[CII] 158 μm emission from L1630 in Orion B

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in collaboration with:

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Introduction

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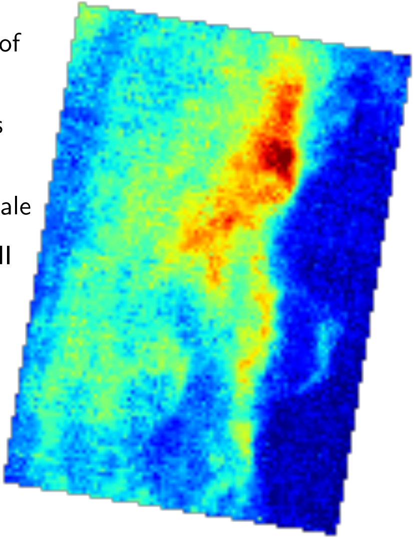
[CII] 158 μm emission

- [CII] fine-structure line one of the brightest far-infrared cooling lines of the ISM, $\sim 1\%$ of total FIR continuum
- [CII] line can be observed in distant galaxies
- correlation of SFR and [CII] intensity: [1] for 46 nearby galaxies, [2] on Galactic scale
- origin of [CII] emission: dense PDRs, cold HI gas, ionized gas, CO-dark gas
- on Galactic scale cf. GOT C^+ [2]
- need to spatially resolve the ISM
- Orion molecular cloud as template region
- velocity-resolved mapping allows to form a 3D picture

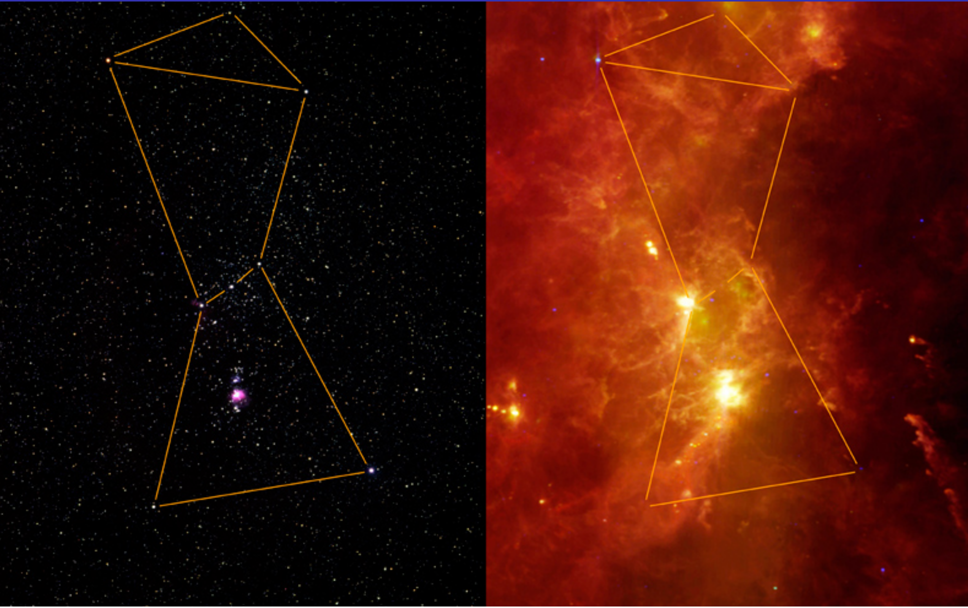


[1] Herrera-Camus et al. (2015) ApJ 800:1, [2] Pineda et al. (2014) A&A 570:A121

The optical window

Image Credit: NASA/ESA/Hubble Heritage Team; M. Robberto/Hubble Space Telescope Orion Treasury Project Team

The infrared window



Left: visible light. Right: infrared light (IRAS). Image Credit: Akira Fujii/NASA/IRAS

