CH^+ and SH^+ absorption spectroscopy with Herschel: probing the turbulent dissipation in the diffuse ISM.

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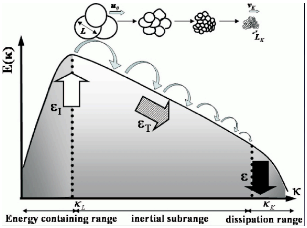
1. Quick overview of turbulence and its unkowns
2. The TDR (turbulent dissipation regions) model
3. Derive turbulence properties from molecular observations

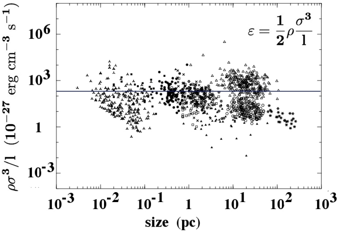
turbulent cascade

- advection force $\mathbf{u} \cdot \nabla \mathbf{u}$
- dissipation forces
  - friction $\nu \nabla^2 \mathbf{u}$
  - compression $\frac{1}{3}\nu \nabla [\nabla \cdot \mathbf{u}]$
  - ambipolar diff. $\gamma_{in}(\mathbf{u}_i - \mathbf{u}_n)$
  - magnetic diff. $\mu \nabla^2 \mathbf{b}$

transfer rate

- $\overline{\varepsilon} = 2 \times 10^{-25}$ erg cm^{-3} s^{-1}

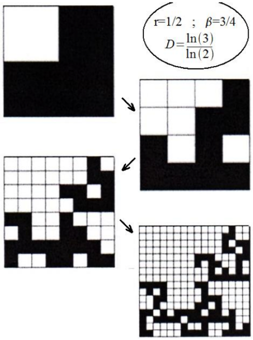




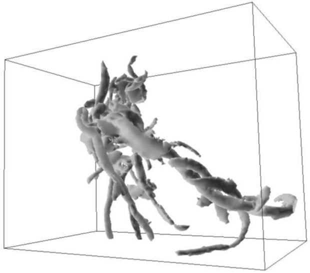
Hennebelle & Falgarone (2012)

intermittency

- in space & time
- local dissipation $\varepsilon = \overline{\varepsilon}/f_v$



Frish (1995)



Moisy & Jimenez (2004)

unresolved questions

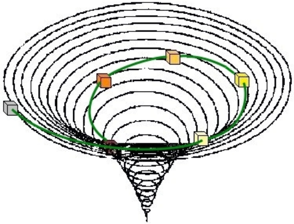
- dissipative scales ?
- dissipative structure ?
- physical processes involved ?
- local rate of dissipation ?

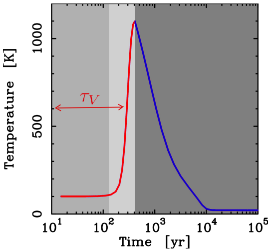
dissipative phase

- magnetized vortices
  $a^2 = 4\nu/l$, $u_{\theta\mathrm{m}}$
- Lagrangian approach
- non-equilibrium chemistry
- turbulent heating processes
  - viscous friction
  - ion-neutral friction

relaxation phase

- Eulerian approach
- no turbulent heating





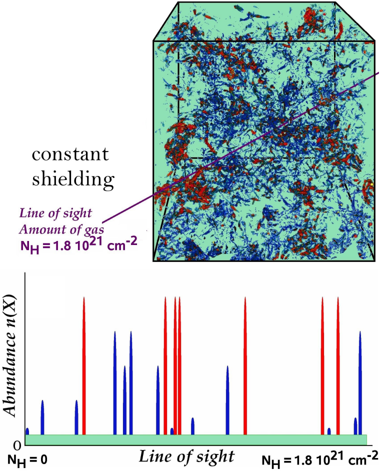
courtesy of P. Hily-Blant

model parameters

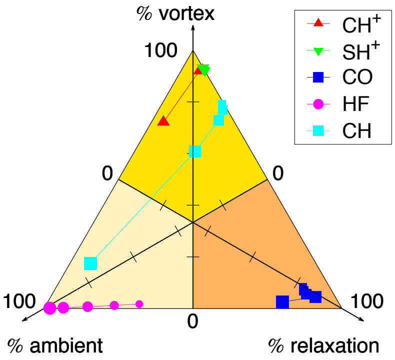
- density n_H
- shielding A_V
- CR ionization ζ

