The structure of the thermally bistable, turbulent and magnetized atomic gas : Hydrodynamical to MHD simulations

E. Saury[1], A. Bracco[1], F. Boulanger[1], M.-A Mivilles-Deschênes[1], P. Hennebelle[2]
1 – Institut d'Astrophysique spatiale, Orsay, France 2 – Service d'Astrophysique, CEA, Saclay, France
Contact : eleonore.saury@ias.u-psud.fr

Context: The properties of the neutral atomic medium (HI) vary greatly in the Milky Way disk. In the solar neighborhood it is composed of a warm diffuse phase (Warm Neutral Medium - WNM) with $n=0.5\ cm^{-3}$, $T=8000K$ and a colder cloud phase (Cold Neutral Medium - CNM) with $n\sim100\ cm^{-3}$ and $T\sim40K$. About 40% of the HI mass is in the cloud phase that fills only ~1% of the volume.
The HI has the properties of a turbulent flow. The WNM turbulent velocity dispersion has the following scaling: $\sigma_{turb}(km/s)=0.9*L(pc)^{1/3}$. Even when integrated over the whole disk height (HWHM of 300 pc at the solar radius), the WNM turbulent velocity dispersion (5.9 km/s) is significantly lower than the thermal motions (8.3 km/s); the WNM is thus expected to have the properties of a subsonic turbulent flow.

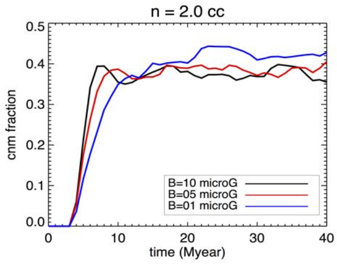
Questions: Do the subsonic turbulent motions of the WNM lead to the formation of the cloud phase in the diffuse ISM via the thermal instability ? What is the impact of the magnetic field on the cold structures in the ISM ?

Method: To study the phase transition and the formation of the cold cloud phase from purely WNM gas, hydrodynamical and MHD numerical simulations of turbulent and thermally bistable HI were performed with HERACLES (Gonzalez et al., 2007). Our simulations include the main heating and cooling processes described by Wolfire et al. (2003), with turbulence stirring applied at larges scales in Fourier space (Schmidt et al., 2009) at each time step. The 3D simulations have a size of 40 pc with 128^3 to 1024^3 cells, leading to resolutions from 0.3 to 0.04 pc. The gas is initially static and uniform, at a temperature of 8000 K, consistent with WNM.

1

MHD – INPUT PARAMETERS AND RESULTS

Hydrodynamical study => initial conditions that statistically reproduce well the observations : $n_0 = 2.0\ cm^{-3}$, $\zeta = 0.5$, $v_S = 7$ km/s



Addition of the magnetic field :
- Initially parallel to the x-axis
- Uniform with |B| from 1 to 10 μG

Mean values of f_{CNM} :
10 μG : 37 ± 2 %
05 μG : 38 ± 2 %
01 μG : 41 ± 3%
=> Validation of the hydrodynamical parametric study

3

DUST POLARIZATION

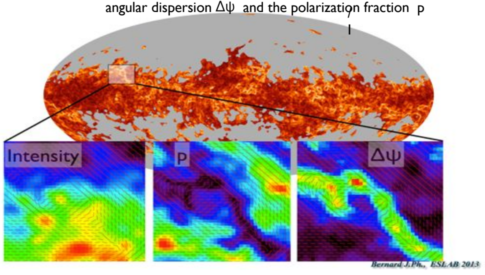
Angular dispersion (Hildebrandt, 2009) :

$$\Delta\psi^2(l) = \frac{1}{N}\sum_{i=1}^{N}[\psi(\mathbf{r}) - \psi(\mathbf{r}+\mathbf{l_i})]^2$$

where ψ is the polarization angle

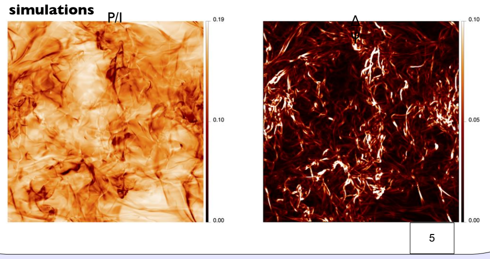
Polarization fraction : $P = p/I$

Planck data : All sky map of the dispersion of the polarization angle => anti-correlation of the angular dispersion Δψ and the polarization fraction p



J.-Ph. Bernard
ESLAB 2013

MHD simulations



5

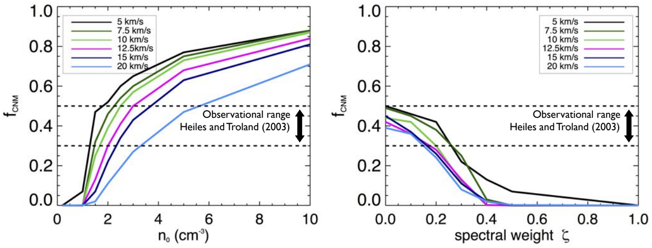
HYDRO – INPUT PARAMETERS AND RESULTS

What we want to reproduce :
- a biphasic medium with :
  - massive fraction of cold gas ~ 0.4
  - Volume filling factor of the CNM ~ 1%
- a sub or transsonic turbulence = Mach~1

