 1974). Furthermore, Jenkins & Tripp (2006, these proceedings) have measured Ci absorption lines towards a sample of ~ 100 stars from the HST archive and find a large variation in the CNM pressure of $500 < P/k_B < 4000\,\mathrm{cm}^{-3}\,\mathrm{K}$, in contrast to what is expected from a model where pressure equilibrium is a key element. Although turbulence is recognized to play an important role in steady-state multiphase models, it is largely treated as an additional pressure source, ignoring its *dynamical* importance.

A fundamentally different and more physical approach to model the structure and evolution of the ISM goes back to the ideas of von Weizsäcker (1951) who suggested that the ISM is essentially a highly turbulent and compressible medium. Indeed, high resolution observations of the ISM show structures on *all scales* down to the smallest resolvable ones, implying a dynamical coupling over a wide range of scales, which is a main characteristic of a turbulent flow with Reynolds numbers of the order of $10^5 - 10^7$ (cf. Elmegreen & Scalo 2004). Another characteristic of widespread ISM turbulence is its enhanced mixing of fluid elements, which, unlike thermal conduction, is largely independent of strong temperature gradients and magnetic fields. Recently, the dynamical importance of turbulence in the ISM and in star formation in molecular clouds has been recognized by several groups using different numerical approaches (e.g. Korpi *et al.* 1999, Vázquez-Semadeni *et al.* 2000, Avillez & Breitschwerdt 2004).

Physically the generation of 3D turbulence is intimately related to vortex stretching and its subsequent enhancement, in contrast to 2D where vorticity is conserved. A natural way to generate vorticity is shear flow in which transverse momentum is exchanged between neighbouring fluid elements. This typically occurs when a flow is decelerated at a surface (giving rise to a boundary layer) like wind gushing down a stre*et al.*ng the wall of a high building, or in case of the ISM, colliding gas flows, like e.g hot gas breaking out of an SNR or superbubble (SB). Various sources of turbulence for the ISM have been identified: stellar (jets, winds, HII regions, SN explosions), galactic rotation, self-gravity, fluid instabilities (e.g. Rayleigh-Taylor, Kelvin-Helmholtz), thermal instability, MHD waves (e.g. due to cosmic ray streaming instability), with SNe representing energetically the most importance source (see e.g. MacLow & Klessen 2004).

We will show in the following sections that the new approach of a turbulent SN driven ISM can reproduce many key observations (Avillez 2000, Avillez & Breitschwerdt 2004, 2005a,b, henceforth AB04, AB05a, AB05b), such as a low volume filling factor of the HIM, large pressure fluctuations in the ISM, observed OVI absorption column densities by Copernicus and FUSE, and WNM gas in thermally unstable temperature ranges.

2. Model setup

We have performed both hydrodynamical (HD) and magnetohydrodynamical (MHD, with a total field of 4.5 μG, with the mean and random components of $B_u = 3.1$ and $\delta B = 3.2$ μG, respectively) simulations to study by adaptive mesh refinement simulations the global and local evolution of the SN driven ISM. We use a grid centred at the solar circle with a square disk area of 1 kpc^2 and extending from $z = -10$ to $+10$ kpc in the directions perpendicular to the Galactic midplane. The finest resolution is 1.25 pc (MHD) and 0.625 (HD), respectively. Gravity is provided by the stars in the disk, radiative equilibrium cooling assuming solar and also 2/3 solar abundances (hence, log (O/H)=-3.07 (Anders & Grevesse 1989) and -3.46 (Meyer 2001), respectively), uniform heating due to starlight varying with z (cf. Wolfire *et al.* 1995) and a magnetic field (setup at time zero assuming equipartition) for the case of MHD runs. SNe types Ia and Ib+c+II are the sources of mass, momentum and energy. SNe Ia are randomly distributed, while the other SNe have their high mass progenitors generated in a self-consistent way according to the mass distribution in the simulated disk (with roughly 60% exploding in associations) and are followed kinematically according to the velocity dispersion of their progenitors. In these runs we do not consider heat conduction, as turbulence provides the dominant mixing process. For setup and simulation details see AB04 and AB05a.

