Carbon fractionation in photon-dominated regions

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Introduction

Within the Herschel key projects "The Warm And Dense ISM" (WADI) and "Herschel Observations of EXtra-Ordinary Sources" (HEXOS) we observe a number of prominent photon-dominated regions (PDRs) to measure their chemical structure, determine their energy balance and dynamic state.

With HIFI at Herschel, we had the first chance to systematically study the ratio of $^{12}C^+/^{13}C^+$ in PDRs. The [^{13}CII] lines were clearly detected in the Orion Bar, NGC3603, Mon R2, and the Carina molecular cloud.

Carbon fractionation

Carbon fractionation is driven by the reaction:

$$^{13}C^+ + CO \leftrightarrow {}^{13}CO + C^+ + 35\ K$$

enriching ^{13}CO and depleting $^{13}C^+$ at low temperature. As a consequence, C^+ fractionation is strong where CO is abundant. However, the effect is weak in the column density ratio of $^{12}C^+$ and $^{13}C^+$ since most ionized material occurs at low A_V.

Observations of [^{13}CII] can actually trace three different hyperfine components that should appear in an intensity ratio of 0.44 (F=2-1) : 0.36 (F=1-0) : 0.20 (F=1-1). In case of the standard isotopic abundance ratio $^{12}C/^{13}C$ of about 60:1, each of the two strongest components is thus expected to be about 0.4/60 times weaker than the [^{12}CII] line.

