Highlights of Astronomy, Volume 16
XXVIIIth IAU General Assembly, August 2012
T. Montmerle, ed.

doi:10.1017/S1743921314012381

Molecular richness of the diffuse interstellar medium: a signpost of turbulent dissipation

Edith Falgarone[1], **Benjamin Godard**[2], **Guillaume Pineau des Forêts**[3] **and Maryvonne Gerin**[1]

[1]LERMA/LRA, Ecole Normale Supérieure & Observatoire de Paris,
24 rue Lhomond, 75005 Paris, France
email: `edith.falgarone@ens.fr`

[2]LUTh, Observatoire de Paris, 92195 Meudon, France
email: `benjamin.godard@obspm.fr`

[3]Institut d'Astrophysique Spatiale, 91405 Orsay, France

Abstract. The *Herschel*/HIFI absorption spectroscopy surveys reveal the unexpected molecular richness of the Galactic diffuse ISM, even in gas of very low average H_2 molecular fraction. In particular, two hydrides, CH^+ and SH^+ with highly endoenergetic formation routes have abundances that challenge models of UV-driven chemistry. The intermittent dissipation of turbulence appears as a plausible additional source of energy for the diffuse ISM chemistry. We present recent results of the so-called models of Turbulent Dissipation Regions (TDR). The abundances of many of the molecules observed in the diffuse ISM, including CO that is used as a tracer of the molecular clouds mass, may be understood in the framework of the TDR models.

Keywords. Astrochemistry, Turbulence, Magnetic Fields, ISM: molecules, ISM: kinematics and dynamics, ISM: general, ISM: evolution

---

1. The puzzles raised by the cold ISM

The cold diffuse interstellar medium (ISM), as defined in the review of Snow & McCall (2006), makes up the mass of nearby molecular clouds. This is best seen on the probability distribution functions (PDF) of their extinction (Kainulainen *et al.* 2009). The cloud mass is comprised in the log-normal part of the PDFs, *i.e.* the transparent and turbulent part.

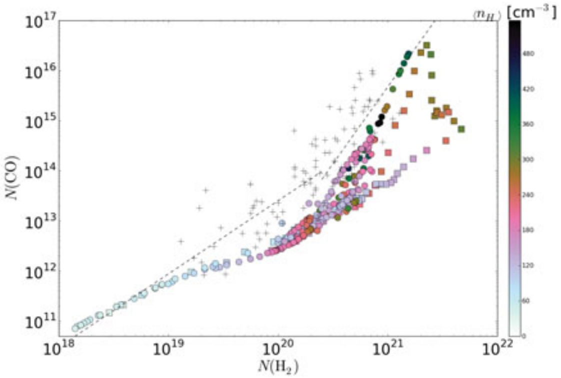

Figure 1. Comparison of observed CO column densities (crosses), derived from absorption lines against nearby stars (see references in Levrier *et al.* (2012)) with state-of-the-art computed values combining the photo-dissociation regions (PDR) model of Le Petit *et al.* (2006) and bi-phasic MHD turbulence simulations of Hennebelle *et al.* (2008).

Molecular abundances of the diffuse gas raise resilient puzzles. For 70 years, the CH^+ abundances have been known to exceed model predictions by two orders of magnitude. This is so because the route to CH^+ is highly endoenergetic and, once formed, CH^+ is rapidly destroyed by collisions with H_2. An additional source of energy is thus required to efficiently form CH^+ in diffuse gas. The observed CO abundances in a broad range of H_2 column densities also exceed model predictions by more than one order of magnitude (Fig. 1 from Levrier *et al.*, 2012).

