Molecular Gas, Dust, and Star Formation in Galaxies
Proceedings IAU Symposium No. 292, 2012
T. Wong & J. Ott, eds.

doi:10.1017/S1743921313001142

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

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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 endoergic 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 cloud 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. Introduction: 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). Clouds devoid of star formation have log-normal PDFs up to extinctions of a few magnitudes, while actively star forming clouds have PDFs with power-law tails up to several tens of magnitude. The cloud mass is comprised in the log-normal part of the PDFs, *i.e.* the transparent part. Interestingly, the log-normal shape of the PDF may be seen as a signature of the multiplicative processes characteristic of turbulence.

Molecular abundances of the diffuse gas raise resilient puzzles. The first one has long been overlooked: the observed CO abundances in a broad range of H_2 column densities exceed model predictions by more than one order of magnitude (Fig. 1 from Levrier *et al.* 2012, Hily-Blant & Falgarone 2007). Another one is 70 years old. It regards the CH^+ abundances in the diffuse medium that exceed model predictions by two orders of magnitude. This is so because the route to CH^+ is highly endoergic and, once formed, CH^+ is rapidly destroyed by collisions with H_2 to form CH_2^+ and CH_3^+. An additional source of energy is thus required to efficiently form CH^+ in diffuse gas.

2. Herschel/HIFI results

Herschel/HIFI has even deepened these puzzles. We have conducted an absorption spectroscopy survey against bright star forming regions of the inner Galaxy (PRISMAS

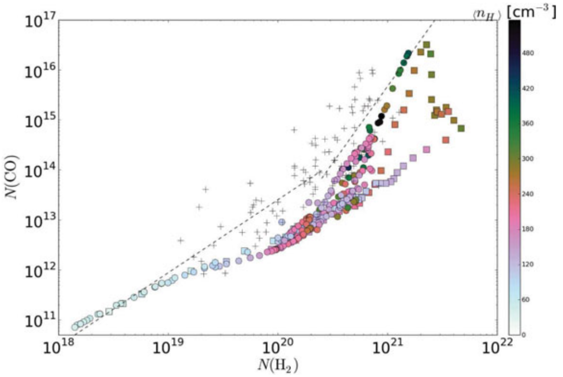

Figure 1. Comparison of observed CO column densities (crosses), derived from absorption lines against nearby stars (see references in Levrier *et al.* 2012) with state-of-the-art computed values combining the photo-dissociation regions (PDR) model of Le Petit *et al.* (2006) and bi-phasic MHD turbulence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

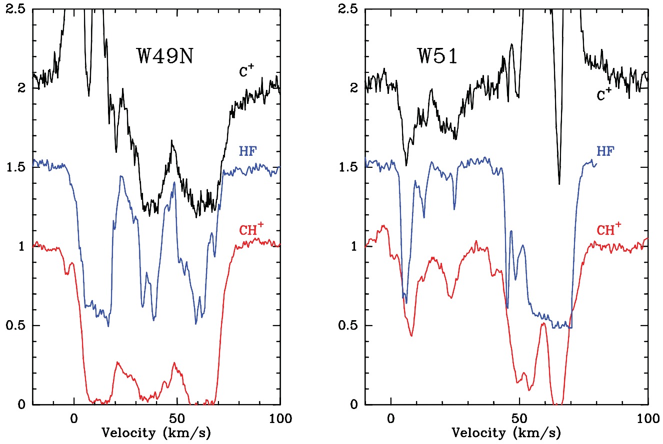

Figure 2. CII, HF and CH$^+$ spectra observed in the direction of W49 and W51. Note the similarity of the velocity coverage of the CII and CH$^+$ absorptions away from those of the star forming regions.

key-project, PI Gerin). Each line of sight samples kiloparsecs of gas in the Galactic plane. The results went beyond our expectations. Not only did we detect CH$^+$(1-0) and ^{13}CH$^+$(1-0) in absorption on all the sight lines, but the CH$^+$ lines are saturated at almost all velocities (Falgarone *et al.* 2010a, Falgarone *et al.* 2010b). We also detected another hydride, SH$^+$, that has a formation endothermicity twice as large as that of CH$^+$ (Godard *et al.* 2012). Moreover, C$^+$ is detected in absorption over the same velocity intervals as the CH$^+$ saturated absorption (Fig. 2). The analysis of both the CI and CII lines along the same lines of sight led us to infer that C$^+$ and CH$^+$ absorptions occur in low density gas ($n_H \sim 50$ to 100 cm^{-3}), at temperatures ~ 100K, values that are those of the cold neutral medium (CNM) (Gerin *et al.*, in prep.). Using HF as a tracer of molecular hydrogen (Neufeld *et al.* 2010), and EVLA atomic hydrogen spectra (Menten *et al.* in prep.), we were able to assess the mean H$_2$ molecular fraction of the absorbing gas: it is low on average and has a large scatter $0.04 < f_{H_2} < 1$ among all the components (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.