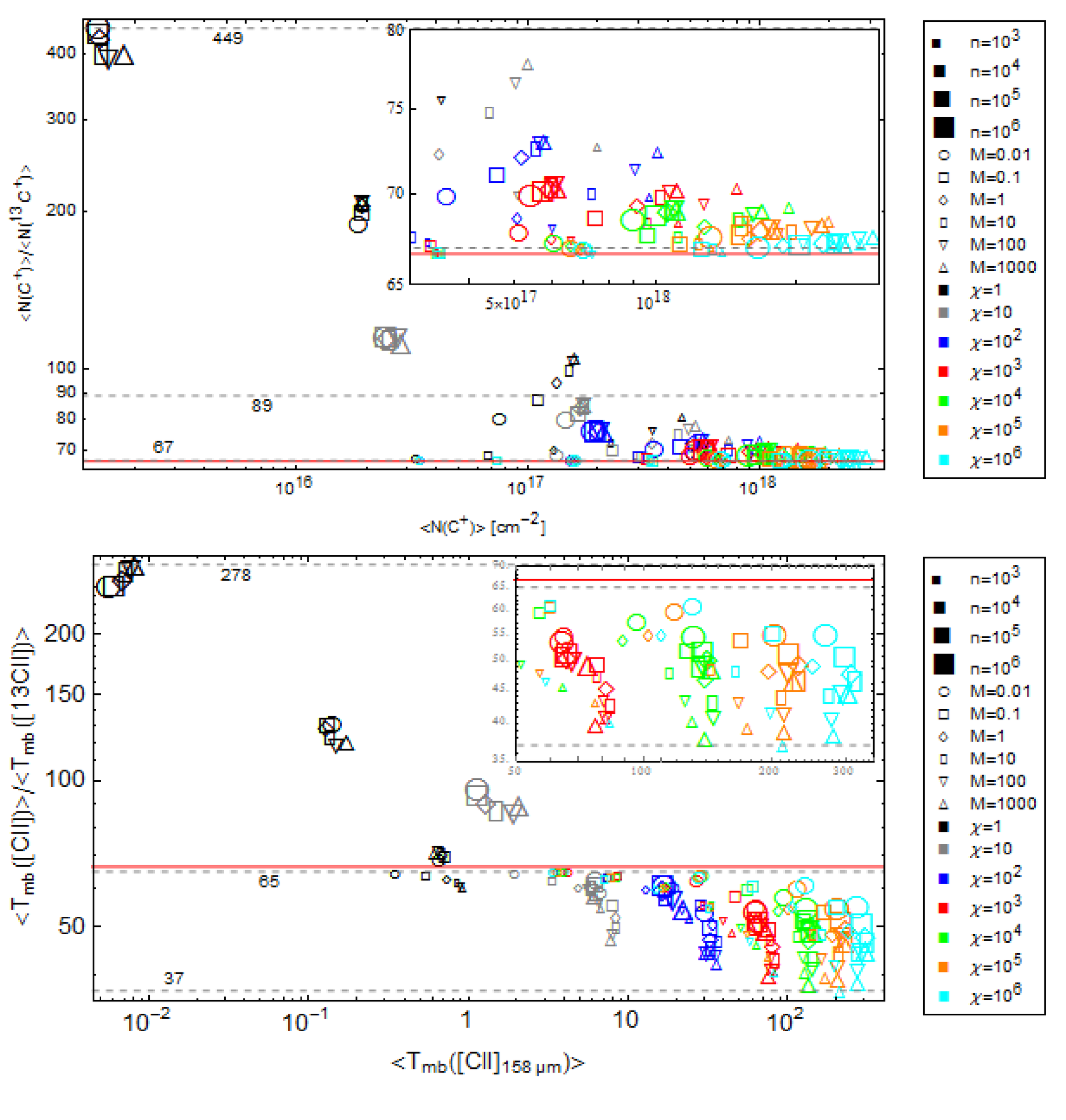


Figure 1: KOSMA-τ model predictions for $C^+/^{13}C^+$ ratios in PDRs with different density, mass, and radiation field. ***Top:*** *Mean (clump-averaged) column density ratio $<N(^{12}C^+)>/<N(^{13}C^+)>$ vs. column density of $^{12}C^+$.* ***Bottom:*** *Corresponding intensity ratio $<T([^{12}CII])>/<T([^{13}CII])>$ as a function of the surface brightnesses $<T([^{12}CII])>$. All models use an isotopic abundance ratio 66:1 indicated as red line. The dashed lines mark minimum, maximum and mean value from the models.*

The expected column density ratio $C^+/^{13}C^+$ is always larger than the isotopic ratio, but models of clumpy PDRs show that the intensity ratio can be as low as 35:1 due to optical thickness of the [^{12}CII]. Intensity ratios above the isotopic ratio occur for relatively low radiation fields and high densities. The lowest ratios are observed for very massive clumps exposed to radiation fields of more than 100 Draine fields, producing a [CII] optical depth of about two. In these clouds, C^+ is only seen in a thin surface layer.

For an ensemble of clumps with a broad size and density distribution and multiple surfaces exposed to decreasing UV field strengths from mutual shielding, we expect intensity ratios of about 50:1 for classical PDRs and regions with low densities; values above the isotopic ratio of about 60:1 should be seen for regions of lower UV fields.

The Orion Bar

The Orion Bar is one of the most prominent PDRs exposed to an UV intensity of ~4 10^4 Draine fields. With HIFI we were able to spectrally map the [CII] and [^{13}CII] lines across the Bar. By using a total-power OTF mode we were immune to self-chopping.

