PDR diagnostics as observed by PACS and SPIRE

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and SAG4 (ISM group of the SPIRE consortium)
How radiation of young stars affects interstellar matter?
Reprocess much of the radiation energy emitted by young massive stars

Origin of most of the non-stellar IR and sub-mm emission from galaxies

Key regions in the chemical and physical evolution of objects from the large scales of the galaxies to the small scale of protoplanetary disks

Spitzer and Herschel provide a wealth of spatial and spectral information of gas and dust emission in the heart of PDR
Sample of nearby galactic PDRs

- Programs: SAG 4, WADI, HEXOS, OT..

- PDRs spanning a wide range of excitation conditions and phases of the ISM:

<table>
<thead>
<tr>
<th>Object</th>
<th>IRAS100</th>
<th>$T_{\text{eff}}$(K), Star</th>
<th>$G_0$</th>
<th>$n_H$ (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orion Bar</td>
<td>20,000</td>
<td>40,000, O6</td>
<td>20,000</td>
<td>$10^5$-$10^7$</td>
</tr>
<tr>
<td>NGC2023</td>
<td>2,000</td>
<td>23,000, B1.5V</td>
<td>1,000</td>
<td>$10^4$-$10^6$</td>
</tr>
<tr>
<td>NGC7023</td>
<td>1,000</td>
<td>17,000, B3Ve</td>
<td>2,600</td>
<td>$10^4$-$10^6$</td>
</tr>
<tr>
<td>Horsehead</td>
<td>500</td>
<td>33,000, O9.4V</td>
<td>100</td>
<td>$10^4$-$10^5$</td>
</tr>
<tr>
<td>p Oph filament</td>
<td>500</td>
<td>22,000, B2V</td>
<td>400</td>
<td>$10^4$-$10^5$</td>
</tr>
<tr>
<td>NGC7023 E</td>
<td>200</td>
<td>17,000, B3Ve</td>
<td>200</td>
<td>$10^4$-$10^5$</td>
</tr>
<tr>
<td>Ced201</td>
<td>100</td>
<td>10,500, B9.5V</td>
<td>200</td>
<td>$\sim10^4$</td>
</tr>
<tr>
<td>IC63</td>
<td>100</td>
<td>30,000, B0.5IV</td>
<td>650</td>
<td>$10^4$-$10^5$</td>
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<tr>
<td>IC59</td>
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<td>30,000, B0.5IV</td>
<td>480</td>
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<td>L1721</td>
<td>100</td>
<td>22,000, B2IV</td>
<td>10</td>
<td>$10^3$-$10^4$</td>
</tr>
<tr>
<td>California</td>
<td>100</td>
<td>37,000, O7</td>
<td>30</td>
<td>$10^3$-$10^4$</td>
</tr>
</tbody>
</table>

$G_0$ : incident FUV radiation field (Habing)
PACS spectral mapping

- Fully-sampled maps
- Total area: 100” x 100”
- Spatial resolution: 6” - 10” (0.01-0.02 pc @ 400 pc)

Resolve the gas cooling lines; each species shows a specific morphology
Inhomogenous medium with dense structures: filaments or clumps?

Bernard et al. (2012)
Parikka et al. in prep.
SPIRE-FTS spectral mapping

- Spectral cube computed with the gridding and super-resolution method **SUPREME** from fully-sampled observations (⇒ **Poster Ayasso**)

- Spatial resolution: 17'' - 42'' (0.03-0.08 pc @ 400 pc)

- Maps of equal areas with SPIRE and PACS

- Dust continuum and gas lines:
  \( ^{12}\text{CO} \ J=4-3 \) to \( ^{12}\text{CO} \ J=13-12 \)
  \( ^{13}\text{CO} \ J=5-4 \) to \( ^{13}\text{CO} \ J=13-12 \)
  \([\text{CI}] \ 370 \& 609\mu\text{m}, [\text{NII}] 205\mu\text{m} \)
  \( \text{CH}^+ \ J=1-0, \text{H}_2\text{O}... \)

- Köhler et al. submitted

Study together the bulk of dust and warm molecular gas. Excited CO localised at the edge.
What are the key processes which regulate the emission of the different components?
Which components originate in the same medium?
Results

1. Role of the different gas coolants
2. Gas thermal pressures
3. Dust properties and density structure
4. Excitation and formation processes of key molecules
1. Gas cooling: spatial distribution

- Trace gas cooling and efficiency of star formation up to high redshift
- Strongest emission at the cloud surface where the gas is warm
- [CII] follows [OI] ⇒ [CII] originates mostly from neutral zone; HII contribution < 25%
- [OI]145µm traces the dense PDR zone where the [CII]/[OI]145µm and [OI]63/145µm decrease
- Self-absorption of the [OI]63µm in PDR

