Results from the C$^+$ Square-Degree Survey: Expanding Bubbles in Orion A

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in collaboration with:

Image credit: ESO/G. Beccari
[C II] 158 \mu m emission

- [C II] fine-structure line one of the brightest far-infrared cooling lines of the ISM, \( \sim 1\% \) of total FIR continuum
- dominant cooling line of warm, intermediate density gas (\( T \sim 50-300 \text{ K}, n \sim 10^3-10^4 \text{ cm}^{-3} \))
- [C II] line can be observed in distant galaxies
- origin of [C II] emission: dense PDRs, cold H I gas, ionized gas, CO-dark gas
- need to spatially resolve the ISM
- Orion molecular cloud as template region
- ideally, velocity-resolved mapping allows to form a 3D picture
- last but not least, the [C II] line is an excellent tracer of stellar feedback
Stellar feedback

- stellar feedback regulates the evolution of galaxies
- stellar winds of massive stars blow large bubbles
- slightly less massive stars create expanding HII regions
- negative feedback: hinder star formation due to cloud destruction
- positive feedback: triggered star formation in swept-up shells
The C$^+$ Square-Degree (C+SQUAD)

- large-scale mapping project in the Orion A molecular cloud
- area of 1.1° × 1.4° centered on the Orion Nebula
- velocity-resolved observations of the [C II] line with SOFIA/upGREAT
- 13 flights in November 2016 and February 2017
- resulting in 2 million spectra
Zooming into the constellation of Orion

**Figure 1:** Left: Photograph of the constellation of Orion. The Horsehead Nebula and the Orion Nebula are visible in this long-time exposure (white rectangles).

**Upper right:** Spitzer/IRAC multi-color image of the Orion Nebula complex. Mid-infrared wavelengths reveal dust and large molecules irradiated by star light.

**Lower right:** The inner Orion Nebula, with the massive Trapezium stars, as seen by the HST. The ionized gas in this regions emits in UV and optical lines. The background PDR and the Orion Bar are mainly visible at infrared and (sub-)millimeter wavelengths.
Figure 2: \([\text{C} \text{II}]\) line-integrated intensity \((v_{\text{LSR}} = 6-20 \text{ km s}^{-1})\) observed by SOFIA/upGREAT in 2015.
From small to large...

[C II] line-integrated intensity from the Orion Nebula complex

black box:
~ 9h with Herschel/HIFI,
~ 35min with SOFIA/upGREAT
Figure 3: [C II] line-integrated intensity ($\nu_{\text{LSR}} = -5$-15 km s$^{-1}$) observed by HIFI (left) and upGREAT (right). The array positions indicated in grey show the position of the Orion Bar consistency observation (Higgins et al., to be submitted).
Figure 4: *Left:* Tile using a polynomial order three correction, *right:* using a spline correction approach (Higgins et al., to be submitted).
Figure 5: A screenshot from the rotating [C II] data cube observed by SOFIA/upGREAT (image credit: NASA/SOFIA).
Figure 6: [C II] emission in three different velocity channels (red: 5 km s$^{-1}$, green: 9 km s$^{-1}$, blue: 13 km s$^{-1}$).
Three-observatory view of the Orion Nebula

Figure 7: (a) Spitzer/IRAC 8 µm intensity. (b) SOFIA/upGREAT [C II] line-integrated intensity. (c) IRAM 30m 12CO(2-1) line-integrated intensity. The 8 µm emission traces FUV-irradiated PAHs in the PDR surfaces, the [C II] line is emitted by mostly neutral gas (T \sim 100\,K), whereas CO traces the molecular gas (T \sim 30\,K).
Figure 8: \([\text{C} \text{II}]\) versus FIR intensity. Purple squares are from Orion B. The color scale in Orion A indicates distance from the Trapezium stars. Grey lines are edge-on model outputs with parameters given in the legend \((G_0,n,A_V,\text{los})\). The blue line is a least-squares regression to the Orion A data with \(\log_{10} I_{\text{[CII]}} = 0.57 \log_{10} I_{\text{FIR}} - 2.64\).
Figure 9: [C II] versus 8 µm intensity. Purple squares are from Orion B. The color scale in Orion A indicates distance from the Trapezium stars. The blue line is a least-squares regression to the Orion A data with $\log_{10} I_{\text{[CII]}} = 0.70 \log_{10} I_{8 \mu m} - 1.79$. 
Figure 10: Excess X-ray emission from the cavity of the Orion Nebula (blue). The green and red channels show the Spitzer/IRAC 4.5 μm and 5.8 μm emission, respectively (Güdel et al. 2008).
Figure 11: Position-velocity diagram of [C II] emission from the Orion Nebula. The lower panel indicates the arc structure of a spherically expanding bubble with $v_{\text{exp}} = 13 \text{ km s}^{-1}$ on a background velocity of $8 \text{ km s}^{-1}$ (red dashed lines).
Figure 12: [C II] spectra in the Veil along previous pv diagram with Gaussian fits. Each spectrum is averaged over \((2\times)75.5'' \times 75.5''\).
Figure 13: Schematic of the wind-blown bubble in the Orion Nebula, created by $\theta^1$ Ori C (Pabst et al. 2019). The geometry of the Huygens Region is not rendered in its full complexity.
The 3D structure of the Orion Nebula