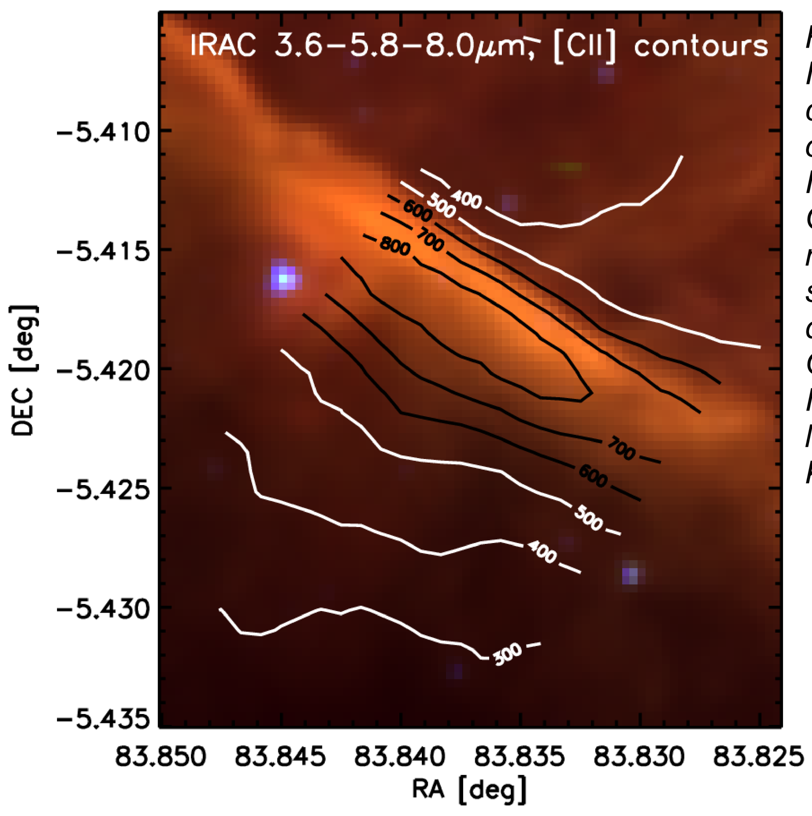


Figure 2: Integrated [CII] contours over-laid on the false-color IRAC map of the Orion Bar. [CII] is mapped in a stripe perpendicular to the Orion Bar. Intensities are labelled in units of K km/s.

[CII] shows a very smooth structure peaking approximately 10'' deeper in the cloud than the PAH emission. The intensity is much larger than in previous KAO observations due to the extended emission that lead to self-chopping there.