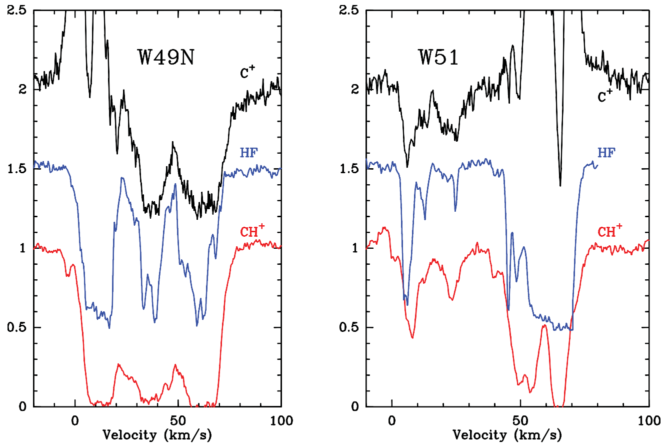

Figure 2. CII, HF and CH^+ spectra observed in the direction of W49 and W51. Note the similarity of the velocity coverage of the CII and CH^+ absorptions away from those of the star forming regions.

Herschel/HIFI has deepened these puzzles. We have conducted an absorption spectroscopy survey against bright star forming regions of the inner Galaxy (PRISMAS key-project, PI Gerin). Each line of sight samples kiloparsecs of gas in the Galactic plane. We detected saturated CH^+(1-0) (and $^{13}CH^+$(1-0)) in absorption on all the sight lines, (Falgarone *et al.* 2010a, 2010b) and SH^+ that has a formation endothermicity twice as large as that of CH^+ (Godard *et al.*, 2012). Last, C^+ is detected in absorption over the same velocity intervals as CH^+ (Fig. 2) and we show that C^+ and CH^+ absorptions occur in the cold neutral medium (CNM) (Gerin *et al.*, in prep.). Using HF as a tracer of molecular hydrogen (Neufeld *et al.* 2010), and e-VLA atomic hydrogen spectra (Menten *et al.* in prep.), we infer the mean H_2 molecular fraction of the absorbing gas: it is low on average and has a large scatter $0.04 < f_{H_2} < 1$ (Godard *et al.*, in prep.). Hence, CH^+ and SH^+ are detected with large abundances even in gas components with very low average H_2 fractional abundance.

UV-driven chemistry is not able either to reproduce these large CH^+ abundances nor the broad range of observed SH^+/CH^+ ratios. The alternative is a warm chemistry that opens the route $C^+ + H_2 \rightarrow CH^+ + H$ and leads to the formation of the pivotal species, CH_3^+. In particular, CH_3^+ reacts with O to form HCO^+, the precursor of CO.

2. Chemistry driven by turbulent dissipation

Turbulence and magnetic fields that support the ISM in the gravitational well of the Galaxy (Cox 2005) are a formidable reservoir of energy. Turbulent dissipation is intermittent (see the review of Anselmet *et al.*, 2001). In the diffuse ISM, the bursts of turbulent dissipation are *locally and temporarily* a dominant source of heating for the gas, large enough to excite the H_2 pure rotational lines by collisions (Falgarone *et al.* 2005; Ingalls *et al.* 2011) and trigger a specific "warm" chemistry. These space-time bursts are modeled as low-velocity MHD shocks (Lesaffre *et al.*, 2012) and/or thin coherent vortices, (*i.e.* the TDR model, for Turbulent Dissipation Regions, Godard *et al.*, 2009) temporarily heating a small fraction of the gas (a few %) to temperatures up to 10^3 K. The heated gas eventually cools down once the dissipation burst is over. The free parameters of the TDR model are constrained by the known large-scale properties of turbulence.

