Low velocity shocks as signatures of turbulent dissipation in diffuse irradiated gas

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B. Godard, P. Guillard
E. Falgarone, F. Boulanger
G. Momferratos, F. Levrier
A. Gusdorf, M. Gerin
Outline

- Two paths for molecules formation
- Turbulence dissipation
- Molecules production and excitation in shocks
- The example of the Stephan's Quintet
- Future prospects and ongoing work
Form $H_2$ molecules on grains. Then:

- \[ H_2 + H_2^+ \rightarrow H_3^+ + X \rightarrow XH^+ + H_2 \]

- \[ H_2 + X \rightarrow XH + H \]

where $X$ is in \{C, O, S, Si\}.

(N is an exception..)
ISM molecular gas chemistry for the dummies like me

- Form $\text{H}_2$ molecules on grains. Then:

  $\text{H}_2 + (\text{H}_2^+) \rightarrow \text{H}_3^+ + X \rightarrow X\text{H}^+ + \text{H}_2$

  *Needs ionisation (Cosmic rays, Irradiation)*

  $\text{H}_2 + X \rightarrow X\text{H} + \text{H}$

  where $X$ is in \{C, O, S, Si\}.

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ISM molecular gas chemistry for the dummies like me

- Form $\text{H}_2$ molecules on grains. Then:

$$\text{H}_2 + (\text{H}_2^+) \rightarrow \text{H}_3^+ + X \rightarrow \text{XH}^+ + \text{H}_2$$

_Needs ionisation (Cosmic rays, Irradiation)_

$$\text{H}_2 + X \rightarrow \text{XH} + \text{H}$$

_Needs thermal energy (Turbulence dissipation, mixing)_

where $X$ is in \{C, O, S, Si\}.

(N is an exception..)
The Kolmogorov cascade

Injection $\Rightarrow$ Kinetic energy $\Rightarrow$ Viscous Dissipation

Compress $\Rightarrow$ Strain $\Rightarrow$
Nature of the dissipation

\[ \varepsilon_t = \varepsilon_v + \varepsilon_o + \varepsilon_a \]

Dissipative heatings:
- Green: viscous
- Red: ohmic
- Blue: ion-neutral drift

2D Slice of a $512^3$ pseudo-spectral
3D incompressible MHD + A.D.
Decaying turbulence from an Orzag-Tang vortex.
Snapshot at peak dissipation.

G. Momferratos
Dissipation in vortices

B. Godard, E. Falgarone, G. Pineau des Forêts (2009)
Dissipation in shocks

Viscous length

Cooling length

\( b=1, n_H=10^2 \) profiles

Temperature (K)

Distance (cm)

J-shocks

\( u=22 \text{ km/s} \)
The Paris-Durham code (?) (soon online thanks to A. Gusdorf)

- Follow a fluid parcel through a steady shock structure:
  J-shock: trigger viscous jump
  C-shock: charge and neutral velocities free to differ
- Cooling / Heating
- Chemical network: 140 species, 1000 reactions
- 150 H₂ levels followed

=> Temperature and chemical structure, line emissivities...
Models of *Irradiated* shocks

- Include basic PDR physics:
  * Integrate Av extinction throughout the shock
  * Include relevant photo-reactions
  * H₂ and CO self-shielding functions

- Check PDR models are recovered for slowly moving fluid parcel.
Comparison with PDR models

- Meudon PDR code
- Shock code
- nH=50/cm³
- u=10⁻⁴ km/s
- G0=1
Comparison with PDR models

- Meudon PDR code
- Shock code

$n_H = 50/cm^3$
$u = 10^{-4} \text{ km/s}$
$G_0 = 1$
$G_0 = 1$
$A_v = 0.1$
$N(H_2) = 10^{20}/cm^2$

Full grid of models:
http://cemag.ens.fr
Molecule production in shocks

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Temperature barrier</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>O + H₂ → OH + H</td>
<td>2980 K</td>
<td>7.5 km.s⁻¹</td>
</tr>
</tbody>
</table>

Adiabatic relation:

\[ T_{\text{max}} = \frac{2(\gamma - 1)}{(\gamma + 1)^2} \frac{\mu}{k_B} u^2 \]
# Molecule production in shocks