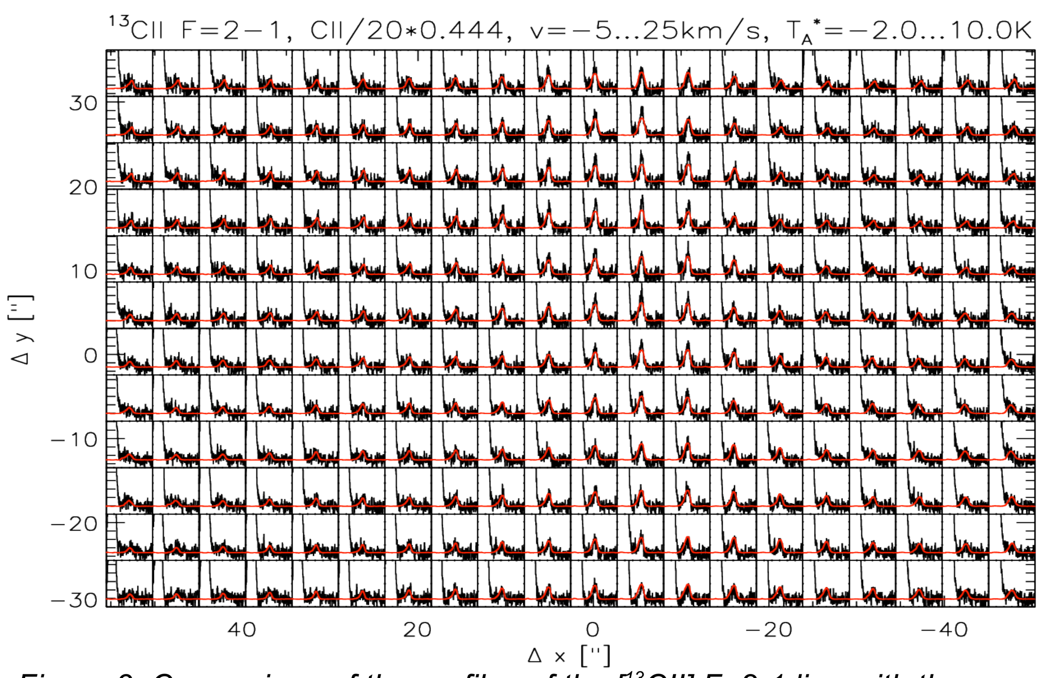


Figure 3: Comparison of the profiles of the [^{13}CII] F=2-1 line with the [^{12}CII] profile scaled by a factor that would correspond to a threefold enhancement of [^{13}CII] relative to the normal isotopic ratio and optically thin lines.

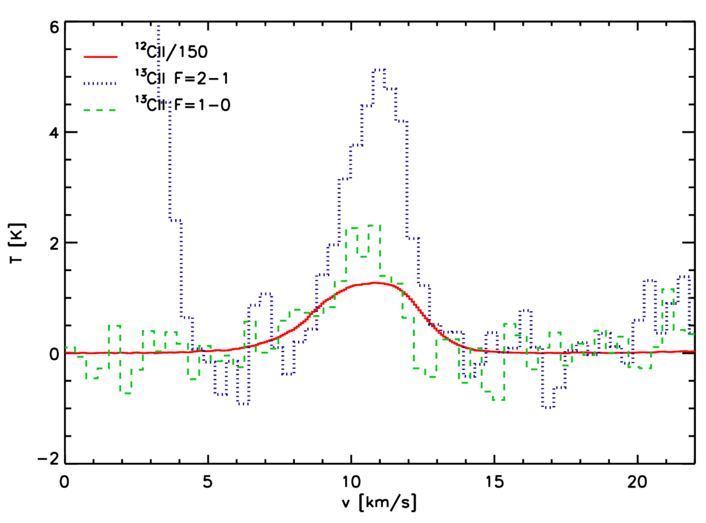


Figure 4: Average profile of the two strongest [^{13}CII] hyper-fine components compared to the [^{12}CII] profile scaled by 0.4/60 that would be expected from the canonical abundance ratio and optically thin lines. The profiles were averaged over all pixels with a [CII] integrated intensity above 700K km/s.

The F=1-0 hyperfine component is only slightly brighter than expected from optically thin [CII] emission and the normal isotopic ratio. However, the F=2-1 component is almost three times brighter. No mechanism is known so far that would explain this anomalous hyperfine ratio. Based on the spatial distribution of the F=2-1 line, we rather suspect a contamination by a weak, unknown [CII] velocity component falling at exactly the same frequency.