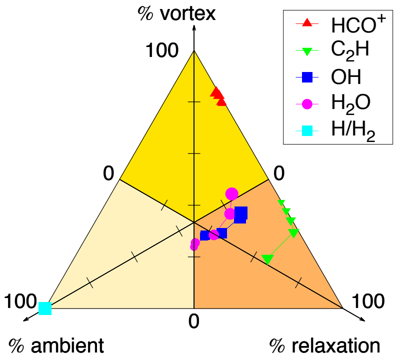
- stretching $a \rightarrow l$
- max rot. vel. $u_{\theta\mathrm{m}} \rightarrow u_\mathrm{in}$
- transfer rate $\overline{\varepsilon} \rightarrow N_V$
- lifetime $\tau_V \rightarrow N_R$

constant shielding



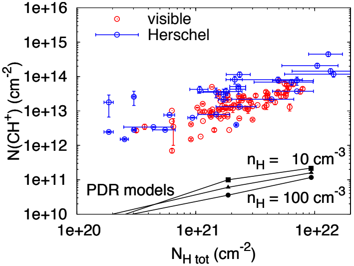
Strategy to derive turbulent properties



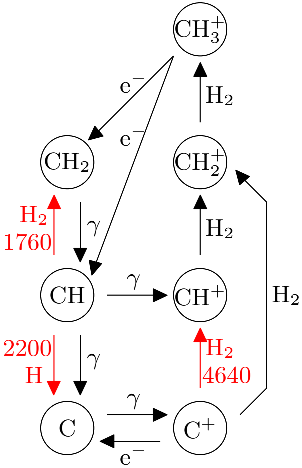


- n_{H} increases with increasing symbol size
- $A_V = 0.4, \qquad \zeta = 3 \times 10^{-17}\ \mathrm{s}^{-1}$

Large scale turbulent energy



- $N(\mathrm{CH}^+)_{\mathrm{local}} = 3 \times N(\mathrm{CH}^+)_{\mathrm{disk}}$



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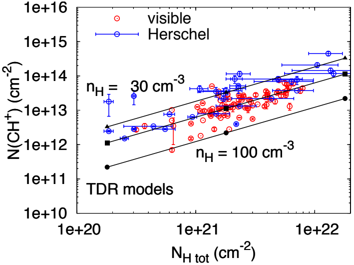
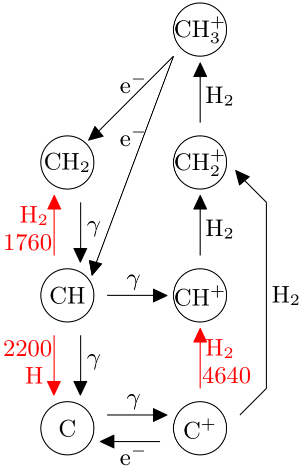
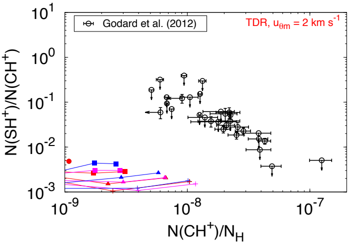
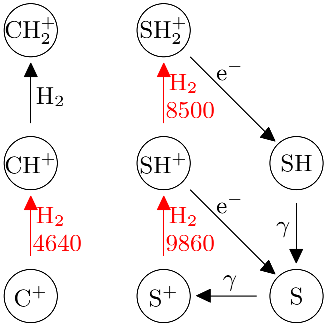




- $N(\mathrm{CH}^+)_{\mathrm{local}} = 3 \times N(\mathrm{CH}^+)_{\mathrm{disk}}$
- $\frac{N(\mathrm{CH}^+)}{N_\mathrm{H}} \propto \overline{\varepsilon}\ n_\mathrm{H}^{-2.2}\ \ A_V^{-0.32}\ \ a^{-0.5}$
- $n_\mathrm{H} < 200\ \mathrm{cm}^{-3}$
- $\frac{1}{5} < \frac{\overline{\varepsilon}}{10^{-24}\,\mathrm{erg\,cm^{-3}\,s^{-1}}} < 5$

Ion-neutral drift in dissipative regions





- $\frac{N(\mathrm{SH}^+)}{N(\mathrm{CH}^+)} \propto \exp(-5220/T_{\rm eff})$
- $T_{\rm eff} = T_r + \frac{1}{3}\frac{\mu}{k}u_{\rm in}^2$
- independent of a and $\overline{\varepsilon}$

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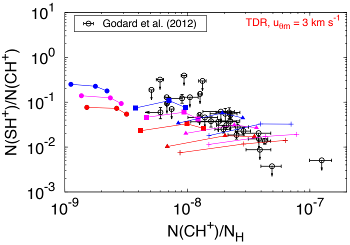

