PDR chemistry revealed by Herschel and SOFIA

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Introduction

Within the Herschel key projects "The Warm And Dense ISM" (WADI) and "Herschel Observations of EXtra-Ordinary Sources" (HEXOS) and in the SOFIA Science Demonstration Time, we observed a number of prominent photon-dominated regions (PDRs) in their main cooling lines and many other tracers not accessible from the ground. Combining these observations with complementary data from the Spitzer Space Telescope and ground-based maps of molecular lines allowed us to study their chemical structure, energy balance, and the kinematics in the sources.

Spatial correlations

From PDR models, we expect a stratified chemical structure with C^+ and first hydrides at the surface, hot CO and atomic carbon at intermediate layers and cold CO and complex molecules deeper in the cloud. We mapped this structure with Herschel and SOFIA.

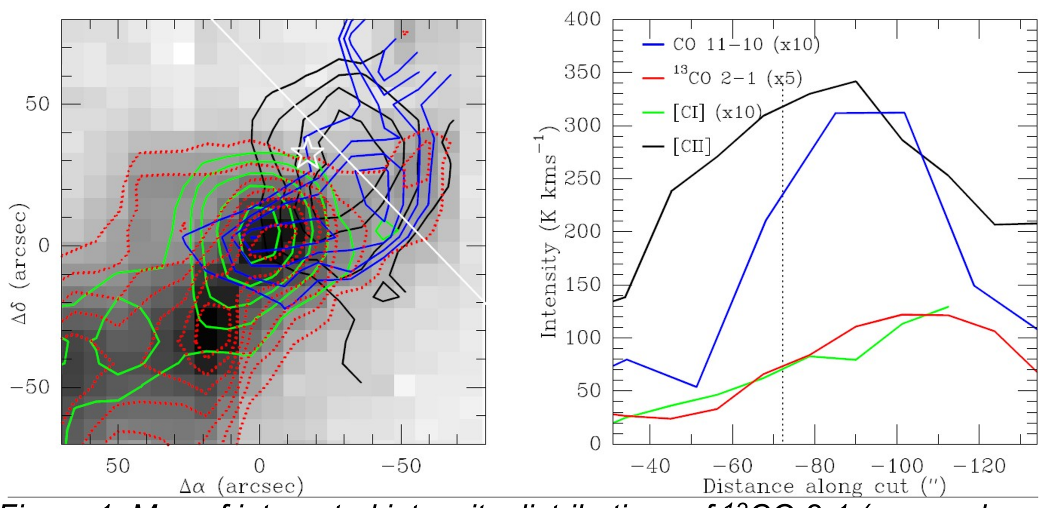


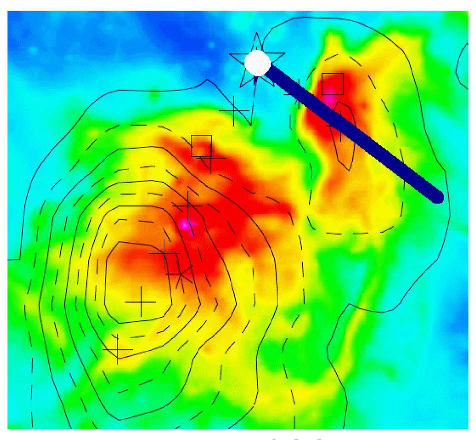
Figure 1: Map of integrated intensity distributions of ^{13}CO 2-1 (greyscale, red contour), [CII] (black), CO 11–10 (blue), and [CI] (green) in CepB. The cut on the right is indicated as white line. The asterisk indicates the embedded HII region (Mookerjea et al. 2012).

We find the expected layering around local UV sources, but atomic carbon never seems to trace transition layers but is best correlated with the column density of cool gas.

By systematically comparing the spatial distribution of the different chemical tracers we determine their diagnostic value for different PDR parameters.

Example: NGC 3603

Figure 2: Optical image of the pillars in NGC3603 (HST, Brandner et al. 2000),



Spitzer/IRAC 8μm image of NGC3603 overlaid by contours of CO 4-3 observed with NANTEN2. The blue line indicates the cut used to analyse the velocity structure in the pv-diagrams.