L1630 in the Orion B molecular cloud - visible

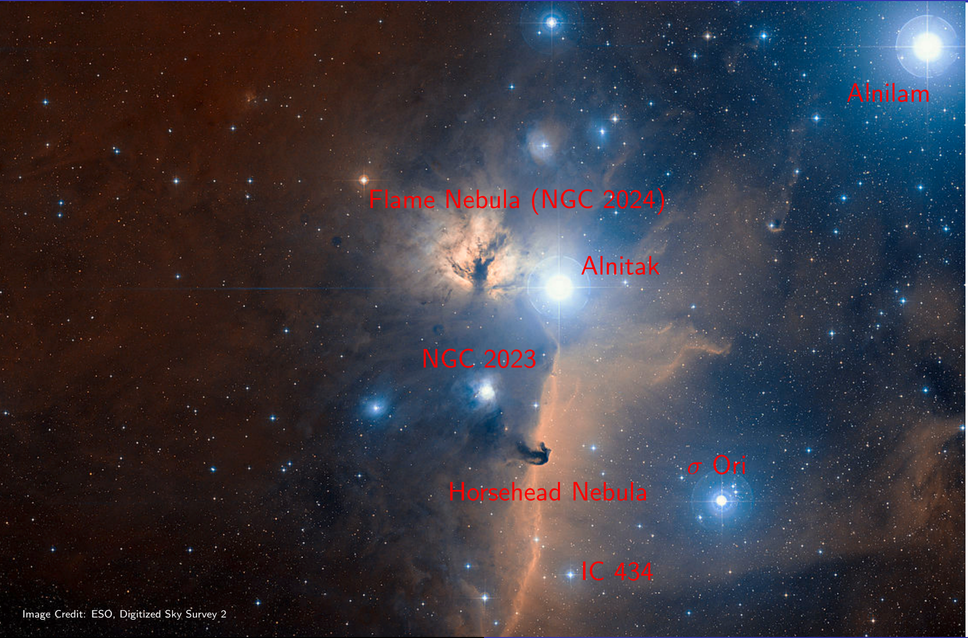


Image Credit: ESO, Digitized Sky Survey 2

L1630 in the Orion B molecular cloud - infrared

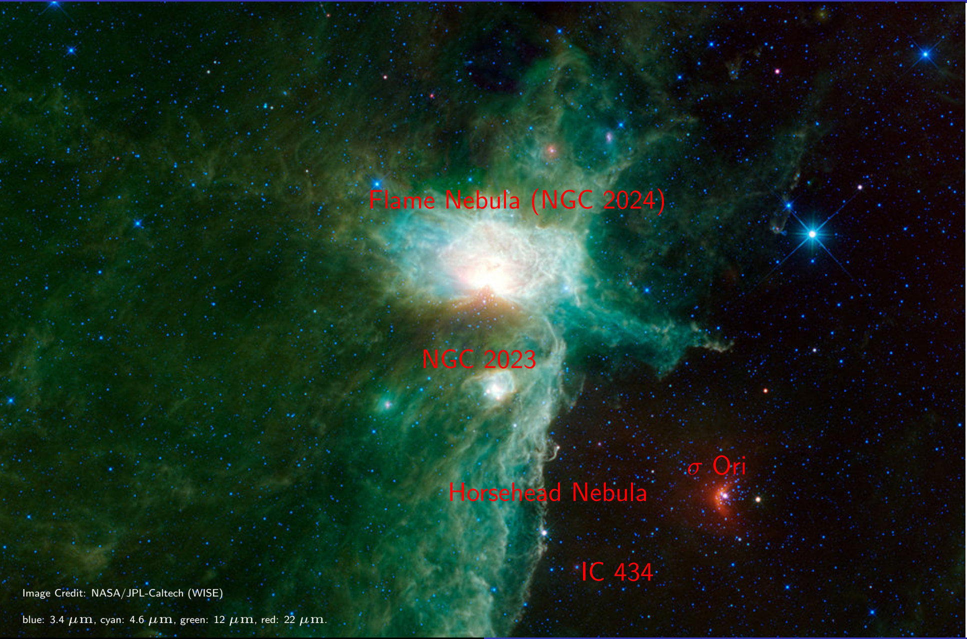
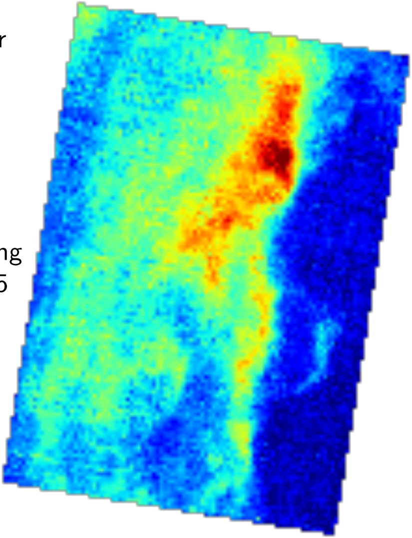


Image Credit: NASA/JPL-Caltech (WISE)

blue: 3.4 $\mu\mathrm{m}$, cyan: 4.6 $\mu\mathrm{m}$, green: 12 $\mu\mathrm{m}$, red: 22 $\mu\mathrm{m}$.