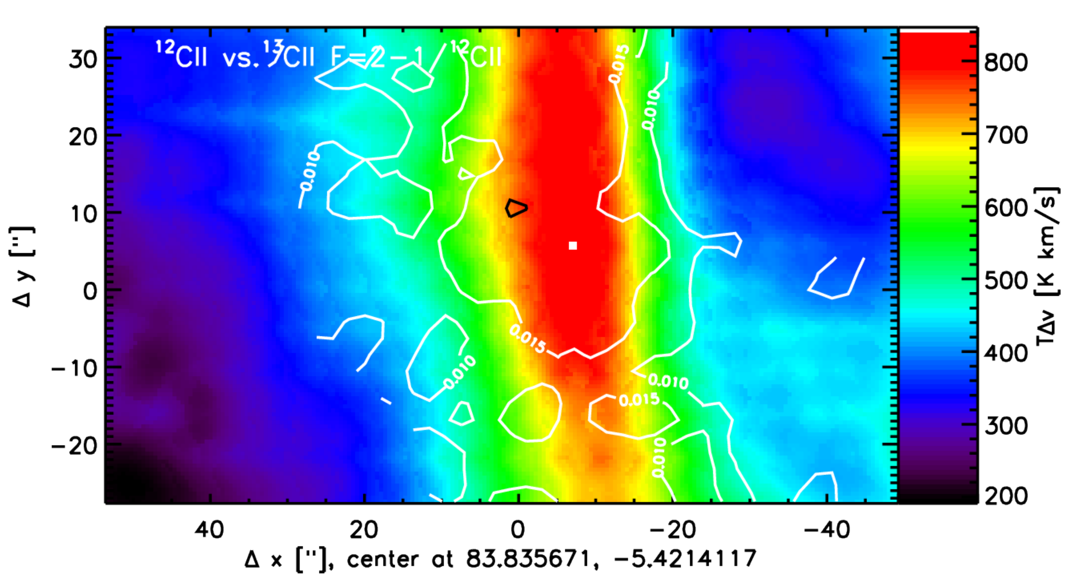


Figure 5: Contours of the [^{13}CII] F=2-1/[CII] ratio overlaid on the integrated [CII] intensities. This supports the contamination theory because the corresponding [^{13}CII] F=1-0/[CII] ratio shows no correlation with the Bar structure.

Other PDRs

[^{13}CII] was also detected in Mon R2, NGC3603 and Carina North using dual-beam switch observations.

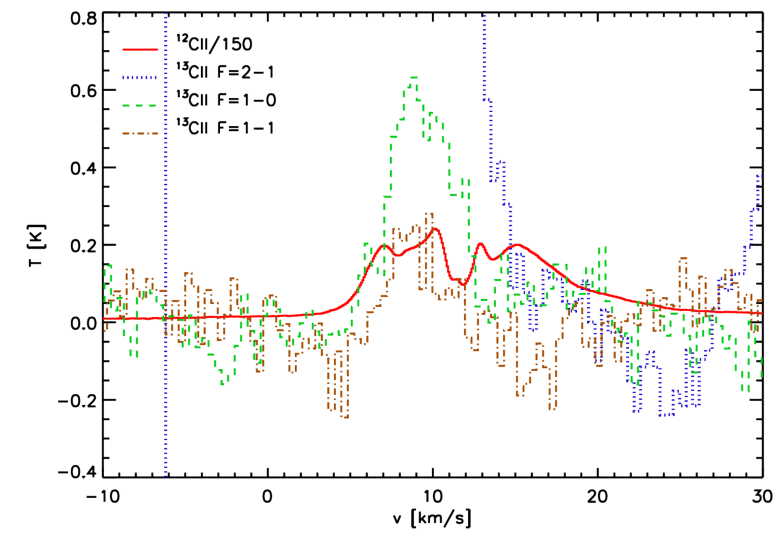
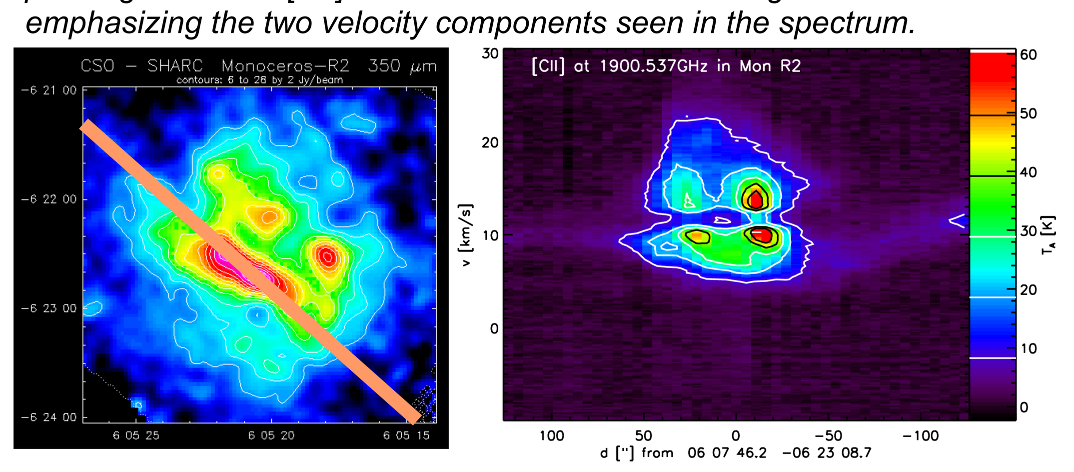