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<tr>
<th>Reaction</th>
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<tr>
<td>O + H₂ → OH⁺ + H</td>
<td>2980 K</td>
<td>7.5 \text{km.s}^{-1}</td>
</tr>
<tr>
<td>C⁺⁺ + H₂ → CH⁺⁺ + H</td>
<td>4640 K</td>
<td>9.4 \text{km.s}^{-1}</td>
</tr>
<tr>
<td>S⁺ + H₂ → SH⁺ + H</td>
<td>9620 K</td>
<td>13.5 \text{km.s}^{-1}</td>
</tr>
<tr>
<td>S⁺⁺ + H₂ → SH⁺⁺ + H</td>
<td>9860 K</td>
<td>13.6 \text{km.s}^{-1}</td>
</tr>
<tr>
<td>C⁺ + H₂ → CH⁺ + H</td>
<td>14100 K</td>
<td>16.3 \text{km.s}^{-1}</td>
</tr>
<tr>
<td>Si⁺⁺ + H₂ → SiH⁺⁺ + H</td>
<td>14310 K</td>
<td>16.4 \text{km.s}^{-1}</td>
</tr>
<tr>
<td>N⁺ + H₂ → NH⁺ + H</td>
<td>14600 K</td>
<td>16.6 \text{km.s}^{-1}</td>
</tr>
<tr>
<td>H₂ dissociation energy</td>
<td>52000 K</td>
<td>31.3 \text{km.s}^{-1}</td>
</tr>
</tbody>
</table>
Molecule production in shocks

![Graph showing molecule production in shocks](image)
Excitation in shocks
$H_2$ lines

$b=0.1, n_H=10^2$: $H_2$ line emission

Line emission (erg/cm$^2$/s/sr)

Shock velocity (km/s)

T (K)

508
844
1682
2332
3474
4415
Excitation in shocks
atomic lines

\[ b=0.1, n_H=10^2: \text{atomic emission} \]
Main coolants in shocks, \( b=0.1 \)
Main coolants in shocks, $b=1$
Ex: Stephan's Quintett

Cluver, Appleton et al. (2010)
Guillard et al. (2009)

$L(H_2) \sim 10^{42} \text{ erg/s}$
$L(H_2) \sim 3 \, L(X)$
$L(H_2) \sim 0.3 \, L(\text{IR})$
$L(H_2) \sim 2 \, L(\text{CII})$
$UV: \ G_0 \sim 1$
Shock driven turbulence

Guillard et al. (2010)

Large-Scale Shock Wave

$V_h \approx 600 \text{ km/s}$

$V_c < V_h$

Hi

$n_H > 0.1 \text{ cm}^{-3}$

H$_2$

Cloud compression and H$_2$ formation

Hot Plasma

$T \approx 5 \times 10^6 \text{ K}$

$n_H \approx 2 \times 10^{-2} \text{ cm}^{-3}$

Fragmentation

$10^6$

$10^7$

time [yr]
Shocks distribution in driven turbulence

Smith, Mac Low & Heitsch (2000) : power-law PDF
Adjust PDF of shocks to observed $\text{H}_2$ emission

Chi square table:

<table>
<thead>
<tr>
<th>$b$</th>
<th>$n_H$</th>
<th>1-Gauss</th>
<th>pow-law</th>
<th>exp.</th>
<th>pw-exp.</th>
<th>2-Gauss</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>$10^2$</td>
<td>371.8</td>
<td>2307.0</td>
<td>54.3</td>
<td>60.8</td>
<td>11.2</td>
</tr>
<tr>
<td>0.1</td>
<td>$10^3$</td>
<td>504.0</td>
<td>1650.4</td>
<td>152.4</td>
<td>61.1</td>
<td>105.6</td>
</tr>
<tr>
<td>0.1</td>
<td>$10^4$</td>
<td>416.1</td>
<td>2139.9</td>
<td>174.3</td>
<td>580.8</td>
<td>155.3</td>
</tr>
<tr>
<td>1</td>
<td>$10^2$</td>
<td>1628.5</td>
<td>184.2</td>
<td>598.5</td>
<td>2.6</td>
<td>2.0</td>
</tr>
<tr>
<td>1</td>
<td>$10^3$</td>
<td>139.3</td>
<td>175.1</td>
<td>35.9</td>
<td>5.0</td>
<td>13.8</td>
</tr>
<tr>
<td>1</td>
<td>$10^4$</td>
<td>130.3</td>
<td>1648.0</td>
<td>12.6</td>
<td>6.3</td>
<td>15.8</td>
</tr>
</tbody>
</table>