L1630 in the Orion B molecular cloud

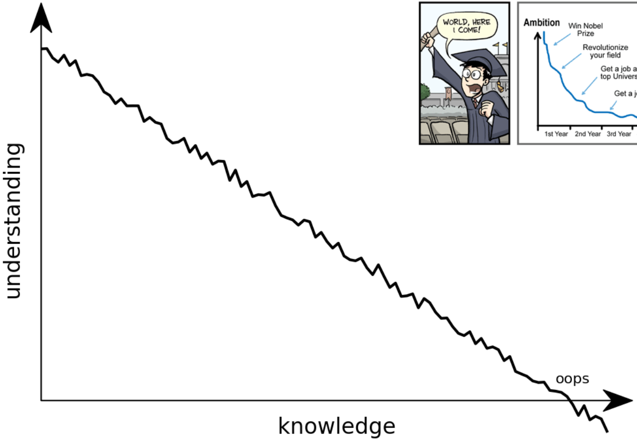
- L1630, comprising the iconic Horsehead Nebula, is illuminated/evaporated by the star system σ Ori at 3 pc distance ($G_0 = 100$).
- edge-on geometry with respect to the illuminating source
- distance from us is 390 pc [3]
- an area of $12' \times 17'$ was observed in [CII] using upGREAT onboard SOFIA in December 2015
- 4.2 hours of Director's Discretionary Time
- beam size $15.9''$, spectral resolution $0.19\,\mathrm{km\,s^{-1}}$



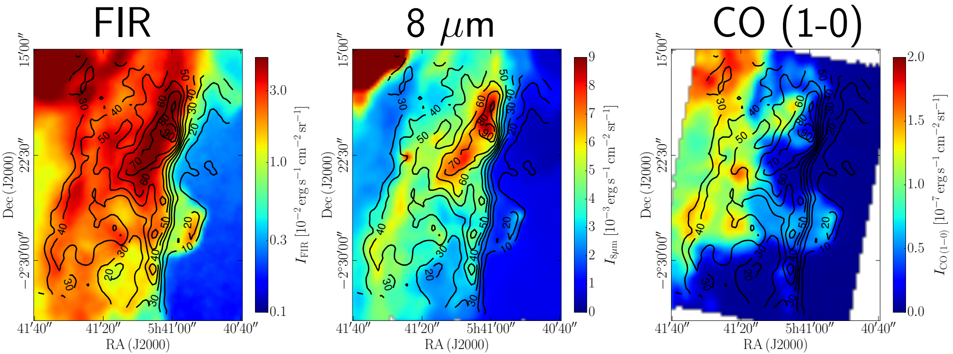
[CII] line-integrated intensity of L1630

[3] Schaefer et al. (2016) ApJ 152:213

Knowledge vs. understanding



Comparison with other gas tracers



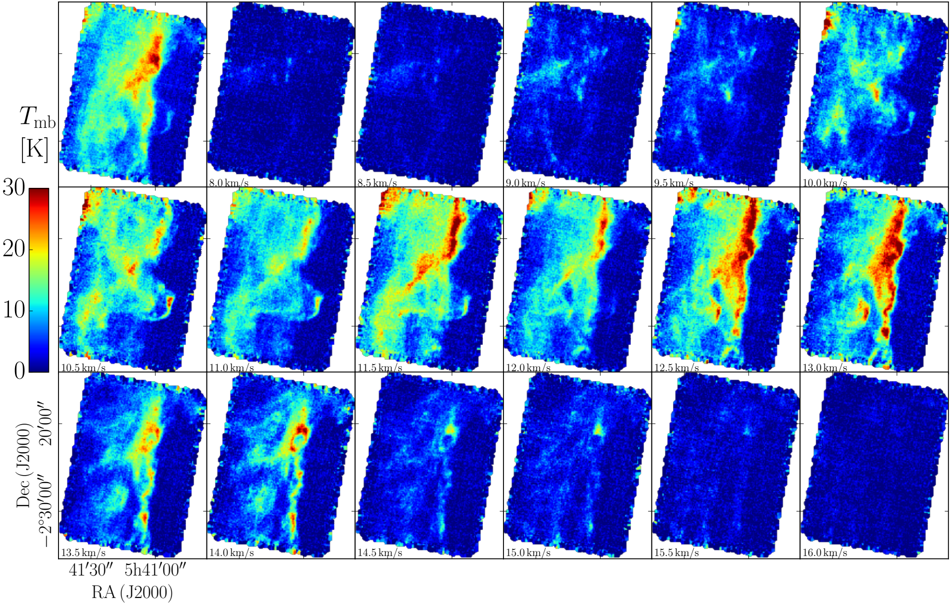
Far-infrared emission (20-1000 μm) traces the UV radiation field re-radiated by dust.

8 μm emission traces the UV field by fluorescence of PAHs at the surface of a cloud.

CO emission traces the molecular gas deeper within the cloud [4].

