The PDR structure and kinematics around the compact H\textsc{ii} regions S235 A and S235 C with [C\textsc{ii}], [\textsuperscript{13}C\textsc{ii}], [O\textsc{i}] and HCO\textsuperscript{+} line profiles

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Photodissociation regions:

- UV flux
- $\Delta A_V < 0.1$
- CII/CI/CO
- O/O$_2$
- HII
- HI
- HII/HI interface
- $A_V$

Tielens & Hollenbach, 1985
Expanding H\textsuperscript{\textsc{ii}} regions $\rightarrow$ expanding PDRs

- Recent observations:

Indirect: no separation between the H\textsubscript{2} and CO dissociation fronts

Goicoechea et al., 2016

Direct: [C\textsc{ii}] 158 micron pv diagram

Pabst et al., 2019, 2020
Expanding H\textsubscript{\textsc{ii}} regions → expanding PDRs

- Time-dependent PDR models:
  - 1D spherical or plane-parallel geometry
  - Non-uniform density structure

1D spherical or plane-parallel geometry

- Hosokawa & Inutsuka, 2005
- Kirsanova et al., 2009
- Bron et al., 2018

Non-uniform density structure

- Krumholz et al., 2007
- Peters et al., 2010
- Arthur et al., 2011

Images: Deharveng et al., 2010
Aims of study

1) Study the geometry and gas kinematics in PDRs around two compact H\textsc{II} regions. Does the [C\textsc{II}] line trace the kinematics there?

2) Test whether the observed properties of the PDRs match the predictions of spherical models.
Anderson et al., 2019

O9.5V and early B-type stars

1.6 kpc, G174+2.5
[CII] at 158 micron:

– no emission from the neutral wall

Anderson et al., 2019
Compact H\textsc{ii} regions S235A and S235C and a stellar cluster between them.
[\textsuperscript{13}C\textsc{ii}] and [C\textsc{ii}] at 158 micron, HCO\textsuperscript{+}(3–2) at 267 GHz

Spitzer 3.6 micron + SOFIA upGRADE deep integrations

SOFIA [C\textsc{ii}] line (colour) + SMT HCO\textsuperscript{+}(3–2) line (contours)
Do the PDRs expand with $V_{\text{exp}} = 2 \text{ km s}^{-1}$?

The [C\text{II}] profiles might be affected by self-absorption effect and do not trace expansion.
We observed additional positions in the \([\text{C}\text{II}]\) and \([^{13}\text{C}\text{II}]\) micron lines in order to determine the optical depth of the \([\text{C}\text{II}]\) emission + \([\text{O}\text{I}]\) line at 63 micron to estimate gas density.
Averaged spectra

Both the [C\textsc{ii}] and [O\textsc{i}] lines have a dip at –16 km s^{-1}.
Map of the $[^{13}\text{CII}]$ spectra in S235 C

1) east-west velocity gradient

2) $V_{[^{13}\text{CII}]} > V_{\text{HCO}^+(3–2)}$ in positions 1 and 3

$T_{\text{ex}} \approx 60-70 \text{ K}$
Map of the $[^{13}\text{C}\text{II}]$ spectra in S235 A

1) east-west velocity gradient

2) $V_{[^{13}\text{C}\text{II}]} > V_{\text{HCO}^+(3-2)}$ in positions 3, 6 and 9

molecular gas is expanding towards the observer
$V_{\text{exp}}$ up to 1 km s$^{-1}$

$3 \leq \tau_{[^{13}\text{C}\text{II}]} \leq 10$

$40 \leq T_{\text{ex}} \leq 90$ K
Interesting fact: the H\textsuperscript{II} regions in the giant molecular cloud G174+2.5 are expanding towards the observer!