Table 1. Average volume filling factors of the different ISM phases for variable SN rate σ (in units of the Galactic rate). The average was calculated using 101 snapshots (of the 1.25 resolution runs) between 300 and 400 Myr of system evolution with a time interval of 1 Myr.

σ^a	$\langle f_{v,cold}\rangle^b$	$\langle f_{v,cool}\rangle^c$	$\langle f_{v,warm}\rangle^d$	$\langle f_{v,hot}\rangle^e$
1	0.171	0.354	0.298	0.178
2	0.108	0.342	0.328	0.223
4	0.044	0.302	0.381	0.275
8	0.005	0.115	0.526	0.354
16	0.000	0.015	0.549	0.436

[a] SN rate in units of the Galactic SN rate.
[b] $T < 10^3$ K, [c] $10^3 < T \leqslant 10^4$ K, [d] $10^4 < T \leqslant 10^{5.5}$ K, [e] $T > 10^{5.5}$ K.

3. Results

In the following we focus on those results of our simulations, which show a clear deviation from the aforementioned standard picture of the ISM. It is important to emphasize that the computational box has to be sufficiently large in order to avoid significant mass loss, and that the evolution time is long enough (400 Myr in our runs) in order to be insensitive of the (necessarily artificial) initial setup and to attain global dynamical equilibrium. In addition we have checked that the results are resolution independent by doubling the resolution and found that changes are less than a few percent.

3.1. *Volume filling factors*

A first striking feature of global ISM simulations in a SN driven ISM is the *continuous* distribution of the plasma over temperature, rather than in distinct phases (for a discussion see below). We have therefore specified temperature regimes that correspond to the classical phases as well as to thermally unstable regimes. The second striking feature is the low volume filling factor of the HIM (see Table 1). This is a result of the unavoidable setup of the Galactic fountain, as the overpressured flow always chooses the path of least resistance. Even for a star formation rate, which is 16 times the Galactic value, the HIM covers less than 50% of the disk volume. It should be stressed that this result is fairly robust and does not depend strongly on the magnetic field as our MHD runs show. Even an initially disk parallel field cannot prevent break-out, as in 3D it is easier to push field lines aside than working against tension forces all the way up into the halo as it is in 2D.

3.2. *The myth of pressure equilibrium*

It has been often argued that there should exist global pressure equilibrium between the various stable phases. This hypothesis would be correct, if there would be sufficient time for relaxation for the various processes responsible for mass and energy exchange like collisional heating, radiative cooling, condensation and evaporation etc.. However, due to the large Reynolds number of the flow, turbulent mixing is the dominant exchange process, and a fortiori this occurs supersonically in a compressible medium. Hence there is in general not enough time to establish pressure equilibrium by pressure waves propagating back and forth. There exists though a global *dynamical* equilibrium, depending on the boundary conditions (e.g. SN rate, gravitational and external radiation field), which results in an “average pressure”, however with huge fluctuations as can be seen in Fig. 1. The fact that the dynamical evolution of the ISM is indeed governed by turbulence may be appreciated by noting that in Fig. 1 structures occur on *all scales*. This may on the other hand cast some doubt on the results, as surely structures will occur below the resolution limit. As our resolution checks have shown, this does not seem to be an issue here,

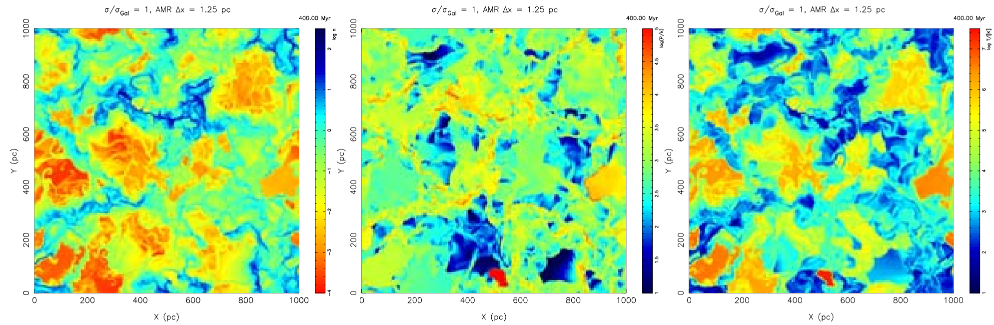

Figure 1. Two dimensional cuts, through the 3D data cube, showing the density n (left panel), the pressure P/k (middle panel) and the temperature T (right panel) distribution in the Galactic plane for an HD simulation with the Galactic SN rate.

since the processes we describe here either dominate on larger scales or do not exhibit any significant energy feedback from smaller to larger scales (as might actually be the case in strong MHD turbulence).

