Tracing the CO-dark gas in (low-metallicity) galaxies

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Dwarfs self-consistent modeling

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NGC6946
NGC4214
Motivations: star formation at low metallicity

- Little molecular gas traced by CO

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- Little molecular gas traced by CO

- Low SFE in HI gas but high SFE in H$_2$ gas

$\Rightarrow$ Efficient SF from H$_2$?

$\Rightarrow$ SF in atomic gas?
  Glover & Clark 2012
  Krumholz 2012

$\Rightarrow$ Time/evolution bias?

$\Rightarrow$ More H$_2$ than seen by CO?

Wyder et al. 2009
Cormier et al. 2014
Tracing the CO-dark gas

- Milky Way: 30% of molecular mass is CO-dark
  
  *(Pineda et al. 2013, GOT C+)*
Tracing the CO-dark gas

- Milky Way: 30% of molecular mass is CO-dark
  
  (Pineda et al. 2013, GOT C+)

- Local dwarfs (IC10, LMC, SMC, NGC6822):
  10-100 more CO-dark than CO-bright gas mass

  + new work on Magellanic Clouds with Herschel and SOFIA
[CII]/CO ratio and PDR structure

[CII] is the main observable at low- and high-redshift

- High [CII]/CO ratios observed in star-forming dwarf galaxies

What is this telling us about the molecular cloud/PDR structure?

Figure adapted from:
Madden 2000,
Stacey et al. 2010
Hailey-Dunsheath et al. 2010
Tracers of the ISM conditions

**Tools:** Herschel, Spitzer and optical observations + Cloudy spectral synthesis models

**ISM diagnostics:**

- \([\text{SIII}]18/33 \Rightarrow \text{electron density}\)
- \([\text{NeIII}]/[\text{NeII}]\)
- \([\text{SIV}]/[\text{SIII}]18 \Rightarrow \text{radiation field}\)
- \([\text{OIII}]/[\text{NII}]\)

- \([\text{OI}]/[\text{CII}]\)
- \([\text{OI}]/\text{L(TIR)} \Rightarrow \text{temperature, density}\)
- \([\text{OI}63/145]\)
- \([\text{CII}]/\text{CO} \Rightarrow A_V\)
Modeling: strategy

**Model grid setting:**

- **Instantaneous SF**
- Abundances varied with Z
- **Stopped at A_V = 10 mag**
- Pressure equilibrium

**Strategy:** *(30 galaxies)*

1) Derive best-fitting model for HII region
2) Predict PDR phase

**Cloudy**

*Abel et al. 2005, Ferland et al. 2013*

**Starburst99**

*Leitherer et al. 2010*

- H+
- PDR HI/H2
- NeIII, SIV, NeII, SIII, OIII, NII
- CII, OI

Five bins of Z [0.05, 0.1, 0.25, 0.5, 1]

Grids varying: $n_H$, $U$, $t_{burst}$

*Cormier et al. 2015*

*Cormier et al. in prep*
- **Haro3**

  **Results over sample:**
  \[
  \log n_H = 2.2 \ [0.5; 3.5 \text{ cm}^{-3}] \\
  \log U = -2 \ [-3; -1] \\
  t_{\text{burst}} = 3 \ [1; 4 \text{ Myr}]
  \]
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\]

\[
t_{\text{burst}} = 3 \quad [1; \ 4 \ \text{Myr}]
\]

**Second HII component usually lower-\(n_H\) and lower-U but less well constrained**
Modeling: $[\text{CII}]$ in the HII region

- Small fraction of $[\text{CII}]$ from the ionized gas: 10% [0%; 30%] in low-metallicity star-forming galaxies
How much mass is seen by $C^+$ and $C^0$?

Modeling: phase transition
• Derived mass more sensitive to $G_0$ than to $n_H$ or $Z$
  (see also Wolfire et al. 2010
  Bisbas et al. 2015
  Sternberg et al. 2015)

Traceable by CII/TIR
Derived mass more sensitive to $G_0$ than to $n_H$ or $Z$
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Traceable by CII/TIR

- Cl sees more mass than CII, but... at $A_V$ of 10!