Figure 14: Geometry of the Orion Nebula (adapted from O'Dell & Harris 2010). The purple line indicates the Veil Shell.
Figure 15: Velocity structure of Orion’s Veil towards the Trapezium stars (Abel et al. 2019). Veil Component III(B) corresponds to the large shell.
Güdel et al. 2008, Science 319, 309
Pabst et al. 2019, Nature 565, 618

Onwards! More bubbles:
Figure 16: [C II] line-integrated intensity. Red rectangles indicate the cuts along which the pv diagrams are extracted.
Figure 17: [C II] pv diagram through M43. The right panel shows the same pv diagram with the arc structure for an expansion velocity of $6.5 \text{ km s}^{-1}$ on a background velocity of $10 \text{ km s}^{-1}$ (red dashed lines).
Tracing expanding bubbles: The M43 Shell

Figure 18: [C II] spectra in M43 along previous pv diagram with Gaussian fits. Each spectrum is averaged over 75.5″ × 75.5″.
Figure 19: \([\text{C} \, \text{II}]\) pv diagram through NGC 1977. The lower panel shows the same cut with the arc structure for an expansion velocity of \(\pm 2 \text{ km s}^{-1}\) (red dashed lines).
Figure 20: [C II] spectrum in NGC 1977 along the previous pv diagram with Gaussian fits, averaged over 200″ × 200″.
Comparison of the pressure terms

<table>
<thead>
<tr>
<th>region</th>
<th>$n$ [cm$^{-3}$]</th>
<th>$T_{\text{gas}}$ [K]</th>
<th>$p_{\text{th}}/k_B$ [cm$^{-3}$ K]</th>
<th>$G_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Veil Shell</td>
<td>0.3</td>
<td>$2 \times 10^6$</td>
<td>$1 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>H$\text{\textsc{ii}}$</td>
<td>50</td>
<td>$8 \times 10^3$</td>
<td>$8 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>PDR</td>
<td>$10^3$-$10^4$</td>
<td>$\sim 100$</td>
<td>$1$-$10 \times 10^5$</td>
<td>$\sim 100$</td>
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<tr>
<td>M43</td>
<td>H$\text{\textsc{ii}}$</td>
<td>500</td>
<td>$7.5 \times 10^3$</td>
<td>$8 \times 10^6$</td>
</tr>
<tr>
<td>PDR</td>
<td>$10^4$</td>
<td>100</td>
<td>$1 \times 10^6$</td>
<td>$\sim 1 \times 10^3$</td>
</tr>
<tr>
<td>NGC 1977</td>
<td>H$\text{\textsc{ii}}$</td>
<td>40</td>
<td>$\sim 10^4$</td>
<td>$\sim 8 \times 10^5$</td>
</tr>
<tr>
<td>PDR</td>
<td>$10^3$</td>
<td>90</td>
<td>$9 \times 10^4$</td>
<td>$\sim 100$</td>
</tr>
</tbody>
</table>

**Table 1:** Physical conditions of respective H$\text{\textsc{ii}}$ region and adjacent limb-brightened PDR shell in M42, M43, and NGC 1977. The density of the M42 H$\text{\textsc{ii}}$ region given here is appropriate for the southern EON, as is $G_0$ in the Veil Shell PDR.

In the Veil Shell, the plasma pressure can drive the expansion. In M43 and NGC 1977, the pressure of the ionized gas drives the expansion.
Comparison of the PDR pressures

<table>
<thead>
<tr>
<th>$p/k_B$</th>
<th>Veil Shell</th>
<th>M43</th>
<th>NGC 1977</th>
</tr>
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<tbody>
<tr>
<td>thermal</td>
<td>1-10 $\times 10^5$</td>
<td>$1 \times 10^6$</td>
<td>$9 \times 10^4$</td>
</tr>
<tr>
<td>magnetic</td>
<td>$2 \times 10^6$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>turbulence</td>
<td>0.5-3 $\times 10^6$</td>
<td>$8 \times 10^5$</td>
<td>$8 \times 10^4$</td>
</tr>
<tr>
<td>radiation</td>
<td>$1 \times 10^5$</td>
<td>$3 \times 10^6$</td>
<td>$8 \times 10^4$</td>
</tr>
</tbody>
</table>