3.3. *Does some interstellar gas reside in thermally unstable phases?*

HI Arecibo Survey observations by Heiles & Troland (2003) have shown that about 48% of the WNM can be found in the thermally unstable regime between 500 K and 5000 K, and that CNM linewidths are in agreement with supersonic turbulent motions in sheetlike (aspect ratios of up to 280) clouds. Taken at face value this strongly supports a picture in which clouds are immersed in a turbulent medium and are deformed by vortex stretching as well as by shock compression. Our simulations show that ISM turbulence can drive and sustain turbulence inside clouds, which is alleviated to some extent by the fractal structure of clouds, resulting e.g. from colliding gas flows (cf. Burkert 2006). Fig. 2 (left)

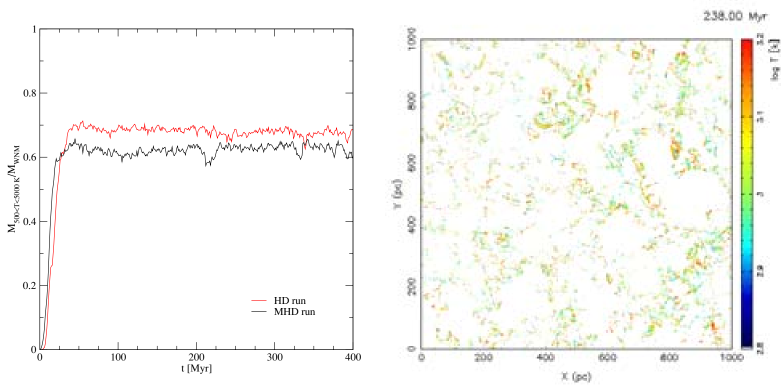

Figure 2. *Left panel:* History of the fraction of mass of the classical thermally unstable gas having $500 < T \leqslant 5000$ K in the disk for the HD (red) and MHD (black) runs. *Right panel:* 2D snapshot of the Galactic plane taken from run HD2a ($\Delta x = 0.625$ pc) at time 238 Myr. The image shows the filamentary structure of the warm neutral gas with $2.8 \leqslant T \leqslant 3.2$ K.

shows the fraction of the WNM derived from our HD and MHD runs in the temperature range between 500 and 5000 K, and the right panel of Fig. 2 demonstrates its filamentary distribution in the narrow band between 630 and 1590 K. The large amount of ISM mass seen in thermally unstable regimes is a direct consequence of SN driven turbulence. Thus, the Field (1965) criterion is necessary, but not sufficient for distributing the ISM

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gas into stable phases over different temperature ranges. It is essential to realize that turbulence has a stabilizing effect by inhibiting local condensation modes. The reason is that turbulence can be regarded as a diffusion process by which energy is efficiently transferred from large to small scales, thus preventing thermal runaway on scales smaller than the minimal length scale over which thermal instability can overcome turbulent diffusion (note the small scale patchy distribution in Fig. 2 (right)), in much the same way as heat conduction stabilizes the solar chromosphere.