Bernard et al. (2012)
Bernard et al. in prep
1. Gas cooling: budget

[ClII] contributes up to 50% for $G_0 \leq 100$

[OI] contributes up to 50% for $G_0 > 1000$
(lower limit since optically thick)

H$_2$ contributes between ~20 and 40%

[Cl], CO lower than 5%

Others (H$_2$O, CH$^+$) <1%

Methods:
(I) maps convolved in the same beam
(II) background emission substracted

Habart et al. in prep.
1. Gas cooling: PDR code

• Meudon code (1.5.2) solves simultaneously the chemical and excitation equilibrium, the radiative transfer and the thermal balance

- Large variation of [CII] and [OI]145 well reproduced
- [OI]63/145 in data < model: opacity inside the PDR not taken into account properly
- [CII]/[OI]145 decreases with increasing G_0 as expected while [CII]/H_2 ~ constant
  ⇒ Amount of warm diffuse gas underestimated by models for G_0<1000
- Diffuse gas irradiated and slowly shocked could produce strong H_2 but not [OI] (Lessafre et al. 2013)
2. Gas temperature and pressure

- CO and dust temperatures are directly dependent on $G_0$
- Excited CO reveals high column densities of warm and dense gas
- $H_2$ rotational temperatures higher while column densities lower than CO
- $H_2$ shifted towards the cloud edge
  $\Rightarrow$ Excited CO traces a denser & cooler gas than $H_2$
- High gas thermal pressure up to $\sim 10^7$-$10^8$ K cm$^{-3}$ in regions of warm CO and dust emission
3. Dust properties and density structure

- DustEM (Compiègne et al. 2011) + radiative transfer model
- Dense filaments with $n_0 > 10^5$ cm$^{-3}$
- Density profile selfconsistently reproduces atomic, molecular (CO) and dust emission
- CO emission comes from $A_v \sim 1$
- Dust evolution in the denser part  (=> 3 Posters: Arab, Köhler, Ysard)

Köhler et al. submitted
4. Excitation process: CO

- First maps of high-excited CO (J=18-17, 19-18, 22-21) in PDRs (Orion Bar)
- Excitation (UV, IR pumping, cosmic rays, chemical reaction, shock) depends on the environment
- Spectacular agreement between morphologies of high-J CO, intermediate-J $^{13}$CO and H$_2$ tracing irradiated dense structures
- CO excitation temperature high at PAH emission peak

$\Rightarrow$ Very strong constrain on the origin of the CO excitation: UV heating

- RADEX & PDR analysis: $P \sim 3 \times 10^8$ K cm$^{-3}$ (size $\sim 0.006$ pc) (=>$2$ Posters: Parikka, Joblin)
- Pressure gradient $\Rightarrow$ photoevaporation supported by gas dynamics in 7023N (=>$\text{Poster Berné}$)
4. Formation process: CH\(^+\) and OH

- CH\(^+\) J=3-2 and OH 85\(\mu\)m lines have similar \(n_{\text{crit}}\) and \(E_u\): ideal for comparison

- CH\(^+\) formation: \(H_2 + C^+ \Rightarrow H + CH^+\) (endothermicity: 4300 K)

- CH\(^+\) correlation with \(H_2^*\)
  \(\Rightarrow\) formation depends on \(H_2^*\) (Naylor et al. 2010, Nagy et al. 2013)

- OH formation: \(H_2 + O \Rightarrow H + OH\)

- Non-correlation between OH and \(H_2^*\)
  \(\Rightarrow\) formation does not depend on \(H_2^*\) (in agreement with Agundez et. al 2010).

- OH emission traces irradiated structures (Goicoechea et al. 2011) but also correlates with a proplyds

(\(\Rightarrow\) Poster Parikka)
Conclusions and Future Prospects

- PACS and SPIRE spectral mapping excellent to study together the bulk of dust and gas morphology and energetics

- Inhomogeneous medium containing small dense structures at high thermal pressures as a consequence of being directly irradiated. How long they stay? Role in star formation? Dust evolution in densest regions: coagulation? Accretion?

- Role of each gas coolants for ≠ radiation and phases: template for distant systems
  - [CII] originates mostly from neutral zone, [CII] contribution >50% to the total cooling for G0<100 while [OI] contribution >50% for G0>1000
  - CO and dust temperatures correlate with G0
  - H₂ traces a large amount of warm diffuse under-estimated by PDR code when G0<1000

- High-J CO, CH+ and OH connected to the dense irradiated structures: constrain for the modeling of the warm ISM closely related disks or active galaxies
  - CO excitation due to UV heating
  - CH⁺ formation depends on excited H₂, but not that of OH
  - Excitation and dynamic (evaporation, turbulence) have to be studied together
Poster by Arab
Poster by Ayasso
Poster by Berné
Poster by Köhler
Poster by Joblin
Poster by Parikka
Poster by Ysard