Table 2: Comparison of the pressure terms in the PDRs of the Veil Shell, M43 and NGC 1977. In the Veil Shell, higher pressures correspond to the limb-brightened edges, while lower pressures apply to the foreground expanding shell. In the PDRs, approximate equipartition holds between the pressure terms. Radiation pressure is less important in the Veil Shell.
## Comparison of the energetics

<table>
<thead>
<tr>
<th>region</th>
<th>M42 (Veil)</th>
<th>M43</th>
<th>NGC 1977</th>
</tr>
</thead>
<tbody>
<tr>
<td>star</td>
<td>$\theta^1$ Ori C</td>
<td>NU Ori</td>
<td>42 Ori</td>
</tr>
<tr>
<td>stellar type</td>
<td>O7V</td>
<td>B0.5V</td>
<td>B1V</td>
</tr>
<tr>
<td>$N_{\text{LyC}} , [10^{47} , \text{s}^{-1}]$</td>
<td>70</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>$L_w , [L_\odot]$</td>
<td>350</td>
<td>$\sim 1.5 \times 10^{-2}$</td>
<td>$\sim 1.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>mass of neutral gas $[M_\odot]$</td>
<td>1500</td>
<td>8</td>
<td>700</td>
</tr>
<tr>
<td>mass of ionized gas $[M_\odot]$</td>
<td>24</td>
<td>0.3</td>
<td>16</td>
</tr>
<tr>
<td>$v_{\text{exp}} , [\text{km s}^{-1}]$</td>
<td>13</td>
<td>6</td>
<td>1.5</td>
</tr>
<tr>
<td>$E_{\text{kin}}$ of neutral gas $[10^{46} , \text{erg}]$</td>
<td>250</td>
<td>0.3</td>
<td>2</td>
</tr>
<tr>
<td>$E_{\text{th}}$ of ionized gas $[10^{46} , \text{erg}]$</td>
<td>3</td>
<td>0.7</td>
<td>5</td>
</tr>
<tr>
<td>$t_{\text{exp}} , [\text{Myr}]$</td>
<td>0.2</td>
<td>0.02</td>
<td>0.4</td>
</tr>
<tr>
<td>$E_{\text{kin}}/(L_w , t_{\text{exp}})$</td>
<td>0.5</td>
<td>50</td>
<td>40</td>
</tr>
</tbody>
</table>

**Table 3:** In M42, the kinetic energy of the neutral shell much exceeds the thermal energy of the ionized gas, while the wind luminosity is sufficient to drive the expansion. In M43 and NGC 1977, the thermal energy of the ionized gas exceeds the kinetic energy of the shell, indicative of pressure-driven expansion.
Summarizing the energetics

Figure 21: Kinetic energy of the expanding bubble shells versus expansion time. The lines are the predictions of wind models (blue) and models of pressure-driven expansion (red) with parameters adequate to the studied regions.
Figure 22: [C II], $^{12}$CO(2-1), and $^{13}$CO(2-1) emission from the Orion Nebula complex. 
[C II] emission traces the cloud surfaces, while CO(2-1) emission traces the molecular background cloud (Goicoechea et al. 2020).
Molecular globules in the shell

Figure 23: Position-velocity diagram of [CII] and $^{12}$CO(2-1) emission from the Orion Nebula (Goicoechea et al. 2020).
Figure 24: Blueshifted CO globules and emission structures detected toward the Veil Shell. Reddish color: $^{12}$CO(2-1) emission, bluish color: IRAC 8 $\mu$m emission (Goicoechea et al. 2020).
Figure 25: Schematic of the wind-blown bubble in the Orion Nebula with molecular globules (Goicoechea et al. 2020).
Summary and outlook

- The first large-scale velocity-resolved [C II] map of the Orion Nebula reveals the large-scale expansion of the Veil, that carries a large portion of the gas mass.

- Other parsec-scale bubbles are observed in M43 and NGC 1977.

- While the expansion of the M42 Veil is driven by the stellar wind of $\theta^1$ Ori C, the expansion of M43 and NGC 1977 is due to the overpressurized gas in the H II region.

- Velocity-resolved [C II] observations are a powerful tool to quantify stellar feedback from massive stars.

- SOFIA/upGREAT is the prime facility because of its high mapping speed.

- Role of magnetic fields in bubble expansion?

- SOFIA Legacy Program FEEDBACK: 11 sources.
The SOFIA Legacy Program FEEDBACK

- PIs: Nicola Schneider & Alexander Tielens
- Science goal: How do massive stars regulate star formation?
- Survey of 11 regions of massive star formation in the \([\text{C}\,\text{II}]\) line using upGREAT on SOFIA. The sample spans a wide range in star formation characteristics and physical conditions.
- The data is non-proprietary.
- About 30% complete as of August 2020