[4] CO (1-0) data from Pety et al. (2017) A&A 599, A98

[CII] channel maps from 8 to 16 km/s, in steps of 0.5 km/s

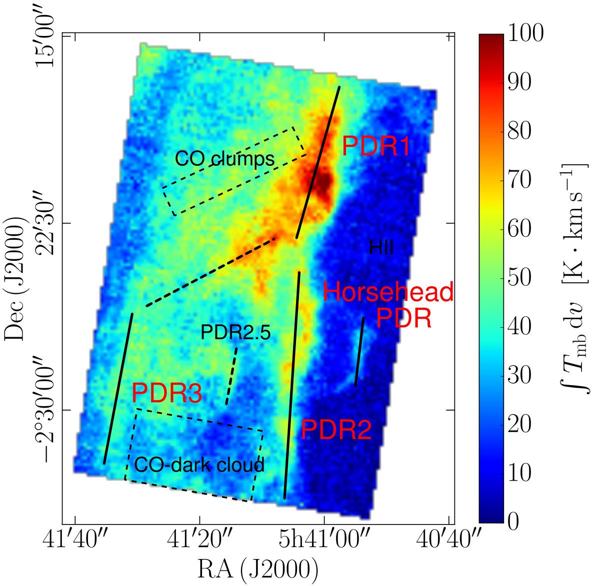


[CII] line-integrated intensity and structures

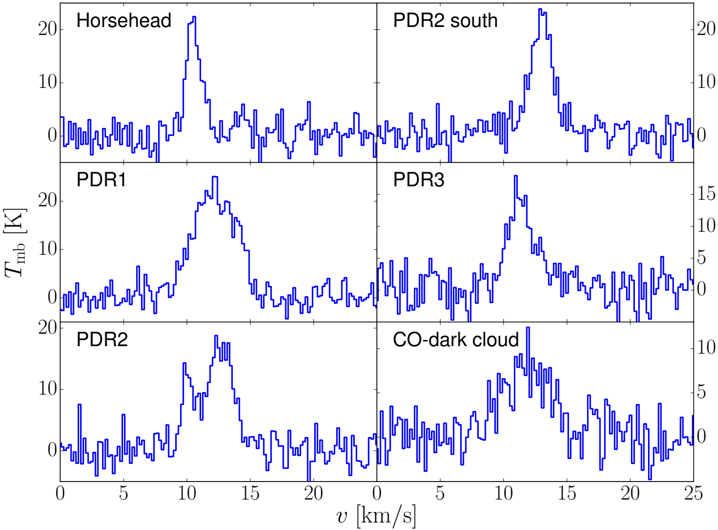
By means of the channel maps and comparison with other data, we identify several regions:

- Horsehead PDR
- PDR1
- PDR2
- PDR3

- PDR2.5
- CO clumps
- CO-dark cloud
- HII region

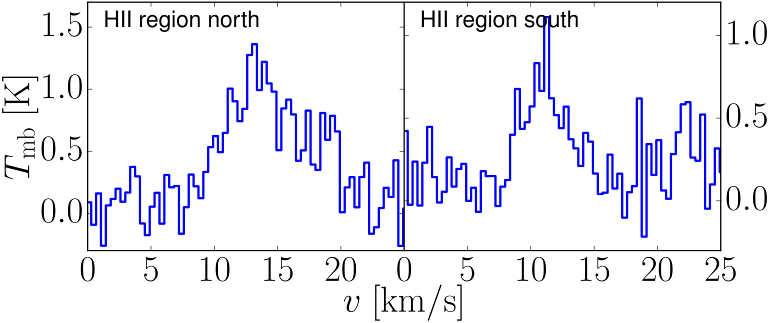


Spectra towards molecular cloud



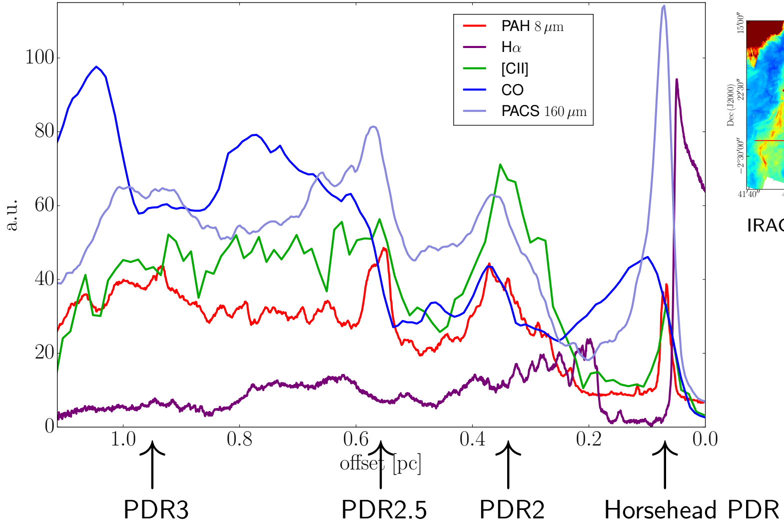
line widths $< 5\,\mathrm{km/s}$

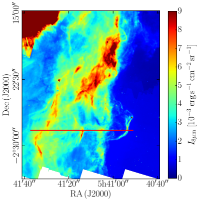
Spectra towards HII region



[CII] line is fainter and broader: $\sim 9\,\mathrm{km/s}$ (left) and $\sim 5\,\mathrm{km/s}$ (right)

