SOFIA/GREAT observations of LMC-N 11: Does [C II] trace regions with a large H_2 fraction?

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Motivations

What diagnostics can [C II] 157 μm hold?

- Important cooling line, carries $\sim 0.1 - 5\%$ of $L_{\rm FIR}$
- SFR tracer *(e.g., de Looze+ 2014)* – C II* also used in DLAs *(Wolfe+ 2003)*
- Diagnostic for physical conditions in PDR models ([C II], [O I] $63, 145\,\mu$m, $L_{\rm FIR}$)
- CO-dark molecular gas tracer *(Madden+ 1997; Wolfire+ 2010)*

Routinely detected at high-z

- Recent detections: *e.g., Aravena+ 2016; Bañados+ 2015; Pentericci+ 2016; Bradac+ 2016*

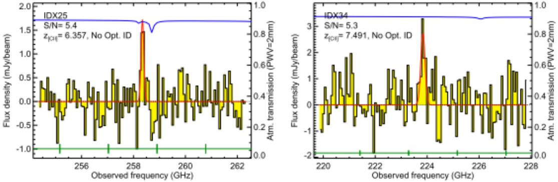

Fig.: *$z > 6$ ALMA [C II] candidates with no optical counterparts in the Hubble-UDF;* *(Aravena+ 2016)*

- Some surprising non-detections *(e.g., Maiolino+ 2015; Carilli+)* – AGN, low metallicity, significant absorption?

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- Diagnostic for physical conditions in PDR models ([C II], [O I] 63, 145 μm, L_{FIR})
- CO-dark molecular gas tracer *(Madden+ 1997; Wolfire+ 2010)*

What is the origin of [C II]?

- CNM, WNM, PDR interfaces with molecular clouds, WIM
- Metal-poor ISM? Low dust abundance (increased PDR clumpiness, lower average A_V)

Previous studies

- **Milky Way** *(Velusamy+ 2010; Piñeda+ 2012, 2015)*, **M 17-SW** *(Pérez-Beaupuits+ 2015)*, **NGC 4214** *(Fahrion+ 2016)*, **LMC-N 159** *(Okada+ 2015)*, **SMC H II regions** *(Requeña-Torres+ 2016)*

⇒ [C II] traces significant CO-dark gas in star-forming regions (especially at low metallicity)
⇒ There might be significant [C II] not associated with the dense star-forming material

Scales and metallicity effects: star-forming regions in Magellanic Clouds

LMC-N 11

LMC

- $1/2\,Z_\odot$
- Range of spatial scales

N 11

- Second largest H II region after 30 Dor ($\sim$ 120 pc)
- At least 3 stellar generations

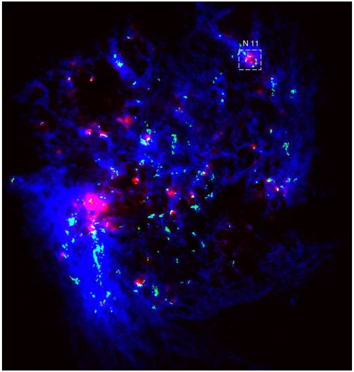


Fig.: *LMC (R: Hα, G: CO(1-0) MAGMA, B: H I 21 cm).*

Fig.: *N 11 (R: Hα, G: IRAC4 (PAH), B: IRAC1 (stars)).*

Rich dataset & wide range of environments

SOFIA/GREAT: [C II] 157 μm and [N II] 205 μm

- 12 pointings previously identified as CO bright cores (MAGMA), [C II] bright spots (PACS)
- PDRs, quiescent CO cloud, ultracompact H II region, stellar cluster