Shared initial conditions:
Physical size of the box : 40 pc.
T_0 = 8000 K
v_0 = 0 km s^{-1}
Turbulence stirring in Fourier space
Heating and cooling from Wolfire et al (2003)

Varying parameters :
- initial density (n_0) : from 0.2 to 10 cm^{-3}
- large scale amplitude (v_S) at 20 pc : from 5 to 20 km s^{-1}
- spectral weight (ζ) : from 0 (purely compressive) to 1 (purely sinusoidal)

⇨ 90 simulations



- $n_0<1.5\ cm^{-3}$ => no transition
- $n_0>3\ cm^{-3}$ => f_{CNM} > 30%
- High v_S : $t_{ref} > t_{turb}$ transition less efficient

Simulations with a minority of compressible modes do not transit

2

SYNTHETIC OBSERVATIONS OF DUST POLARIZATION:
Stokes parameters computation

$$I = \int \rho\,\mathrm{d}s$$

$$Q = -p_0 \int \rho\cos^2(\gamma)\cos(2\psi)\,\mathrm{d}s$$

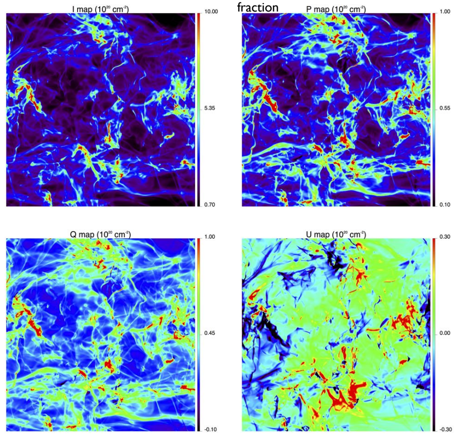
$$U = p_0 \int \rho\cos^2(\gamma)\cos(2\psi)\,\mathrm{d}s$$

$$P = \sqrt{Q^2+U^2}$$

γ= angle between the magnetic field B and the plane of the sky

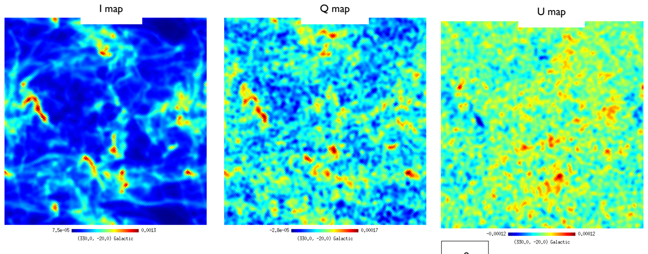
Ψ= angle between the y-axis and the projection of the magnetic field, $B_\perp$, on the plane of the sky

$\mathbf{p_0}$ = 0.2 the intrinsic dust polarization fraction



4

SYNTHETIC OBSERVATIONS OF DUST POLARIZATION:
Healpix projected, Planck noise addition and smoothed



6

SUMMARY AND CONCLUSION

We performed a parametric study on hydrodynamical simulations to determine the initial conditions that lead to the formation of 40% of CNM with a Mach number close to 1. We conclude that the ISM turbulence cascade on its own cannot induce a transition from WNM into CNM at the average density of the WNM (Frame 2). The production of CNM is likely to be due to turbulent motions of moderate amplitude associated to a compressive event of the WNM that could be led by transient phenomena such as outflows, supernova explosion or spiral density waves.

We used the obtained initial conditions and added the magnetic field in order to study its impact on the formation of the cold structure of HI. The three amplitudes of the magnetic field used here (1, 5 and 10 μG) lead to the formation of the same amount of cold gas (Frame 3). This result validates the parametric study performed on hydrodynamical simulations and suggests that we need to define an other method to constrain the magnetic field. In the context of the new Planck data, the study of the polarization of the dust emission in diffuse regions of the sky is now promising.

Therefore, we computed the Stokes parameters of the simulations in order to create synthetic observations comparable to the Planck data. We observe :
- that each structure in intensity has a counterpart in Q and U (Frame 4), which is also observed in the Planck data,
- an anti-correlation between the polarization fraction P/I and the dispersion of the angle ΔΨ, also in agreement with the data (Frame 5).

Finally, we projected the simulations in Healpix, added the Planck noise and smoothed them to the Planck resolution. This will allow us to use exactly the same analysis on data and synthetic observations and, therefore, to compare them as accurately as possible. We note that the faintest structures in the simulations are not so clearly visible in data because of the presence of the noise.