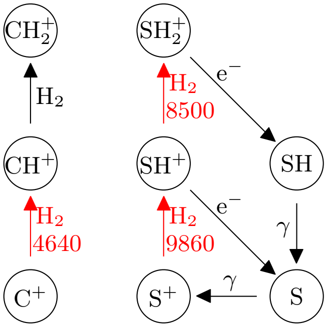

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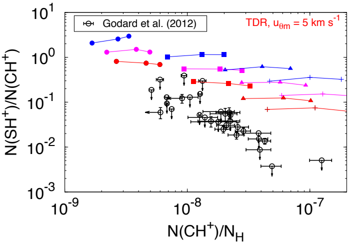

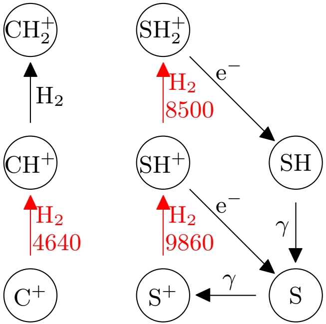

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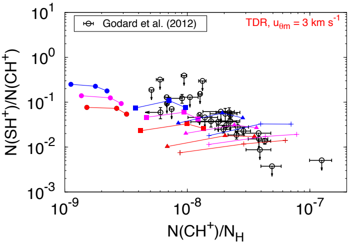

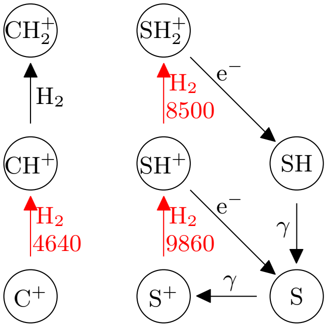

- $2.5 \leqslant u_{\theta \mathrm{m}} \leqslant 3.5$ km s^{-1}
- reproduces the correlation
- SH abundance reproduced (SOFIA-GREAT, Neufeld et al. 2012)

- $\frac{N(\mathrm{SH}^+)}{N(\mathrm{CH}^+)} \propto \exp(-5220/T_{\mathrm{eff}})$
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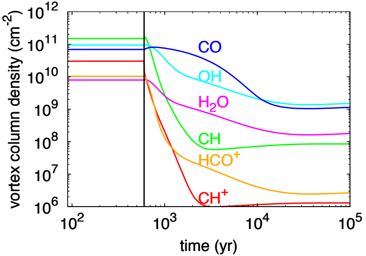
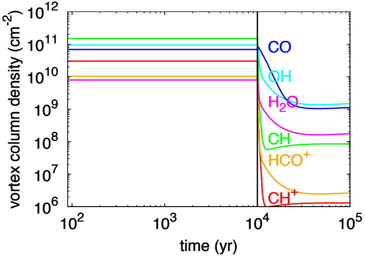
- independent of a and $\overline{\varepsilon}$

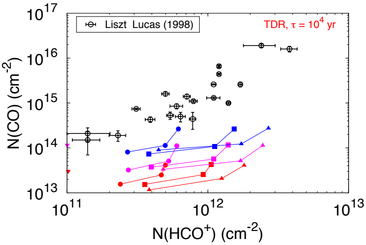
TURBULENT DISSIPATION TIMESCALE



- CO formation in TDR : $CH^+ \dashrightarrow CH_3^+ \rightarrow HCO^+ \rightarrow CO$
- $\tau_R(CO) \sim 100 \times \tau_R(CH^+) \sim 100\tau_R(HCO^+)$

Turbulent dissipation timescale





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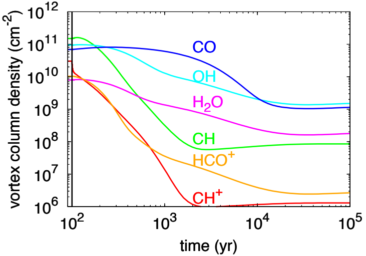

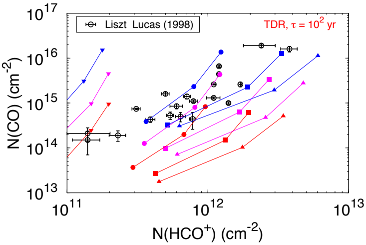

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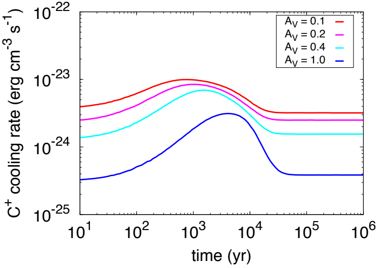
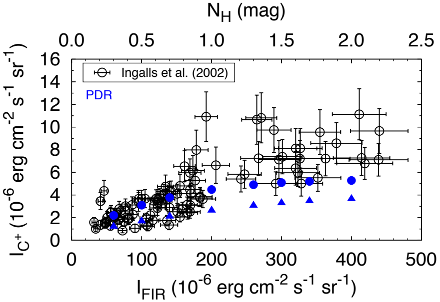
Stretching of turbulent dissipation regions