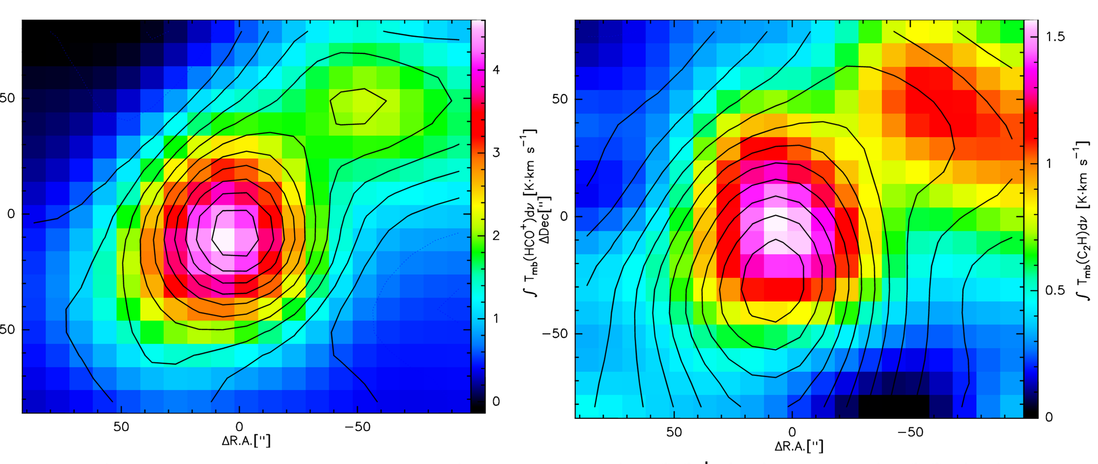


Figure 3: Integrated intensities of the lines of HCO^+ (left, colors), CS (left: contours), C_2H (right, colors), and CH (right, contours) around 540GHz observed with Herschel/HIFI

- The PAH emission traces directly illuminated surfaces, but no embedded clump surfaces
- C_2H and HCO are confirmed as a good PDR surface tracers
- CH is always very extended, also tracing diffuse gas between the molecular clouds
- HCO^+ is sensitive to UV excitation and density allowing a detailed fit of the PDR parameters

Velocity structure

By comparing the line profiles of different species we can quantify how different layers are dynamically affected by radiation pressure, turbulent mixing, and photo-evaporation.

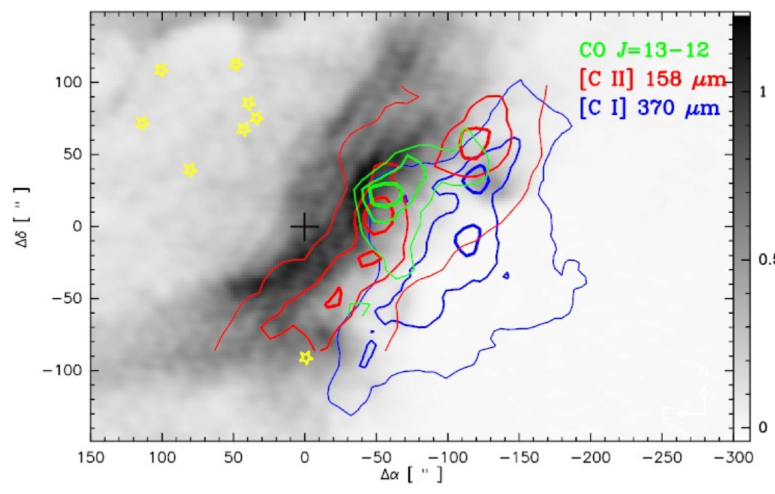


Figure 4: Contours of the integrated [CII], [CI], and CO 13-12 emission in M17SW (Pérez-Beaupuits et al. 2012) overlaid on the 21 cm continuum emission by Brogan & Troland (2001).