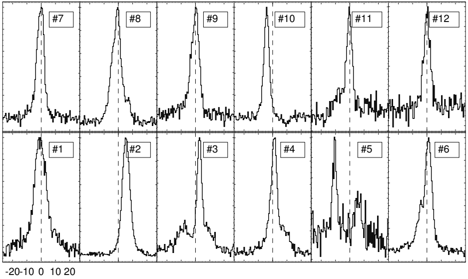


Fig.: *[C II] spectra observed with GREAT.*

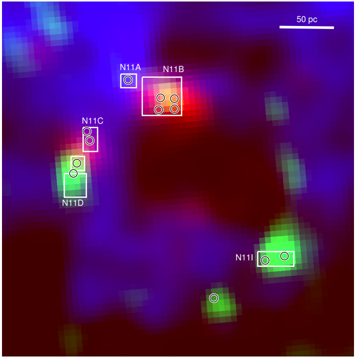


Fig.: *N 11 (R: Hα, G: IRAC4 (PAH), B: IRAC1 (stars)).*

& *Herschel*, *Spitzer*, CO(1-0) MOPRA/MAGMA, CO(1-0) ALMA, H I 21 cm ATCA+Parkes, VLT/GIRAFFE...

Some comparisons

- *Herschel*/PACS [C II] fluxes lower by 1.5 on average (but point-source vs. extended-source flux calibration)

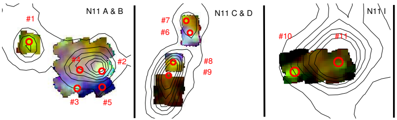


Fig.: *PACS (R: [C II], G: [O I], B: [O III] 88 μm) & CO(1-0).*

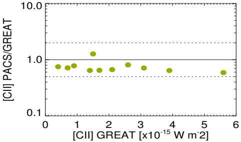


Fig.: *Comparison of GREAT and PACS [C II] fluxes.*

- ALMA CO(1-0) observation of N 11B (PI Lebouteiller)

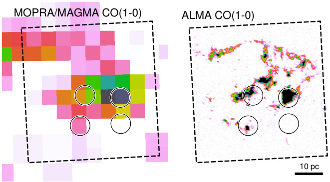


Fig.: *MOPRA/MAGMA and ALMA CO(1-0) in N 11B.*

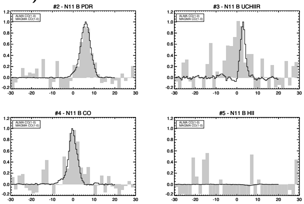
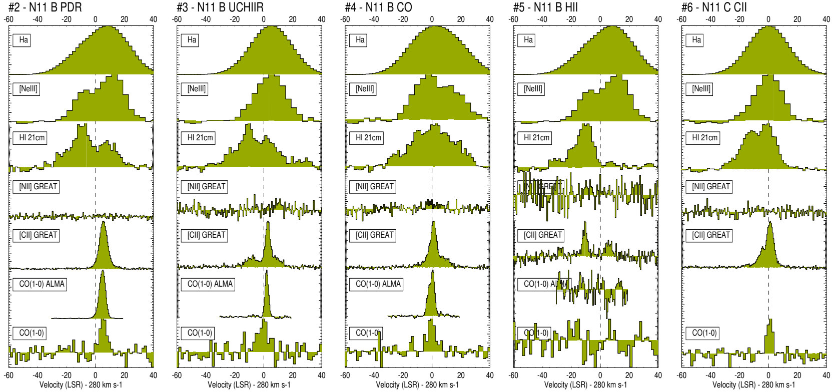


Fig.: *MOPRA/MAGMA and ALMA CO(1-0) profiles.*

Profiles



CO: usually a single component – FWHM $3-8\,\mathrm{km\,s^{-1}}$
[C II]: more structure – (Total) FWHM $4-10\,\mathrm{km\,s^{-1}}$
H I: even more structure – (Total) FWHM $16-40\,\mathrm{km\,s^{-1}}$
Hα and [Ne III] $\lambda3868$: $15\,\mathrm{km\,s^{-1}}$ resolution, kinematic (non-thermal) width $15-25\,\mathrm{km\,s^{-1}}$.