Line cut through the molecular cloud

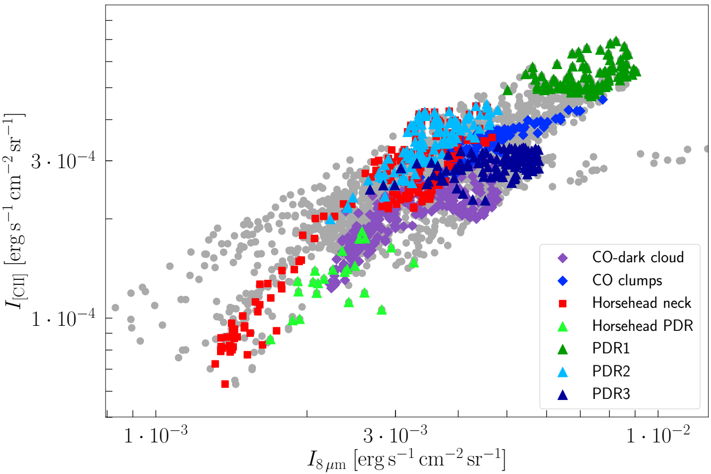




IRAC 8 μm image

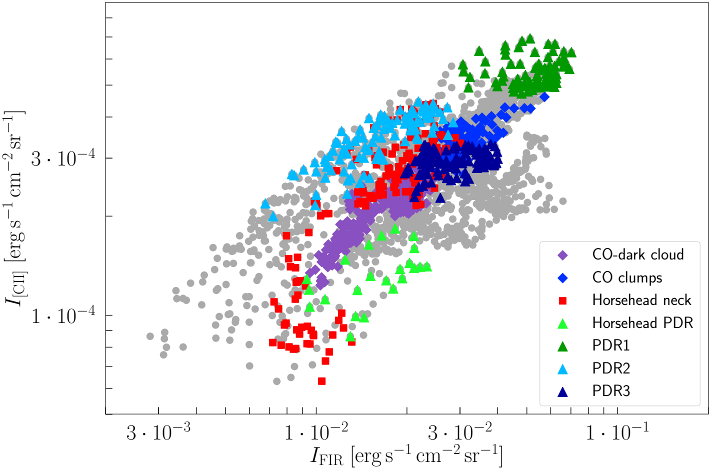
We recognize the prototypical layered structure of a PDR.

Correlation plot $I_{[\mathrm{CII}]}$ vs. $I_{8\,\mu\mathrm{m}}$



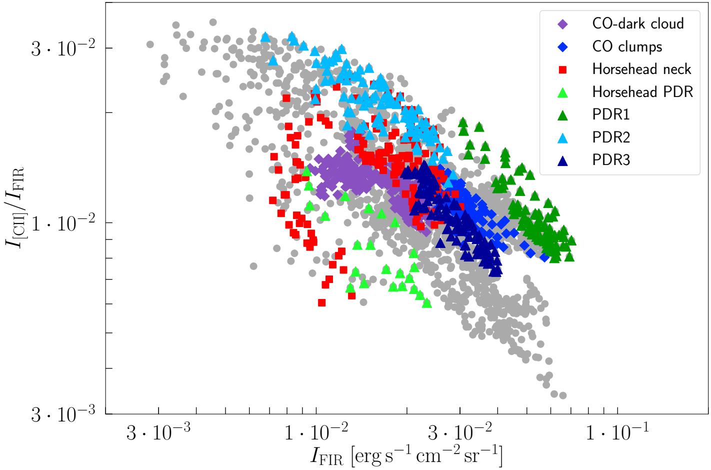
[CII] emission is well-correlated with PAH emission.

Correlation plot $I_{\mathrm{[CII]}}$ vs. I_{FIR}



Correlation of [CII] with FIR emission is not as good as with PAH emission.