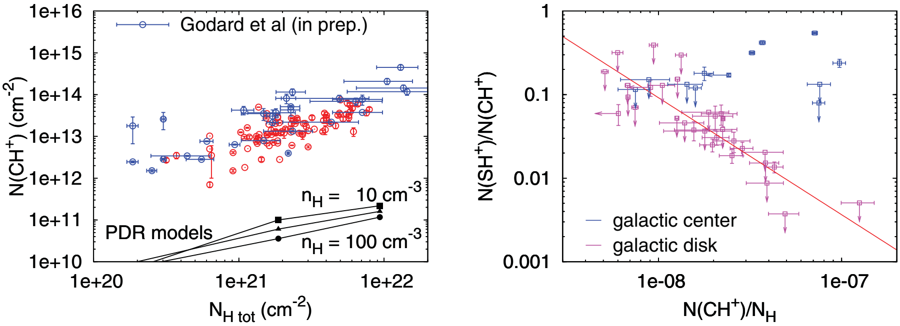

Figure 3. *(Left)* Observed CH^+ (red, visible data, blue, *Herschel*/HIFI data) compared to PDR model predictions. *(Right)* Observed SH^+/CH^+ abundance ratios as a function of the CH^+ abundance.

UV-driven chemistry is not able either to reproduce these large CH^+ abundances nor the broad range of observed SH^+/CH^+ ratios (Fig. 3). In PDR models, this ratio is constant and set by the slow radiative associations that initiate the formation of CH^+ and SH^+, independently of the gas temperature. The alternative to UV-driven chemistry, 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. A remarkable property of CH_3^+ is that one of its photodissociation products is CH^+ so, unlike most molecules, CH^+ abundance may increase as the UV field increases (Falgarone *et al.* 2010a).

3. 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. In the diffuse ISM, the bursts of turbulent dissipation are *locally and temporarily* a dominant source of heating for the gas. It is because the dissipation of turbulence is intermittent (see the review of Anselmet *et al.*, 2001) that the heating rate of the gas is 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 (Flower & Pineau des Forêts 1998, 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. Dissipation is due to both viscosity and ion-neutral friction induced by the decoupling of the neutral fluid from the magnetic fields within the vortex. Since the diffuse medium has a low density, its chemical and thermal inertia are large. The chemical relaxation times of molecular species cover 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:
- the agreement of CH^+ and SH^+ observations with model predictions. An illustration is shown in Fig. 4(left). The large range of the SH^+/CH^+ abundance ratio is also reproduced.
- the scaling of CH^+ abundances with the turbulent dissipation rate.
- the rotational excitation of H_2 in diffuse gas.

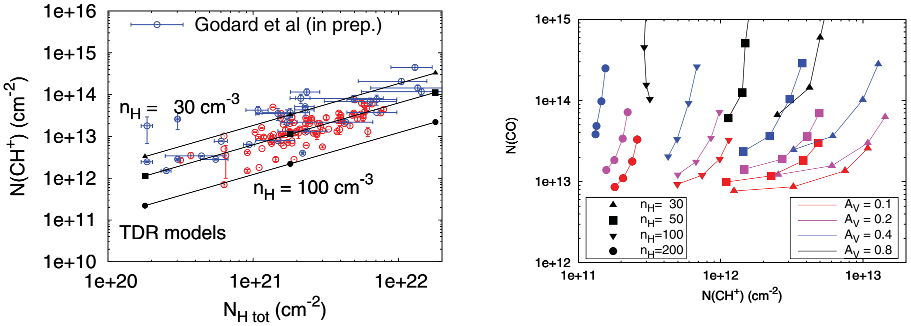

Figure 4. *(Left)* The CH^+ data compared to TDR models. *(Right)* CO and CH^+ column densities computed in TDR models for different densities and UV-shieldings and a total gas column density $N_H = 1.8 \times 10^{21}$ cm^{-2}. The free parameter along each curve, is the rate-of-strain (Godard *et al.* in prep.)

- the CO abundance of diffuse molecular gas.

Fig. 4(right) displays the predicted CO column densities for $N_H = 1.8 \times 10^{21}$ in various models. The range of observed CH^+ column densities in the diffuse ISM for this total column density is $N(CH^+) = 0.2$ to 5×10^{13} cm^{-2} (Fig. 4, left). The predicted CO columns are those observed to be far in excess to PDR predictions (see Fig. 1) in the correct range of H_2 columns (~ 0.2 to $\sim 1 \times 10^{21}$ cm^{-2}) provided by that of f_{H_2}. An interesting characteristic of these models is that a fraction as small as a few percent of warm gas, heated by the dissipation of turbulent energy, is sufficient to reproduce the observed H_2 line excitation diagram, as well as the abundances of specific molecules like CH^+ and SH^+, but also CO. The data tend to be in better agreement with low rates-of-strain, *i.e.* 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.

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