[C II] in the ionized gas

Integrated measurement: [C II]+[O I]/PAH (PACS+*Spitzer*)

- Gas cooling / gas heating (PE), probe of PE heating efficiency *(Helou+ 2001; Croxall+ 2012; Lebouteiller+ 2012; Okada+ 2013)*
- Remarkably tight ratio across N 11. No regions with significantly larger ratio than PDR-dominated regions

Integrated measurement: [N II]/[C II] (PACS)

- *Integrated* ratios [N II]122, 205 μm/[C II] ($\lesssim 0.05, 0.02$) much lower than theoretical ratio in ionized gas

Line width for resolved components (GREAT)

- Width < thermal broadening for C^+ in ionized gas ($7\,\mathrm{km\,s^{-1}}$). Exceptions: multiple components and one component toward #5

[N II] 205 μm profile (GREAT)

- Expected [N II] 205 μm *profile* assuming [C II] originates fully from the ionized gas $\gg$ observed upper limit
- Again one possible exception toward #5 (where the [C II] fraction in the ionized gas is $\lesssim 2/3$)

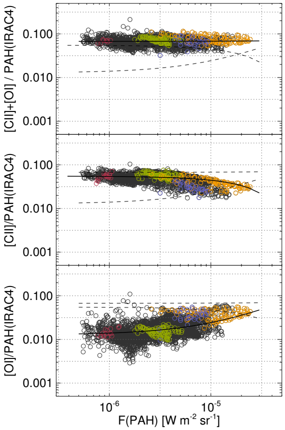


Fig.: *[O I]/PAH (bottom), [C II]/PAH (middle) and [C II]+[O I]/PAH (top) vs. PAH flux.*

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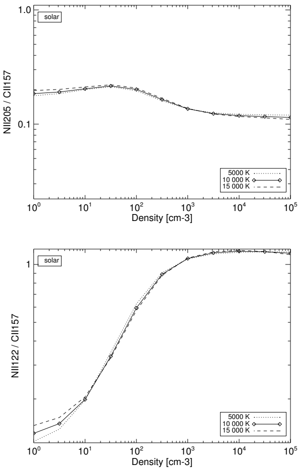

Fig.: *Theoretical [N II]/[C II] in the ionized gas.*

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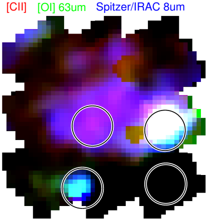

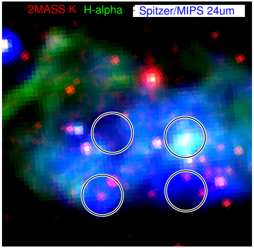

Fig.: *Pointing #5 observes toward stellar cluster LH 10, dominated by [O III], 24 μm, Hα emission.*

[C II] in the ionized gas

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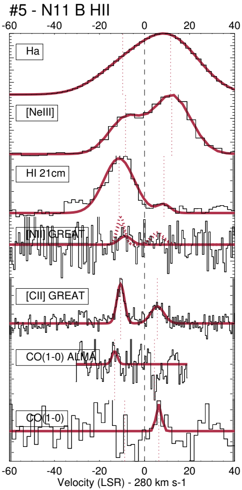

Fig.: *One component toward pointing #5 could be associated with H I or with the ionized gas.*

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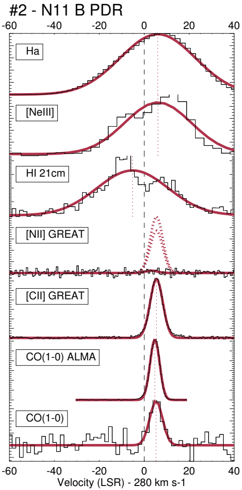


Fig.: *[C II] originates from the neutral medium in most if not all components toward all pointings.*

[C II] decomposition method (1/2): CO → [C II] → H I

- Fitting increasingly complex profiles and add (as few) components as necessary
- Always a [C II] component with same velocity and width as the CO component
- ⇒ [C II] appears wider because of multiple components (not because of larger-scale envelope around CO emitting-region)