Correlation plot $I_{[\mathrm{CII}]}/I_{\mathrm{FIR}}$ vs. I_{FIR}



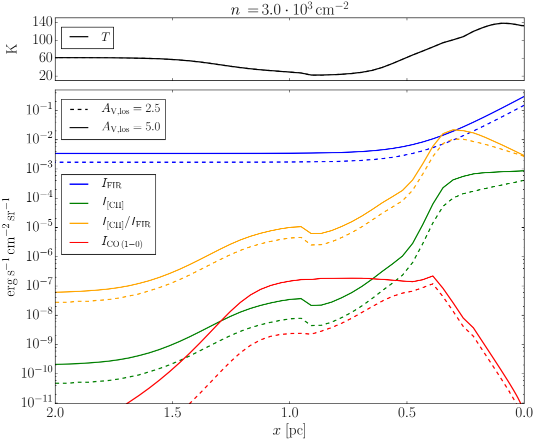
[CII] cooling efficiency $I_{[\mathrm{CII}]}/I_{\mathrm{FIR}}$ varies by a factor of 10 within the mapped area.

Modelling the correlation plots

- We built edge-on models based on [5] with FUV intensity $G_0 = 100$ appropriate for σ Ori, $A_{\mathrm{V,los}}$ and n determined from the data.
- We determined the line-of-sight depth of the cloud $A_{\mathrm{V,los}}$ from the dust optical depth τ_{160}, i.e FIR continuum photometry.
- We find $A_{\mathrm{V,los}} \simeq 5.0\,\mathrm{mag}$ in PDR1, $A_{\mathrm{V,los}} \simeq 2.5\,\mathrm{mag}$ in PDR2, and $A_{\mathrm{V,los}} \simeq 0.5\,\mathrm{mag}$ in the Horsehead PDR
- We determined the gas density n from the scale length of the line cuts, assuming $A_{\mathrm{V}} = 2$ for the transition $C^+/C/CO$.
- We find $n \simeq 3 \cdot 10^3\,\mathrm{cm}^{-3}$ in PDR 1 and 2, $n \simeq 4 \cdot 10^4\,\mathrm{cm}^{-3}$ in the Horsehead PDR

[5] Tielens&Hollenbach (1985), Wolfire et al. (2010), Hollenbach et al. (2012)

Model result for $n = 3 \cdot 10^3\,\mathrm{cm}^{-3}$ on physical scale

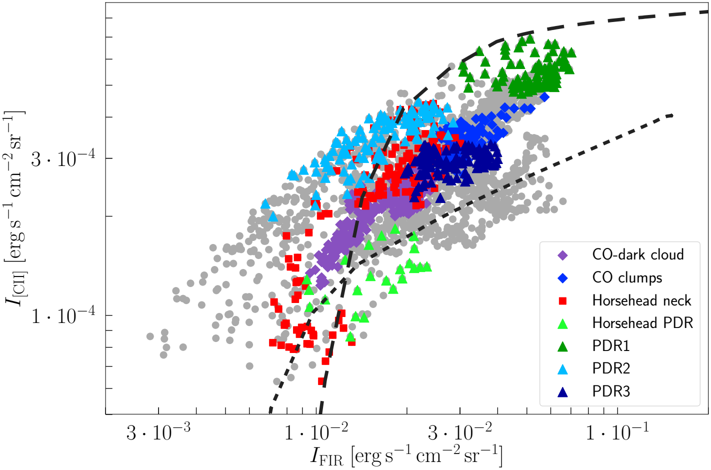


In a nutshell:

Luke-warm surface layers, $T \simeq 120\,\mathrm{K}$, emitting in [CII] and FIR

Colder gas mainly emits in CO, transition $C^+/C/CO$ at $A_V \simeq 2$

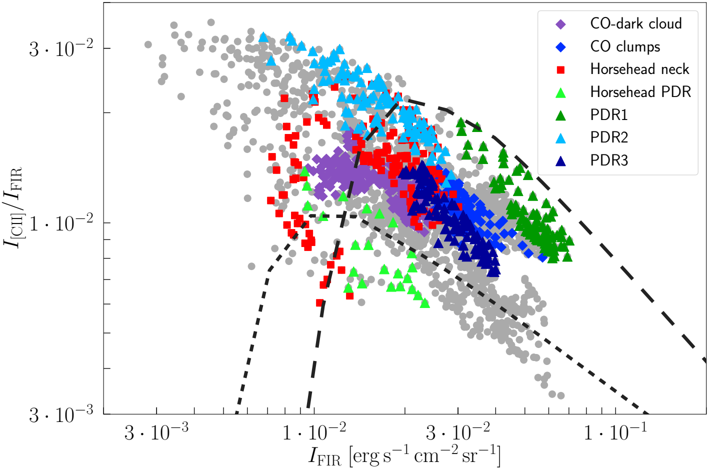
Correlation plot $I_{[CII]}$ vs. I_{FIR} with models



Dotted line: $n = 3.0 \cdot 10^3\,\mathrm{cm}^{-3}$, $A_{\mathrm{V,los}} = 2.5\,\mathrm{mag}$.