How does this apply to galaxies?
Most of the CO has formed CO-dark gas **does not dominate** the mass budget.
• Average depth of the clouds lower
CO-dark gas \textit{dominates} the mass budget
The [CII]/CO ratio as a total mass tracer

- CO-dark gas **dominates** the mass budget
- [CII]/CO as a new tool
- ALMA CO follow-ups for robust calibration

*Madden+ in prep.*
The Schmidt-Kennicutt relation for dwarfs

Open triangles: \( \text{H}_2 \) from CO
Filled triangles: total \( \text{H}_2 \) (from \([\text{CII}]\))
Blue: upper limit in CO
Red: detected in CO

- Offset of dwarf galaxies in Schmidt-Kennicutt relation reduced by CO-dark gas

\( \Sigma(\text{SFR}) \) vs \( \Sigma(\text{H}_2 - \text{total}) \)

\text{Madden}+ \text{ in prep.}
NGC4214: close-up view on separate regions

Low-metallicity ISM properties: result of evolution or intrinsically different?

D = 2.9 Mpc
Z = 1/3 solar
SFR = 0.1 $M_{\odot}$/yr

U, B band
Hα+[NII]
[OIII]

Ubeda et al. 2007
MacKenty et al. 2000

PACS [CII] map
CO(1-0) contours
GREAT: 5 pointings

Region I
SSC 3-5Myr
more evolved and diffuse

Region II
OB associations 2Myr
Younger and more compact
NGC4214: C+ associated with the dense phase?

<table>
<thead>
<tr>
<th>Region</th>
<th>I(CII) attributed to CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region I</td>
<td>75%</td>
</tr>
<tr>
<td>Region II</td>
<td>55%</td>
</tr>
<tr>
<td>Region III</td>
<td>20%</td>
</tr>
</tbody>
</table>

Fahrion+ subm.
NGC4214: effects of evolution

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<th>Region</th>
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</tr>
</thead>
<tbody>
<tr>
<td>I(CII) attributed to CO</td>
<td>75%</td>
<td>50%</td>
<td>20%</td>
</tr>
<tr>
<td>CO-dark H$_2$ mass</td>
<td>80%</td>
<td>65%</td>
<td>&lt;10%</td>
</tr>
<tr>
<td>Covering factor</td>
<td>1/3</td>
<td>1/2</td>
<td></td>
</tr>
<tr>
<td>D(PDR)</td>
<td>170pc</td>
<td>110pc</td>
<td></td>
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Porosity and CO-dark gas linked to evolution

Fahrion+ subm. Dimaratos+ 2015
NGC6946: mapping full disks with FIFI-LS

- Extend coverage from bright regions to full maps at high resolution with FIFI-LS
- What is the full dynamic range of C+ emission across a disk galaxy?

PIs: F. Bigiel & A. Krabbe

D. Cormier, S. Madden, Ch. Fischer, I. de Looze, A. Leroy, J. Stutzki, A. Poglitsch, N. Geis, A. Bryant, A. Bolatto & FIFI-LS Team
FIFI-LS map reveals much increased scatter in relation.

How accurate is CII as a SFR tracer across full disks? Which other local conditions matter?

Does the scaling change away from bright star-forming regions (inter-arm, outer parts) and how?
Nearby galaxies: full physics of star-formation

- Unique opportunity with FIFI-LS and upGREAT
- Significant progress in ISM studies going from small fields to full galaxy maps at many different wavelengths
- Such maps do not exist at matched, high resolution for any PDR tracer / CII.

Example: EMPIRE survey at IRAM 30m – 500hr
to map high-density molecular gas tracers and probe conditions in the immediately star-forming gas across a sample of disk galaxies.
Conclusions

✧ Modeling HII region + PDR in individual galaxies: representative physical conditions ($G_0, n_H, A_V$)

✧ Mass budget: most of the molecular gas is not traced by CO at low metallicity

✧ No clear metallicity dependence but rather on $G_0$ / evolution of regions ($A_V$)

✧ CO-dark gas can be calibrated with [CII]/CO

✧ [CII] is a reliable tracer of the PDR in low-metallicity galaxies need SOFIA to disentangle HI/CO contribution map all regimes within galaxies