Generic PDF shapes:

<table>
<thead>
<tr>
<th>PDF</th>
<th>formula</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power-Law</td>
<td>$u^{-p_1}$</td>
<td>1</td>
</tr>
<tr>
<td>Exponential</td>
<td>$\exp(-p_1 u)$</td>
<td>1</td>
</tr>
<tr>
<td>Piece-wise exponential</td>
<td>at $u = 3, 10, 20, 40$</td>
<td>3</td>
</tr>
<tr>
<td>1-Gaussian</td>
<td>$e^{-(u-p_1)^2}$</td>
<td>1</td>
</tr>
<tr>
<td>2-Gaussian</td>
<td>$e^{-(u-p_1)^2} + p_3 e^{-(u-p_2)^2}$</td>
<td>3</td>
</tr>
</tbody>
</table>
Adjust PDF of shocks to observed H$_2$ emission

The two best fits:

H$_2$ rotational lines: $b=1$, $n_H = 10^2$
Adjust PDF of shocks to observed $\text{H}_2$ emission

PDFs for $b=1$, $n_H = 10^2$
Conclusions

- Molecules are enhanced in low velocity shocks
- Molecular observations probe shock statistics
- We find a bi-modal distribution in both the SQ and the Chamaeleon line of sight
- A significant fraction of the material on these line of sight is shocked
- CO column-densities and CII emission can be significantly affected by low velocity shocks
- Read more in Lesaffre et al. (2012)
Ongoing work:

**CHEMSES = DUMSES + chemistry**

- 10 species, 7 \( H_2 \) levels
- \( 10^{16} \) cm
- 32 species, 7 \( H_2 \) levels
- \( 1024^2 \) pixels, decaying 2D turbulence, \( U_{\text{rms}} \sim 2 \text{ km/s} \)
Molecules enhanced by dissipation of 2D turbulence

$G_0 = 1$
$A_v = 0.1$
The cunning plan..

Intermittent statistics of the dissipation

Molecular yields from Shocks (for example)

Dissipation strength

G. Momferratos

=> Molecules formation
Main coolants $b=0.1$
Main coolants $b=1$

$\textbf{b}=1, n_H=10^2$: main coolings

- H2
- C+
- C
- O
- CO
- H2O
- OH
- H

Normalized cooling vs $u(\text{km/s})$
Code validation: steady-state shock at 3 km/s
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Dissipation in shocks

Viscous length

Cooling length

J-shocks

$b=1, n_H=10^2$ profiles

Temperature (K)

Distance (cm)

$u=22$ km/s
J- and C-type shocks

$b=1, n_H=10^2$ profiles

$V_{magnetosonic}=21$ km/s

Temperature (K)

$10^{-2}$ $10^{2}$ $10^{3}$ $10^{4}$ $10^{5}$

$10^{12}$ $10^{13}$ $10^{14}$ $10^{15}$ $10^{16}$ $10^{17}$ $10^{18}$

distance (cm)

$u=20$ km/s $u=22$ km/s

C-shocks

J-shocks
Maximum temperature in shocks

\[ b=1, n_H=10^2 : \text{max Temperature} \]

![Graph showing maximum temperature in shocks](image-url)
Molecule production in shocks

\[ b=1, n_H=10^2 : \text{neutrals} \]
Molecule production in shocks

\[ b=1, n_H=10^2 : \text{ions} \]

Column-density (\(1/\text{cm}^2\))

\[ \text{u(km/s)} \]

C+  
CH+  
S+  
SH+  
H3+
Excitation in shocks

$H_2$ lines
Excitation in shocks
atomic emission