S235: Anderson et al., 2019
S235A and C: this study
S233: Ladeyschikov et al., 2015
S231, S232 do not have dense molecular gas on the front and back neutral walls
Comparison of $N_{C^+}$ и $N_{CO}$

Spitzer 3.6 micron $N_{\text{low-J CO}}$ (archival data) $N_{\text{low-J HCO+}}$

The HII regions are situated on the border between the dense molecular and more diffuse atomic gas.
MARION: chemo-dynamical model of an expanding HII region + PDR

- 1D gas/dust dynamics based on Zeus code.
- ionization & dissociation
- cooling & heating
- chemical reactions

after MARION calculation:
- Radiative transfer with SIMLINE code (Ossenkopf et al.-2001)

Gas in PDRs:
Kirsanova et al., 2009, 2019, 2020

Dust and PAHs in PDRs:
Pavlyuchenkov et al., 2013
Akimkin et al., 2015, 2017
Murga et al., 2019
Best model selection criteria:

We can trace the evolution of the physical parameters of the H\textsubscript{II} regions and select the moment of best agreement between the simulated and observed values of the parameters.

– radii of the H\textsubscript{II} regions $\approx 0.1 – 0.3$ pc.
– $n_e = 1000$ and $500 \text{ cm}^{-3}$ within a factor of 2 for S235A and C S235 C, respectively.
– single-peaked profiles of the $[^{13}\text{C}\text{II}]$ and HCO\textsuperscript{+}(3–2) lines
– the average intensities of the [C\text{II}], $[^{13}\text{C}\text{II}]$, [O\text{I}] and the $[^{13}\text{C}\text{II}]$ lines are close to the observed values within a factor of 2.
– expansion velocity $\approx 1 \text{ km s}^{-1}$.
– $3$ $\leq$ $\tau_{\text{CII}}$ $\leq$ $10$ and $3$ $\leq$ $\tau_{\text{CII}}$ $\leq$ $5$ for S235 A and S235 C, respectively.
$T_{\text{eff}} = 27000 \text{K}$

Best models:

$S235A: n_{\text{gas}} = 5 \cdot 10^4 \text{ cm}^{-3}$

$S235C: n_{\text{gas}} = 5 \cdot 10^3 \text{ cm}^{-3}$

Model age:

$S235A: 6 \cdot 10^4 \text{ years}$

$S235C: 3 \cdot 10^4 \text{ years}$
PV diagrams for the best models:

- the $[^{13}\text{C} \text{II}]$ is single-peaked
- the HCO$^+$(3–2) line is single-peaked
- the $[\text{C} \text{II}]$ line is single-peaked, the line is not optically thick!
- the [O\text{I}] line is double-peaked

- the peak-to-peak velocity difference of the [O\text{I}] line is $V_{\text{red}} - V_{\text{blue}} = 2 \cdot V_{\text{exp}}$
Problem: low $\tau_{\text{CII}}$

Solution 1: increase thickness of the C$^+$ layer

original width multiplied by 2

original width multiplied by 3

photons penetrate deeper in non-uniform and clumpy medium
Problem: low $\tau_{\text{CII}}$

Solution 2: increase elemental abundances

CLOUDY «ISM» set of abundances: $x(\text{C})=2.5\cdot10^{-4}$ instead of «high-metallicity» abundances: $x(\text{C})=1.2\cdot10^{-4}$ (Wakelam & Herbst, 2008)
Conclusions

The double-peaked [C\textsc{ii}] and [O\textsc{i}] line profiles arise due to with high optical depth and are not tracing the expansion of the PDRs.

However, an expanding motion of the [C\textsc{ii}]-emitting layer into the molecular layer with a velocity up to 1 km s\textsuperscript{-1} was found in both PDRs with [\textsuperscript{13}C\textsc{ii}] and HCO\textsuperscript{+}(3-2) lines.

Physical parameters of the H\textsc{ii} regions and integrated intensities of the [\textsuperscript{13}C\textsc{ii}], [C\textsc{ii}], and [O\textsc{i}] lines are reproduced by a 1D spherical model. However, the model does not reproduce the double-peaked [C\textsc{ii}] line profiles and high optical depth of the line.

The [O\textsc{i}] line profiles are the best tracers of the expanding motion in the considered PDR models in comparison with the [C\textsc{ii}], [\textsuperscript{13}C\textsc{ii}], and HCO\textsuperscript{+}(3-2) lines.

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