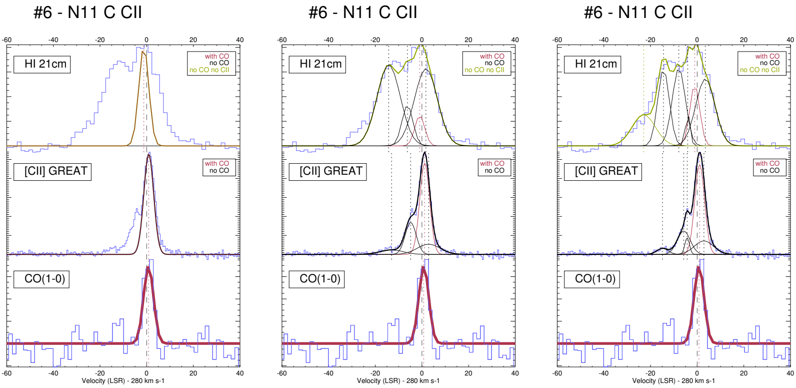
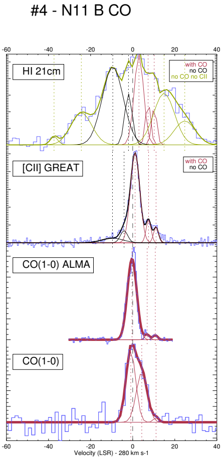
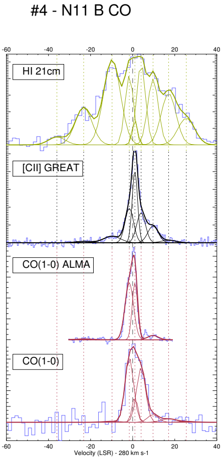


Fig.: *The number of necessary components increases from CO to [C II] to H I.*

[C II] decomposition method (2/2): simultaneous fit

- The minimum number of components identified in CO, [C II], and H I are now fed back to all the tracers ⇒ Individual component properties





Statistics on components

Regimes

- No bright [C II] components with low $f(H_2)$ (as derived from CO)
- Two main regimes
  - Bright, narrow, [C II] components with large $f(H_2)$
  - Faint, broad, [C II] components with low $f(H_2)$
- Some components with moderately bright [C II] components & low $f(H_2)$ $\Rightarrow$ Candidates for CO-dark molecular or atomic gas

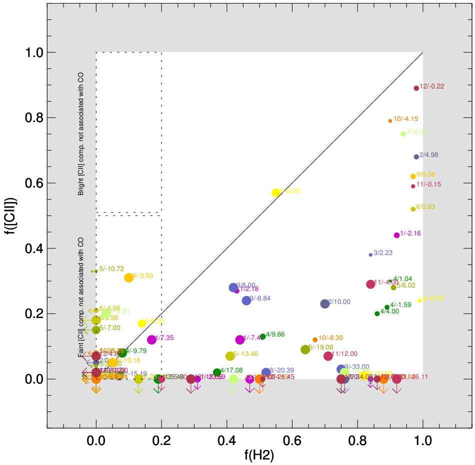


Fig.: Fraction of [C II] in component vs. molecular gas fraction. Size of symbol $\propto$ component line width.

Theoretical expectations

Method

- Calculate theoretical [C II] intensity for collisions with H^0, e^-, and H_2
- Using observed column densities of individual components for H^0 and H_2
  - *Allowing* $10\times$ *more to accommodate for low spatial resolution (H I and CO) or for dense PDRs not well traced by H I 21 cm*
- Two phases: neutral atomic $n(\mathrm{H}^0) = 500\,\mathrm{cm}^{-3}$, and molecular $n(\mathrm{H}_2) = 10^{3-4}\,\mathrm{cm}^{-3}$
- Using 6×10^{20} K km s^{-1} cm^{-2} for X_{CO} *(Roman-Duval+ 2014)*