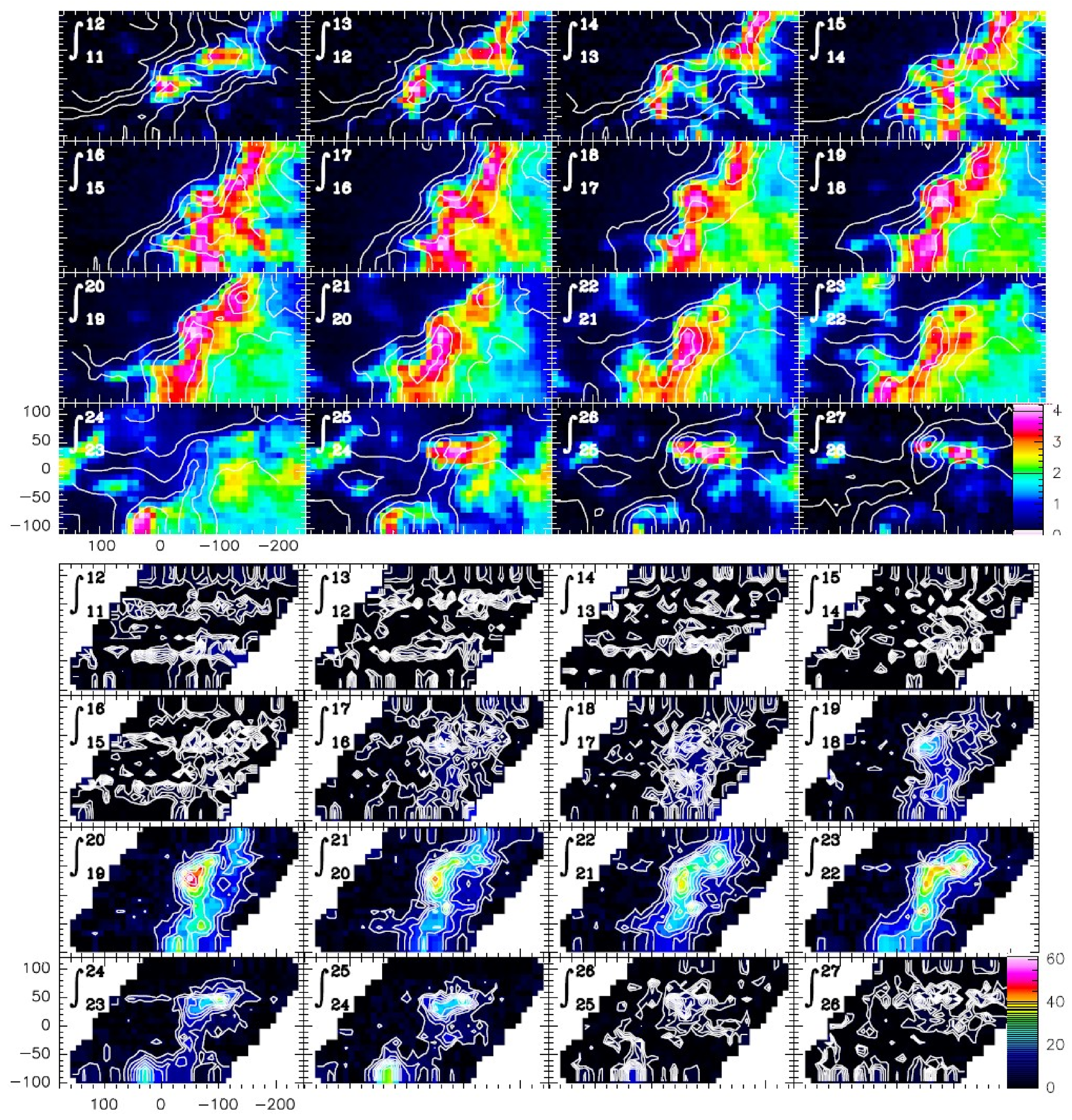


Figure 5: Channel maps of [CII] (contours, top), CO 2-1 (colors, top), and CO 13-12 (bottom) in M17SW.

The [CII] velocity distribution is always considerably wider than that of all other tracers, including HI. It shows additional wings and velocity components. The best correlation is found with low-J CO.