Dashed line: $n = 3.0 \cdot 10^3\,\mathrm{cm}^{-3}$, $A_{\mathrm{V,los}} = 5.0\,\mathrm{mag}$

Correlation plot $I_{[CII]}/I_{FIR}$ vs. I_{FIR} with models

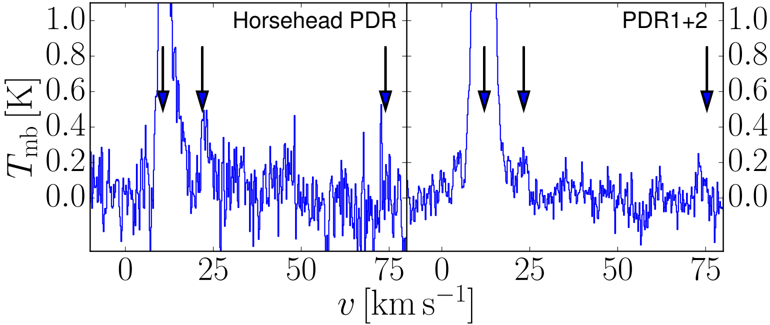


Dotted line: $n = 3.0 \cdot 10^3\,\mathrm{cm}^{-3}$, $A_{\mathrm{V,los}} = 2.5\,\mathrm{mag}$.
Dashed line: $n = 3.0 \cdot 10^3\,\mathrm{cm}^{-3}$, $A_{\mathrm{V,los}} = 5.0\,\mathrm{mag}$

$\Rightarrow$ Increases peak ratio by a factor of 2!

We determine physical properties of the molecular cloud:

We detect one [^{13}CII] line (left: averaged over 180 spectra, right: 3140 spectra):



Due to averaging over some range of conditions, the [CII] optical depth and excitation temperature are not well-determined.

Guevara et al. (priv. comm., in prep.) report $\tau_{[\mathrm{CII}]} \simeq 2$ in the Horsehead PDR from deep observations. For PDR1 and 2 we infer the C^+ column density from the dust optical depth, and the excitation temperature from single spectra.

We determine physical properties of the molecular cloud:

- from line cuts we determine the gas density:
  - $n \simeq 3 \cdot 10^3\,\mathrm{cm}^{-3}$ in PDR1 and 2
  - $n \simeq 4 \cdot 10^4\,\mathrm{cm}^{-3}$ in Horsehead PDR
- from [CII] emission and N_{C^+} (from τ_{160}) we find temperatures:
  - $T \simeq 90\,\mathrm{K}$ in PDR1 and 2
  - in Horsehead PDR for $\tau_{\mathrm{[CII]}} \simeq 2$, $T \simeq 60\,\mathrm{K}$;
    from rotational H_2 lines: $T \simeq 265\,\mathrm{K}$ [6]
    models predict $T \simeq 140\,\mathrm{K}$

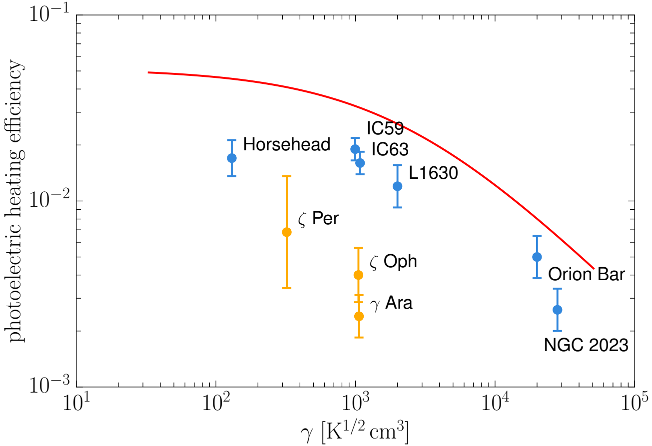
[6] Habart et al. (2011) A&A 527:A122

We determine physical properties of the molecular cloud:

- from τ_{160} we estimate the gas mass within the mapped area (210 arcsec^2):
  - L1630 gas mass: 280 $M_\odot$
  - CO-emitting gas: 250 $M_\odot$
  - [CII]-emitting PDR surfaces: 20 $M_\odot$ (about 8%)
- total luminosity:
  - $L_{\mathrm{[CII]}} \simeq 14\,L_\odot$
  - $L_{\mathrm{FIR}} \simeq 1200\,L_\odot$
  - ratio: $\sim 10^{-2}$
  - compare [CII] cooling efficiency in PDR surfaces: $(1.1 \pm 0.3) \cdot 10^{-2}$

Photoelectric heating efficiency

With the physical properties we derived we can compare with the theoretical heating efficiency by PAHs and very small grains:



In red is the theoretical curve as of [7]. Lower 5 data points are also from [7].