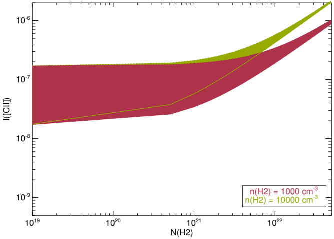
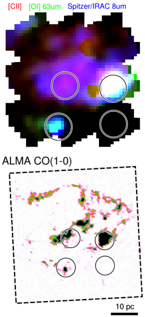


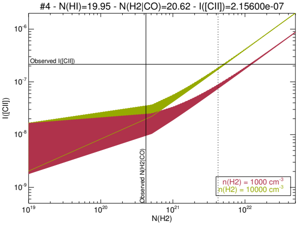
Fig.: *Expected [C II] line intensity for given H^0, H_2 column densities and volume densities.*

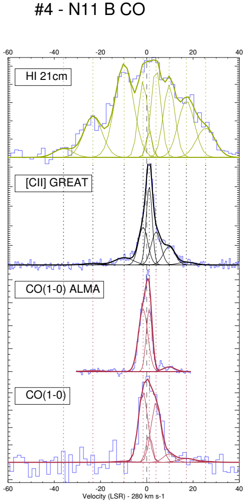
Theoretical expectations

Results

- Many [C II] components associated with CO require either much larger column densities (dense PDRs / CO-dark gas)
- Collisions with H_2 dominate there + discrepancy even using ALMA (high) column densities ⇒ CO-dark gas?







"Well-behaved" clouds

- Some pointings (#9, #11, #12, #7, and #8), *despite being CO bright*, do not have any component that requires extra density and/or CO-dark gas
- Common property: quiescent CO clouds
- $\Rightarrow$ Indirect evidence of CO-dark gas in other pointings due to presence of massive stars

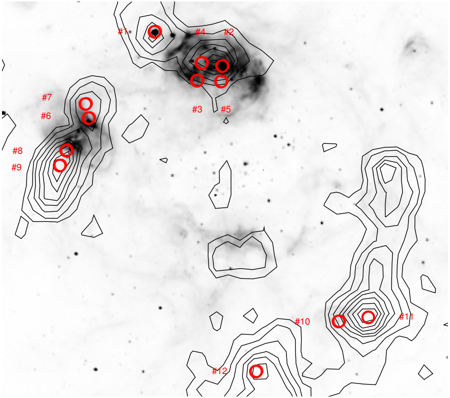
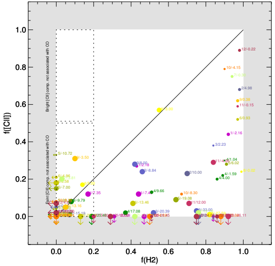
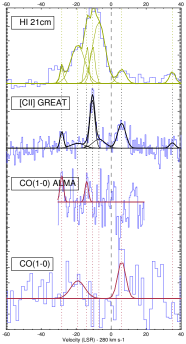


Fig.: *Hα image of LMC-N 11, with CO(1-0) contours.*

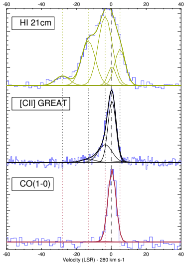
- Weak [C II] components not associated with (bright) CO are compatible with theoretical calculation
- Collisions with H^0 are enough for these components ([C II] in CNM candidate?) – interestingly hard to probe in more distant sources, beam effect? *(Fahrion+ 2016)*



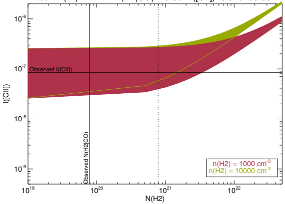
#5 - N11 B HII



#9 - N11 D



#9 - N(HI)=21.14 - N(H2|CO)=19.89 - I([CII])=8.51916e-08



Prospectives

Observations

- Entire region scale: what phases dominate and what is the fraction of CO-dark gas? $\Rightarrow$ mapping capabilities of upGREAT
- Ionized gas contamination $\Rightarrow$ deeper [N II] 205 μm, new [O I] 63 μm – Hα – radio continuum – H radio recombination line *(Pérez-Beaupuits+ 2015)*