3.4. *Comparison of O*VI *distribution to Copernicus and FUSE data*

The discovery of the widespread OVI absorption line toward background sources led to the discovery of the HIM (e.g. York 1974, Jenkins & Meloy 1974) and identified SNRs as a major source of hot gas. Ever since, starting with the "tunnel network model" of Cox & Smith (1974), to reproduce the observed OVI column densities, N(OVI), has been a touchstone of ISM modeling. In collisional ionization equilibrium OVI is the most abundant ionization stage at $T \sim 3 \times 10^5$ K, a temperature which is typical for transition regions between HIM and cooler gas, like e.g. in conductive interfaces. In the MO model these occur in large numbers between the HIM and embedded clouds and lead to an n(OVI) number density about an order of magnitude larger than the average value of $1.7 \times 10^{-8}\,\mathrm{cm}^{-3}$. On the other hand our simulations show, that if turbulent mixing is

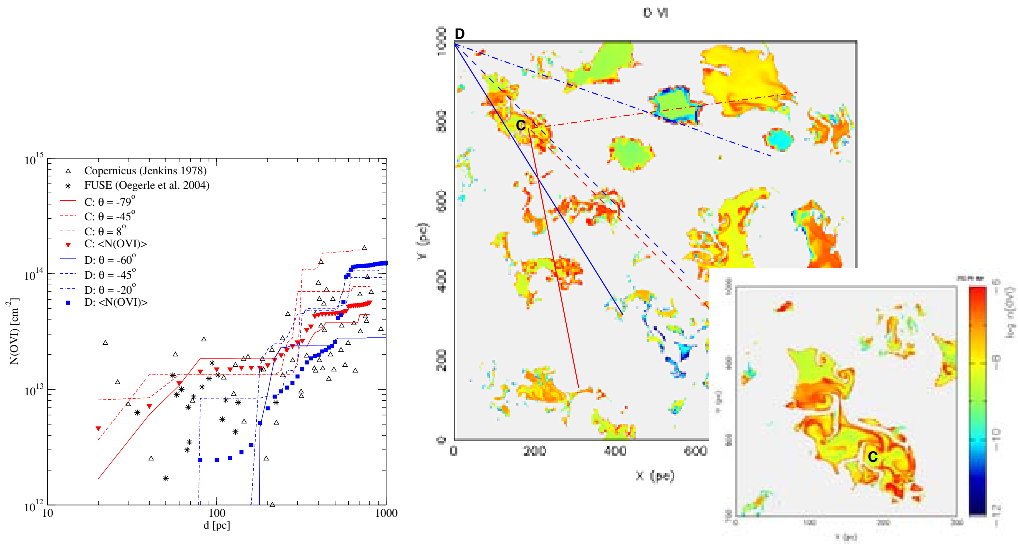

Figure 3. *Left panel:* Comparison of FUSE (stars) and COPERNICUS (open triangles) OVI column densities with spatially averaged (red triangles and blue squares) and single lines of sight (red and blue lines) N(OVI) measurements in the simulated disk at time $t = 393$ Myr. The LOS are taken at positions C (red) and D (blue) that are located inside and outside of a bubble cavity, respectively, as shown in the right panel. *Right panel:* OVI density distribution (in logarithmic scale) in the midplane at time $t = 393$ Myr. The panel also includes a zoom of the bubble located in position C. The colour scale varies between 10^{-12} and $10^{-6}\,\mathrm{cm}^{-3}$; grey corresponds to zero OVI. Note the eddy-like structures of OVI inside the bubbles.

the dominant process in energy redistribution, the number of interfaces is reduced, as energy transport is not primarily driven by temperature gradients but by a turbulent cascade from larger to smaller eddies. Fig. 3 (left) shows a comparison between both Copernicus and FUSE data and our simulations, which is remarkably good and yields a time averaged value of $n(\mathrm{OVI}) = 1.81 \times 10^{-8}\,\mathrm{cm}^{-3}$ without any tuning. Even the measured

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n(O VI) inside the Local Bubble is in excellent agreement with the FUSE data. Fig. 3 (right) stresses that the O VI distribution occurs mainly in regions separated by a length scale of about 100 pc. This provides an extreme inherent clumpiness, which ensures the dispersion of the column density to be roughly independent of distance, d, (for $d > 100$ pc; for details see AB05b) rather than declining with the number N_{cl} of interspersed clouds like $1/\sqrt{N_{cl}}$, fully consistent with FUSE observations (Bowen *et al.* 2005.)