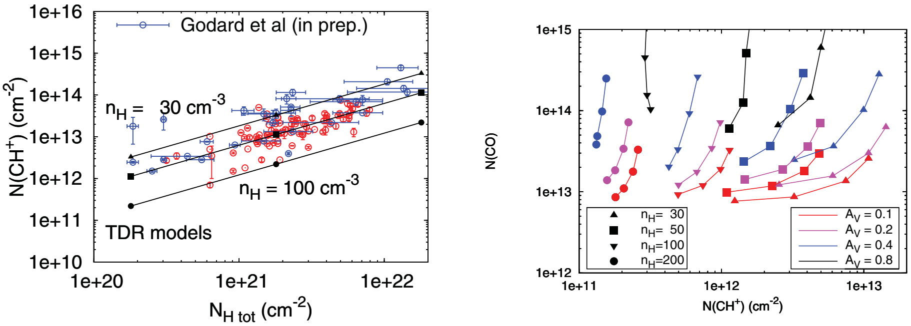

Figure 3. *(Left)* The CH$^+$ data compared to TDR models. *(Right)* CO and CH$^+$ column densities computed in TDR models for different densities and UV-shieldings and a total gas column density $N_{\rm H} = 1.8 \times 10^{21}$ cm^{-2}. The free parameter along each curve, is the rate-of-strain (Godard *et al.* in prep.)

Dissipation is due to both viscosity and ion-neutral friction induced by the decoupling of the neutral fluid from the magnetic fields. The chemical and thermal inertia are large. The chemical relaxation times span a broad range, from 200 yr for CH$^+$ up to 5×10^4 yr for CO. A random line of sight through the medium therefore samples 3 phases: *(i)* actively dissipating regions, *(ii)* relaxation phases, and *(iii)* the ambient medium.

The main successes of the TDR model are: *(i)* the agreement of CH$^+$ and SH$^+$ observations with model predictions (Fig. 3, left). *(ii)* the scaling of CH$^+$ abundances with the turbulent dissipation rate, *(iii)* the rotational excitation of H_2 in diffuse gas, and *(iv)* the CO abundance in diffuse molecular gas (Fig. 3, right). A fraction as small as a few percent of warm gas is sufficient to reproduce the observations (H_2 excitation diagram, CH$^+$, SH$^+$, but also CO abundances). The comparison with data tend to favor models in which dissipation is dominated by ion-neutral friction.

In summary, many of the molecules we observe in the diffuse medium, including CO that is used as a tracer of the molecular mass in galaxies, are too abundant to be explained by state-of-the-art chemistry models driven by the UV-field. A plausible alternative is that they are the outcome of a specific non-equilibrium chemistry triggered by the bursts of turbulent dissipation.

References

Anselmet, F., Antonia, R., & Danaila, L. 2001, *P&SS* 49, 1177
Cox, D. 2005, *ARAA* 43, 337
Falgarone, E., Godard, B., Cernicharo, J., *et al.* 2010a, *A&A* (Letters) 521, L15
Falgarone, E., Ossenkopf V., Gerin M., *et al.* 2010b, *A&A* (Letters) 518, L118
Falgarone, E., Verstraete, L., Pineau des Forêts, G., & Hily-Blant, P. 2005, *A&A* 433, 997
Godard, B., Falgarone, E., Gerin, M., *et al.* 2012, *A&A* 540, 87
Godard, B., Falgarone, E., & Pineau des Forêts, G. 2009, *A&A* 495, 847
Hennebelle, P., Banerjee, R., Vazquez-Semadeni E., *et al.* 2008, *A&A* (Letters) 486, L43
Ingalls, J., Bania, T., Boulanger, F., *et al.* 2011, *ApJ* 743, 174
Kainulainen, J., Beuther, H., Henning, T., & Plume, R. 2009, *A&A* (Letters) 508, L35
Le Petit, F., Nehmé, C., Le Bourlot, J., & Roueff, E. 2006, *ApJS* 164, 506
Lesaffre, P., Pineau des Forêts, G., Godard, B., *et al.* 2012, *A&A* in press
Levrier, F., Le Petit, F., Hennebelle, P., *et al.* 2012, *A&A* 544, 22
Neufeld, D., Sonnentrucker, P., Phillips, T., *et al.* 2010, *A&A* (Letters) 518, L108
Snow, T. & McCall, B. 2006, *ARAA* 44, 367