Figure 6: Comparison of the profiles of the [^{13}CII] hyperfine lines in ***Mon R2*** *with the [^{12}CII] profile from the same position scaled by the factor 0.4/60. The F=2-1 component is blended with the [^{12}CII] line.*



p-v diagram of the [CII] line for the indicated cut through the PDR emphasizing the two velocity components seen in the spectrum.

In Mon R2, the blue-shifted velocity component of the source shows about a factor 3 enhancement of the [^{13}CII] lines relative to the "canonical value", indicating an optical depth of the [CII] line of about three. A big puzzle is the complete non-detection of the red component in [^{13}CII]. This could be the first observation of strong fractionation in a PDR.

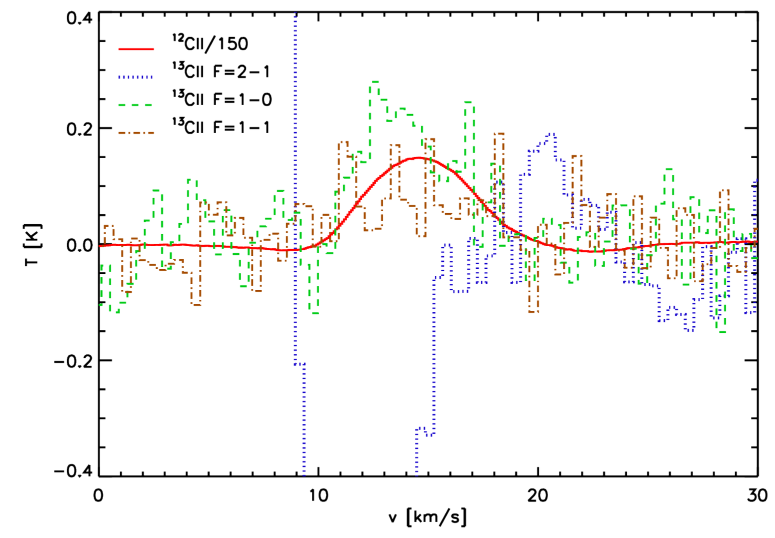


Figure 7: Comparison of the profiles of the [^{13}CII] hyperfine lines in ***NGC3603 MM2*** *with the [^{12}CII] profile from the same position scaled by the factor 0.4/60.*

In NGC3603 and Carina North, the F=2-1 component falls into a [CII] spectral feature resulting from self-chopping, but the two weaker components can be resolved being consistent with an increase of the [^{13}CII] intensity by a factor of about 1.5 relative to the canonical value.

Summary

- Our detections of [^{13}CII] in PDRs showed only a moderate reduction of [^{12}CII]/[^{13}CII] compared to the canonical ratio and optically thin lines. The main isotopic line shows optical depths slightly above unity with the largest value τ([CII]) ~ 2-3 for the blue component of MonR2.
- Most observations show no indication for an increased $C^+/^{13}C^+$ ratio, i.e. no signature of fractionation. This means that most of the emission must stem from material facing a high UV field. Taking the clumpy nature of the PDRs, this indicates that radiation is efficiently redistributed over a large volume.
- The non-detection of [^{13}CII] in the red velocity component in Mon R2 indicates the first direct observation of C^+ fractionation in a PDR. It needs to be investigated why that material differs from the other regions.
- There is a strong anomaly in the hyperfine ratio of the F=2-1/F=1-0 components in the Orion Bar that still waits for an explanation. Future observations of the F=1-1 component are needed to confirm or resolve the puzzle.