Calculations

- Decomposition tricky, no unique solution but some robustness for results
- PDR models to improve the (naive) theoretical predictions – H I 21 cm favors the lower density gas
- What cools the H I components not seen in [C II]? Very diffuse gas with [C II] too faint?
- LMC only $1/2\,Z_\odot$. Lower metallicities need to be explored for effects on the CO-dark gas (but at extremely low metallicities, photoelectric effect may not dominate anymore)

Summary

SOFIA/GREAT observations of [C II] and [N II] 205 μm in LMC-N 11

- **No evidence of [C II] in the ionized gas (only one exception, maybe)**
- **Most of the [C II] is associated with components with large $f(\mathrm{H_2})$**
- **The brightest [C II] component toward all pointing is always associated with CO, with similar velocity and width**
  - Theoretical calculations suggest that most [C II] bright components associated with CO require either CO-dark gas or significantly larger column densities
  - Consistent with large X_{CO} factor calculated in 30 Dor? *(Chevance+ 2016)*
- **Some [C II] components associated with CO are ok with theoretical calculation**
  - Quiescent CO clouds
- **Several extra components seen in [C II], some seem to be associated with H I. Usually relatively broad.**
  - Most extra components agree with theoretical expectations (CNM faint components?)

END – extra slides

SOFIA/GREAT vs. *Herschel*/PACS

All except one pointing observed with *Herschel*/PACS (SHINING program).

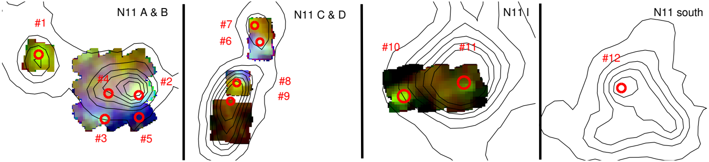


Fig.: *PACS observations [C II] in red, [O I] in green, and [O III] 88 μm in blue. CO(1-0 contours)*

[C II] 157 μm

- PACS fluxes lower by $\sim$ 50% on average
- Caveat #1: using 14.1" for HPBW as measured in 2014, i.e., assuming observations are close to diffraction limit
- Caveat #2: Flux calibration extended/point-source

[N II] 205 μm

- Upper limits with GREAT and PACS

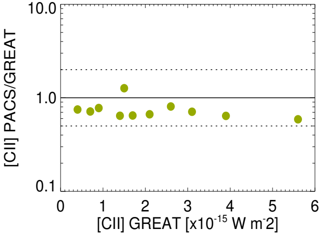


Fig.: *Comparison of GREAT and PACS [C II] fluxes.*

CO(1-0) observations in N 11B

- ALMA CO(1-0) observation (PI Lebouteiller)
- Drastic improvement of S/N and velocity resolution, especially toward stellar cluster where [C II] is detected
- Good agreement with MAGMA (matched to 45")

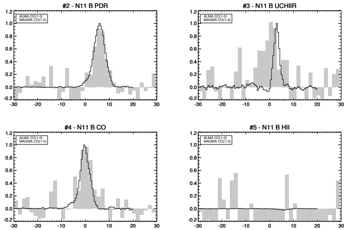
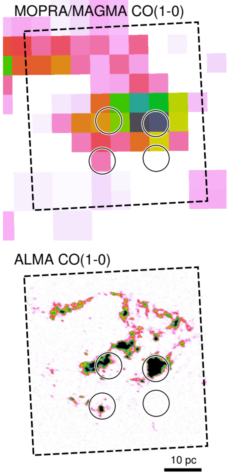