4. Conclusions

Recent high resolution multi-wavelength observations in conjunction with theoretical research have shown that the ISM in star forming galaxies is a highly complex "ecosystem". The key to a better understanding of its nature and evolution lies in the systematic study of compressible HD and MHD turbulence (for more detailed studies see Avillez & Breitschwerdt, these proceedings). Numerical high resolution 3D simulations offer a unique possibility to investigate the nonlinear interaction of the physical processes at work, together with a careful analysis of scaling laws. Since the SN driven ISM model can already explain many important features, as we have shown, we feel encouraged to implement further processes, such as e.g. non-equilibrium cooling, self-gravity and cosmic rays into our bottom-up model. Since these studies require a huge amount of massive parallel computing power, we are just at the beginning.

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Discussion

ARONS: How do you account for reconnection in the MHD simulations?

BREITSCHWERDT: Reconnection occurs at smaller scales, mediated by numerical resistivity. There is also evidence of a small scale dynamo in the simulations.

PADOAN: You find that for $T < 100$ K magnetic pressure is dominant, but you don't allow the density to grow at the level it should grow in molecular clouds at the scale (0.6 pc) you resolve (no molecular cooling). Furthermore, viscous dissipation of the turbulent velocity (numerical dissipation on the smallest scales) would also reduce the ram pressure.

BREITSCHWERDT: As I have emphasized in my talk, we do not describe the formation of molecular clouds, as we have not yet included molecular cooling and self-gravity. On the smallest scales there should be a transition ala viscous dissipation, so ram pressure will not be the driver at these scales.

DICKEY: I saw in your simulation an effect that is very clear in the 21-cm surveys which is an offset in the gas midplane from the bottom of the gravitational potential.

BREITSCHWERDT: This sounds intriguing. I think that the simulations reflect the effect that the supernova explosions both in the thin and in the extended disk are not distributed symmetrically due to the density/temperature criterion of star formation.

HEYER: Simulations are long enough for the gas to have flowed through spiral potential. Are spiral shocks/gas streaming comparable to turbulent ram pressure component?

BREITSCHWERDT: I agree that spiral density shock waves should be included. My guess would be that SN driven turbulence would dominate thoroughly, as the flow is largely controlled by ram pressure.

MAROV: My question is about conservation laws in 3D turbulence. It is known that 3D Navier-Stokes equations have the second integral of motion which gives rise to spirality preserving in the non-viscous limit. Did you observe spirality in your simulation approach and could it be distinguished on a small eddies background?

BREITSCHWERDT: We see the generation of vorticity and the eddies carry helicity if that's what you mean. But since we do not include galactic rotation there is no net helicity due to Coriolis forces.

MAC LOW: Several groups find $E_{kin} \propto t^{-1}$ for mildly supersonic turbulence (Mac Low *et al.* 1998; Stone, Ostriker & Gammie 1998; Padoan & Nordlund 1999). What is interesting in your results is the slow decay of cold gas $E_{kin} \propto t^{-0.5}$.

BREITSCHWERDT: Yes this is true. The slower decay lasts however only for a few million years and it should be due to the feeding of turbulence from gas cooling down from higher temperatures.

ELMEGREEN: If you were to connect your results with star formation, I imagine you would say stars form in the dense clumps and the clumps form by supernova and other shocks. But then how do you get the observed sensitivity to Toomre Q for star formation, and how do you get the Schmidt law? What is missing from the models?

BREITSCHWERDT: One of the biggest challenges for the next decade is to close the gap between large scale simulations (on which turbulence is driven) and the process of star formation on small scales. I am confident that this is only a matter of increasing computer power. Our present simulations are limited on small scales due to the lack of self-gravity and on the large scales due to the lack of galactic rotation. Both improvements are currently being built in.

FALL: Have you measured the velocity and density correlations in your simulations and compared them with observations (scaling-type relations presented yesterday)? What does the agreement or disagreement between your simulations and observations tell you about the driving mechanisms and or other properties of turbulence in the ISM?

BREITSCHWERDT: We have extracted structure functions of order p from the simulations and have determined the scaling exponent $\xi(p)$ and found that the Hausdorff dimension of the most dissipative structures is 2, implying dissipation by sheets rather than filaments. I agree that it would be useful also to determine the density correlation functions and compare them directly to observations.

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