- under-emission during the dissipative burst ~ 100 yr
- over-emission during the relaxation period $\sim 10^4$ yr

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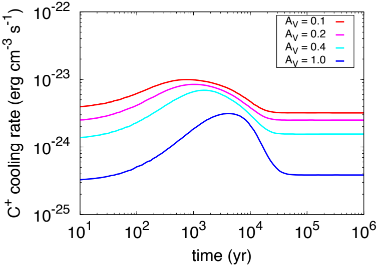
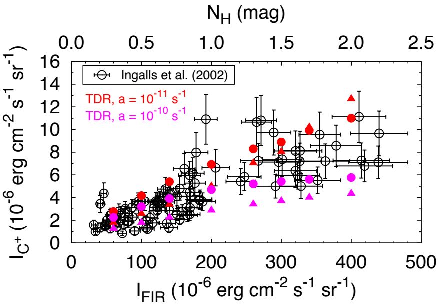
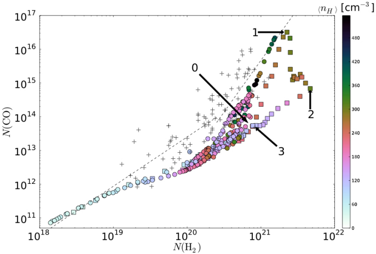


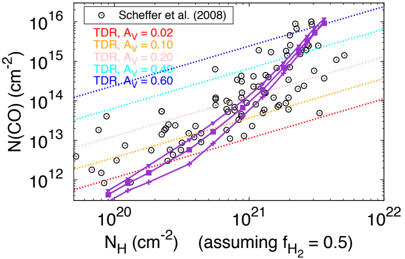


- under-emission during the dissipative burst ~ 100 yr
- over-emission during the relaxation period $\sim 10^4$ yr
- $10^{-12} \leqslant a \leqslant 10^{-10}$ s^{-1} $\rightarrow 100 \leqslant l \leqslant 1000$ AU

Additional TDR predictions



Levrier et al. (2012)



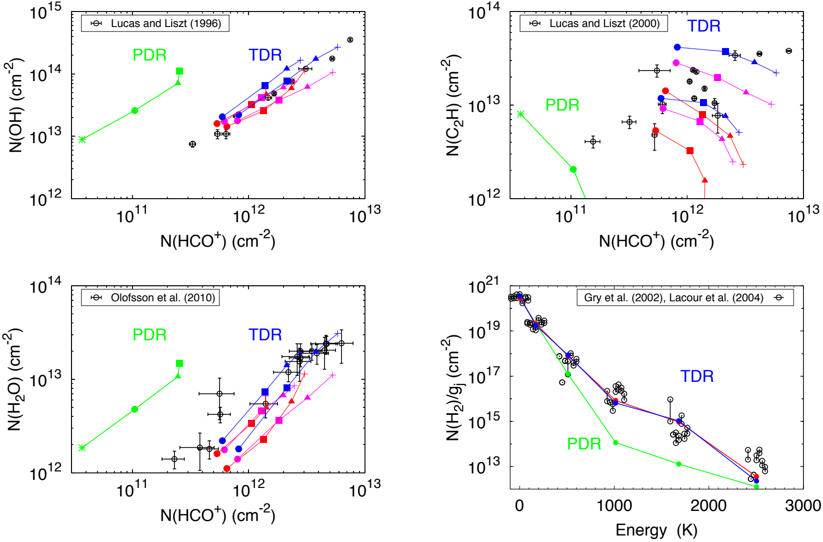
realistic fragmentation + PDR

- $N(\mathrm{CO})_{\mathrm{obs}}/N(\mathrm{CO})_{\mathrm{PDR}} > 10$
- explains the bending of $N(\mathrm{CO})$ at $N(\mathrm{H_2}) \sim 2 \times 10^{20}$

TDR

- if complete fragment. no bending
- if no fragment. strong bending and $N(\mathrm{CO})$ too small at small N_H

Additional TDR predictions



Summary

- properties of turbulent dissipation
  - CH^+ / H → dissipation rate $n_H, \bar{\varepsilon}$
  - SH^+ / CH^+ → ion-neutral decoupling $n_H, u_{\theta m} = u_{in}$
  - C^+(160μm) / FIR → stretching $a \rightarrow l$
  - CO / HCO^+ → timescale τ_V
- agreement with other molecular tracers
  - CO / H_2 → fragmented medium
  - column densities of OH, H_2O, C_2H, CH, SH, and $H_2^\star$
  - ... and their correlations

Future contributions

open issues

- explain H_2S abundances
- interpret velocity profiles

ALMA perspectives

- mapping the dissipative scales
- turbulence in extragalactic media