Fig.: *Comparison of MOPRA/MAGMA and ALMA CO(1-0) maps in N 11B.*



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[C II] in the ionized gas

[N II]/[C II] intensity ratio with PACS

- *Integrated* ratios [N II]122 μm/[C II] ($\lesssim 0.05$) and [N II]205 μm/[C II] ($\lesssim 0.02$) much lower than theoretical ratio in ionized gas $\Rightarrow$ most [C II] arises from neutral gas

Thermal broadening

- Expected thermal broadening for C^+ in ionized gas: $\approx 7\,\mathrm{km\,s^{-1}}$.
- Observed $< 7\,\mathrm{km\,s^{-1}}$, except for pointings with multiple components and for one resolved component toward pointing #5

[N II] 205 μm with GREAT

- We calculate the expected [N II] 205 μm *profile* assuming [C II] originates fully from the ionized gas
- No significant evidence of ionized gas contamination, except maybe toward #5 (where the [C II] fraction in the ionized gas is $\lesssim 2/3$)

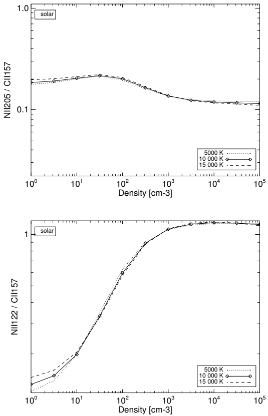

Fig.: *Theoretical [N II]/[C II] in the ionized gas.]*

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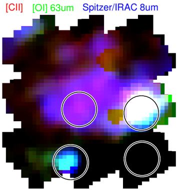
[N II] 205 μm with GREAT

- We calculate the expected [N II] 205 μm *profile* assuming [C II] originates fully from the ionized gas
- No significant evidence of ionized gas contamination, except maybe toward #5 (where the [C II] fraction in the ionized gas is $\lesssim 2/3$)



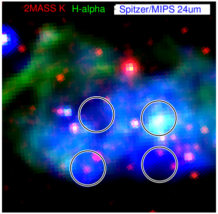


Fig.: *Pointing #5 probes a region toward the stellar cluster LH 10 dominated by [O III], 24 μm, Hα emission.*

[C II] in the ionized gas

[N II]/[C II] intensity ratio with PACS

- *Integrated* ratios [N II]122 μm/[C II] ($\lesssim 0.05$) and [N II]205 μm/[C II] ($\lesssim 0.02$) much lower than theoretical ratio in ionized gas $\Rightarrow$ most [C II] arises from neutral gas

Thermal broadening

- Expected thermal broadening for C^+ in ionized gas: $\approx 7\,\mathrm{km\,s^{-1}}$.
- Observed $< 7\,\mathrm{km\,s^{-1}}$, except for pointings with multiple components and for one resolved component toward pointing #5

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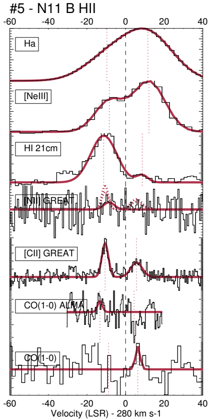

Fig.: *One component toward pointing #5 could be associated with H I or with the ionized gas.*

[C II] in the ionized gas

[N II]/[C II] intensity ratio with PACS

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- We calculate the expected [N II] 205 μm *profile* assuming [C II] originates fully from the ionized gas
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$\Rightarrow$ Contamination of [C II] in the ionized gas is unlikely, even for individual components

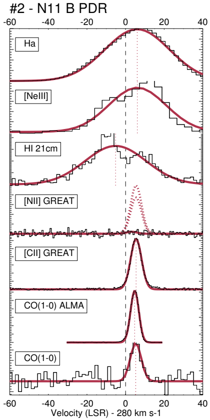


Fig.: *[C II] originates from the neutral medium in most if not all components toward all pointings.*

[C II]+[O I]/PAH

Photoelectric efficiency (PE)