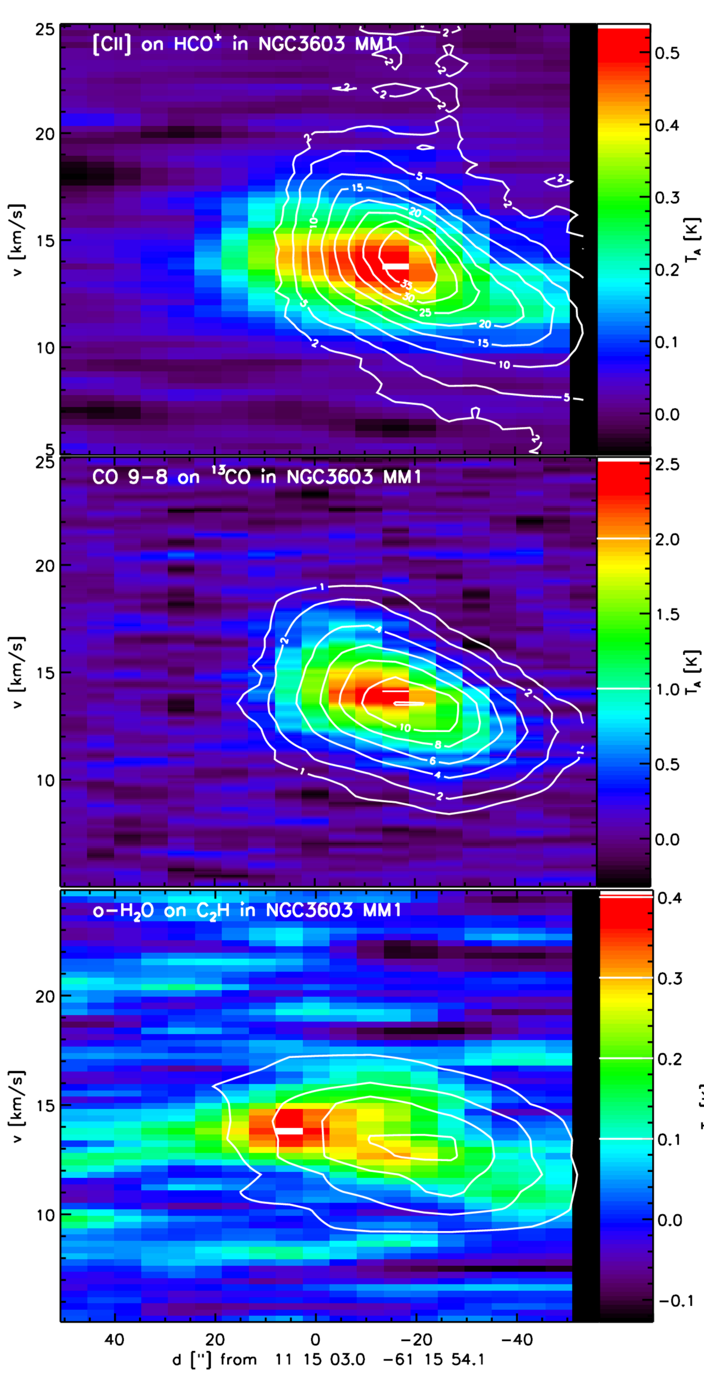


Figure 6: pv diagrams in NGC3603 MM1 (cut): [CII] (top,contours) HCO^+ 6-5 (top, colors) CO 9-8 (center, contours) ^{13}CO 10-9 (center,colors) H2O (bottom, contours) C2H (bottom, colors)

[CII] peaks deeper in the core and is red-shifted relative to molecular tracers (Ossenkopf et al. In prep)

Lines are broadened towards the UV source, indicating a pressure gradient.

[CII] shows a turbulent tail of material away from the sources.

For simple sources exposed to a high UV field we find a systematic spatial and velocity offset of [CII] relative to the tracers of dense material. C^+ must be blown from the surface into a clumpy medium.

Photoelectric heating

Photoelectric heating is governed by the ionization of polycyclic aromatic hydrocarbons (PAHs). We studied the relation between the heating efficiency and PAH charges using spectroscopy with PACS onboard *Herschel* and the IRS onboard of *Spitzer*. To derive the fraction of the charged PAHs, we decomposed the MIR spectra into contributions of neutral (PAH^0) and ionized PAHs (PAH^+) by fitting them with a set of template spectra (Pilleri et al. 2012).

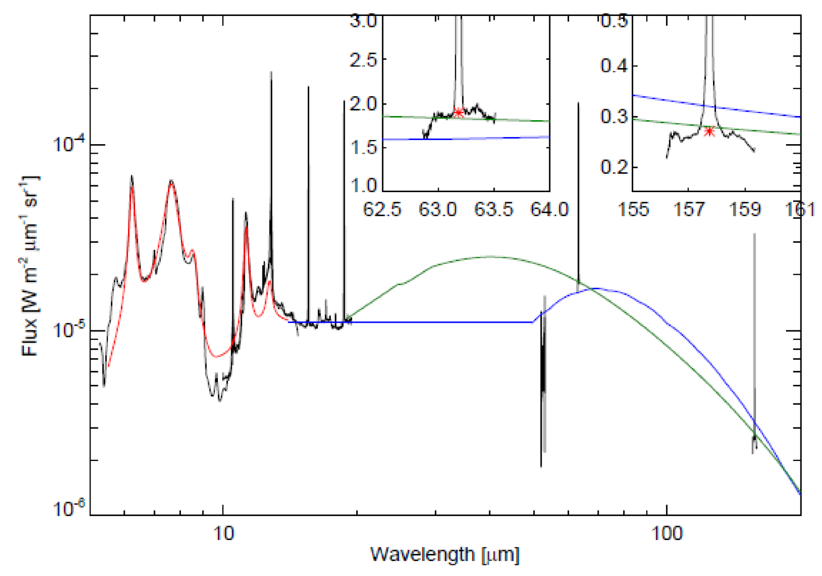


Figure 7: Combined fit of continuum and cooling lines for Carina North, The remaining uncertainty is due to the gap between Spitzer IRS and PACS wavelength coverage.