Photoelectric heating efficiency determined from [CII] and [OI] (Horsehead PDR, [8]) cooling efficiency.

Horsehead PDR: $\rightarrow$ $\gamma \simeq 3 \cdot 10^2\,\mathrm{K}^{1/2}\,\mathrm{cm}^{-3}$, $\eta \simeq (1.7 \pm 0.4) \cdot 10^{-2}$

PDR1: $\rightarrow$ $\gamma \simeq 2 \cdot 10^3\,\mathrm{K}^{1/2}\,\mathrm{cm}^{-3}$, $\eta \simeq (1.2 \pm 0.3) \cdot 10^{-2}$

[7] Bakes&Tielens (1994) ApJ 427:822, [8] Goicoechea et al. (2009) ApJ 699:L165

Summary

We used

- comparison with various gas and dust tracers (e.g. FIR, 8 μm, CO emission) to determine the origin of [CII] emission
- channel maps to identify structures
- correlation plots to study the behavior of [CII] emission with other gas and dust tracers (FIR, 8 μm)
- PDR models to fit the correlation plots
- line cuts to determine the gas density
- single spectra to determine the gas kinetic temperature

Conclusions

- by velocity-resolved [CII] observations we can discern connected structures within the L1630 molecular cloud
- 95% of [CII] emission in the studied area come from the molecular cloud, mainly PDR surfaces
- 5% stem from HII region
- [CII] traces gas with little to no CO emission (cf. CO-dark gas)
- [CII] cooling efficiency is $\sim 10^{-2}$
- our edge-on models are able to reproduce the correlations in [CII] and FIR emission
- models of photoelectric heating by PAHs and very small grains overestimate the heating efficiency we measure

A preview of Orion A

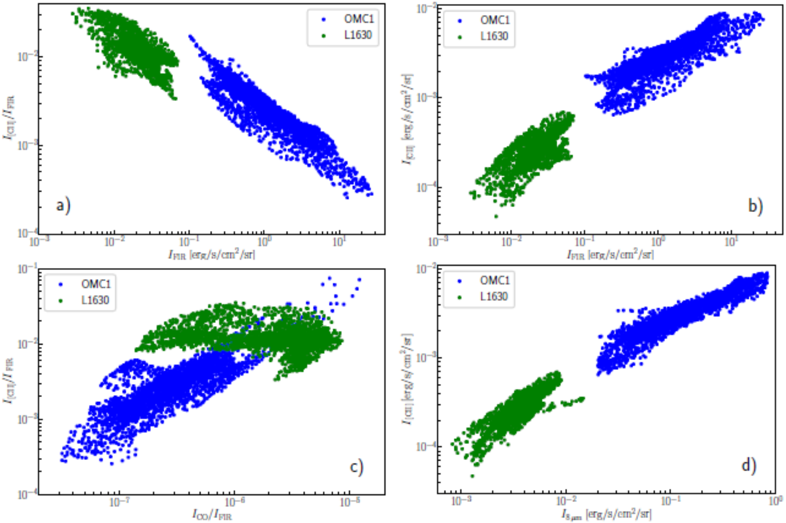
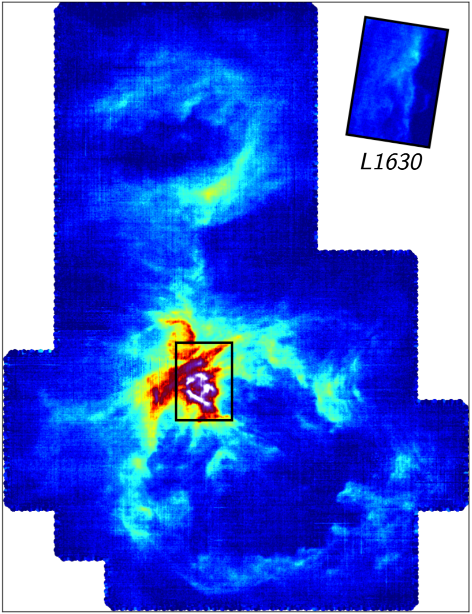


Fig. 19. Correlation plots for L1630 (Orion B) and OMC1 (Orion A); the OMC1 data are convolved to 25″ resolution, L1630 data to 36″ resolution. CO data are for the CO (1–0) line in L1630 and for the CO (2–1) line, divided by 8 (see Sect. 4.10), in OMC1.

Pabst et al. (2017) A&A 606:A29; Goicoechea et al. (2015) ApJ 812:75

This is not the end...



[CII] line-integrated intensity of the Orion Nebula (M42)

black box:
∼ 9h with HIFI/*Herschel*,
∼ 35min with GREAT/SOFIA

SOFIA in morning light, 2016-11-17

Thanks to all who have made this study possible.
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