- Ratio [C II]+[O I]/PAH as probe of PE heating efficiency *(Helou+ 2001; Croxall+ 2012; Lebouteiller+ 2012; Okada+ 2013)*
- Gas cooling in neutral gas: [C II] + [O I] (+...)
- Gas heating (PE): PAH or FIR
- Remarkably tight [C II]+[O I]/PAH across N 11. No regions with significantly larger ratio than PDR-dominated regions
- ⇒ Circumstancial evidence that *integrated* [C II] arises from the neutral gas

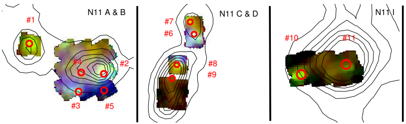


Fig.: *PACS observations [C II] in red, [O I] in green, and [O III] 88 μm in blue. CO(1-0 contours)*

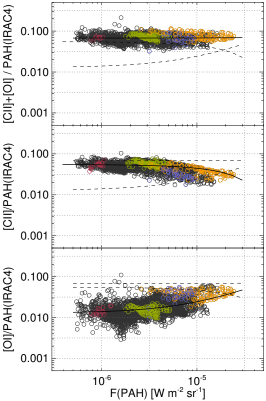


Fig.: *[O I]/PAH (bottom), [C II]/PAH (middle) and [C II]+[O I]/PAH vs. PAH flux.*

H I

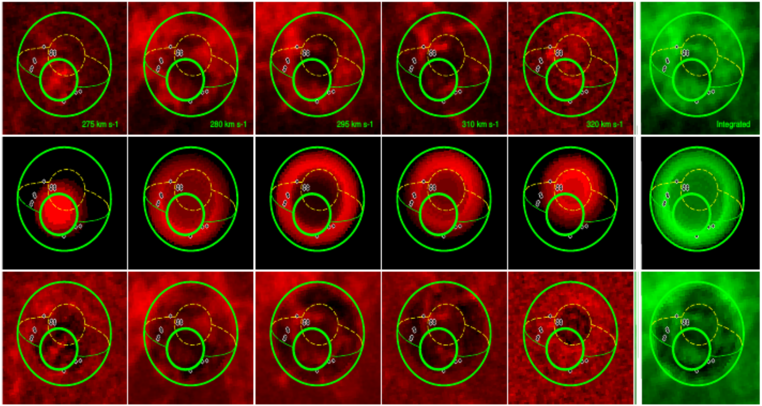
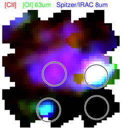


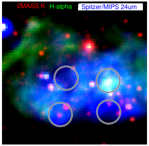
Fig. 5. H I cube at different velocity cuts. The rightmost panel shows the integrated flux. The top row shows the observed H I, the middle row shows a simple model as an expanding shell, and the bottom panel shows the residuals.

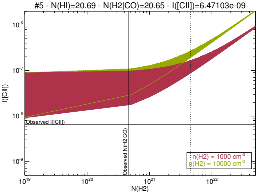
Theoretical expectations

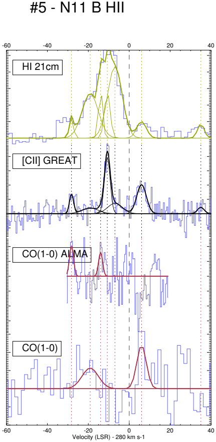
Results

- Brightest [C II] components usually require either much larger column densities and/or volume densities. CO-dark gas is also a plausible explanation.
- Multiple high column-density components in beam not always an issue
- Low densities sometimes required, e.g., for all components toward #5









Summary of data

Instrument	Tracer	LSF FWHM [$\mathrm{km\,s^{-1}}$]	PSF FWHM [″]
SOFIA/GREAT	[C II], [N II]	1.2	≈ 14.1, ≈ 19.1
Herschel/PACS	[C II], [N II], ...	250	12
MAGMA	CO(1-0)	0.53	45
ALMA	CO(1-0)	0.1	2
ATCA+Parkes	H I 21 cm	1.6	60
VLT/GIRAFFE	Hα, [Ne III]	17, 15	≈ 1