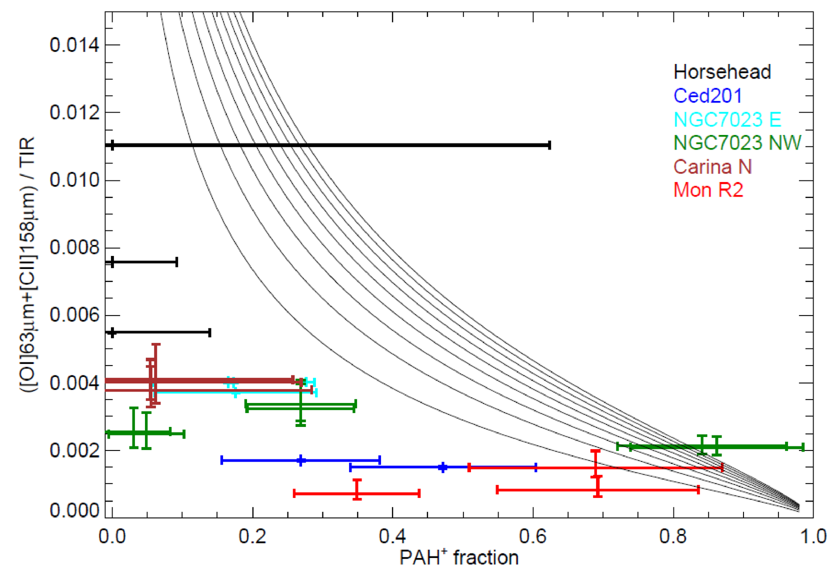


Figure 8: The gas heating efficiency, measured as the intensity of the two main gas cooling lines relative to the total radiative energy throughput, as a function of the fraction of ionized PAHs, PAH^+. The black lines represent the theoretical curves from Bakes & Tielens (1994) for different dust sizes.

The expected anti-correlation of the PE heating efficiency with PAH^+ fraction is confirmed. However, the theoretical models for the PE heating efficiency systematically overestimate the observed efficiency (Okada et al., submitted).

Summary

- The observed layering of species in PDRs becomes quantitatively understood
  - This can be used to fit the gas density from the observed stratification in a clumpy medium
  - CI remains a puzzle, not following the layering or clumpy structure seen in other species
- The physics of surfaces is still not understood:
  - Role of PAHs for H_2 formation
  - Contribution to total electron density balance
- Low-density gas is dynamically affected by UV radiation
  - The dominant process is acceleration through radiation pressure
  - UV creates local heating and velocity gradients but is irrelevant for large-scale collapse

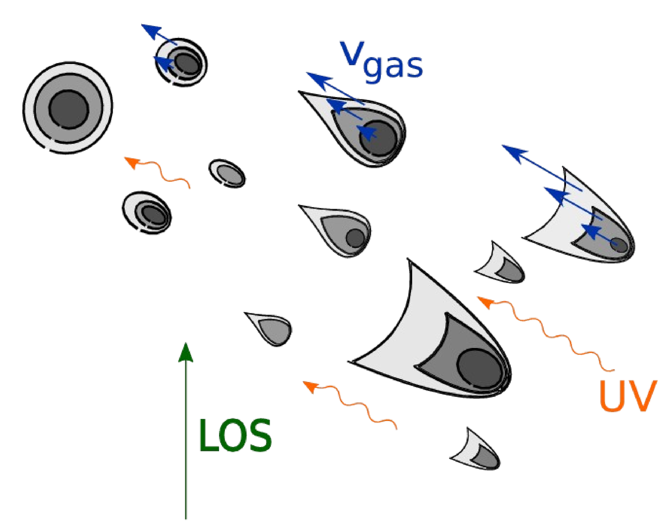


Figure 9: Schematic representation of the gas dynamics in a clumpy PDR with radiative acceleration of thin, photo-evaporating gas, best traced through [CII].

- **Statistically, there is no significant radiative triggering of star-formation on global scales.**