To Bubble or Not to Bubble

Stellar Feedback in Orion and 30 Doradus

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Ballyfest Visegrád May 27, 2025

Aspects of stellar feedback and star formation

- interaction of massive stars with molecular clouds drives evolution of ISM
- [C II] 158 μm line is an excellent tracer of stellar feedback as it is the dominant cooling line of warm, intermediate-density gas ($\sim$ 1% of FIR continuum)
  and it can be observed in distant galaxies

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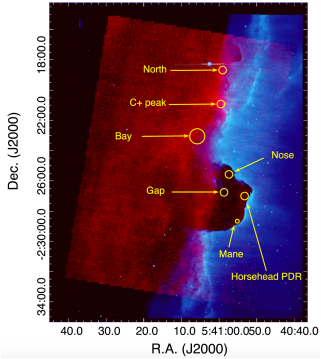
- **The Local Truth**: we observe nearby star-forming regions with different characteristics
- but we select bright targets, while large percentage of emission is in faint extended regions

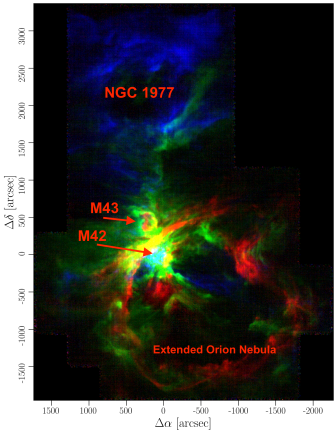
Three feedback regions

Horsehead Nebula



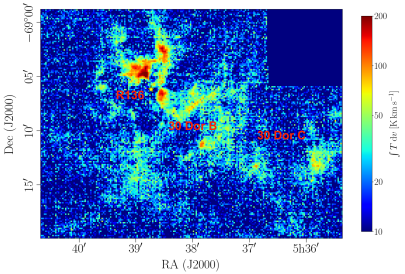
[C II] line-integrated emission superimposed on Hα image (Fig. 11 in Bally+2018)

Orion Nebula Complex



[C II] emission. Red: 5-6 $\mathrm{km\,s^{-1}}$, Green: 9-10 $\mathrm{km\,s^{-1}}$, Blue: 13-14 $\mathrm{km\,s^{-1}}$

30 Doradus



[C II] line-integrated emission

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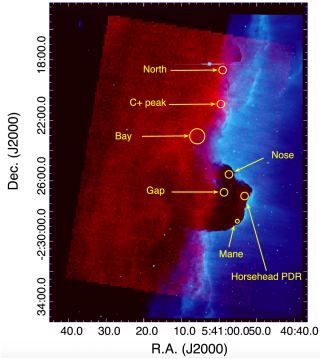
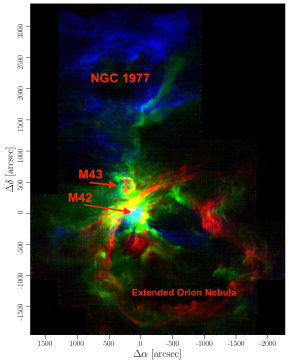


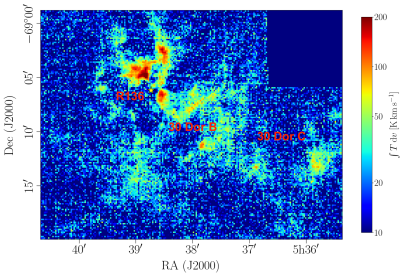
σ Ori AB (O9.5V+B0.5V)
photo-evaporation
3-4 Myr / 1 Myr
$\sim 100\,M_\odot$ neutral atomic gas

Orion Nebula Complex



θ^1 Ori C (O7V) / θ^2 Ori A (O9V)
(adiabatic?) bubble expansion
1 Myr / 0.2 Myr
$\sim 1500\,M_\odot$ neutral atomic gas expanding

30 Doradus



300 O stars, 17 WR stars
bubble foam
2 Myr
$\sim 10^6\,M_\odot$ neutral atomic gas expanding

$\sim 100\times$ as big as the Orion Nebula

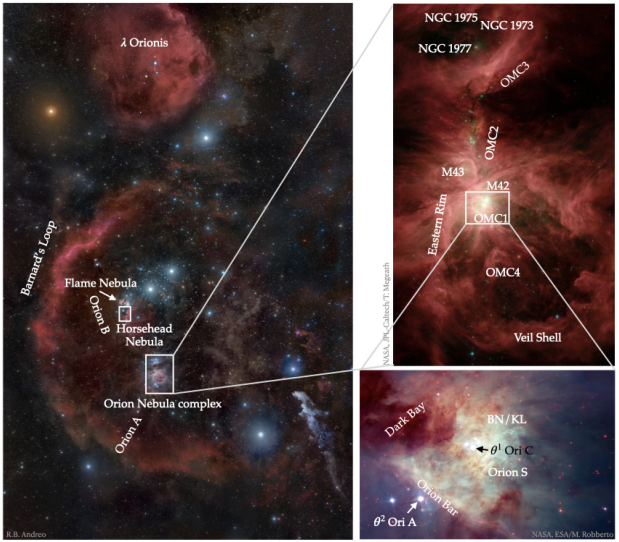
Chu&Kennicutt 1994, Evans+2011, Ochsendorf+2014, Bally+2018, Pabst+2019, 2020, Cheng+2021

The bigger picture

Visual image of Barnard's Loop in the Orion-Eridanus superbubble

O'Dell+2011
Ochsendorf+2015
Abdullah+2022

Zooming into the constellation of Orion



Left: Constellation of Orion (Rogelio Bernal Andreo). The Horsehead Nebula and the Orion Nebula are visible in this long-time exposure.

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 wavelenghts.

[C II] emission from L1630 in Orion B

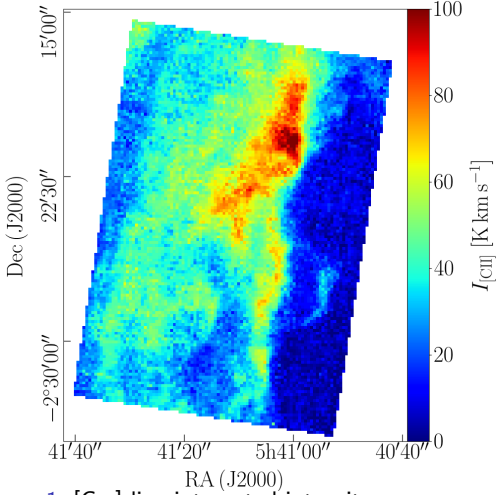


Figure 1: [C II] line-integrated intensity ($v_{\rm LSR}$ = 6-20 km s^{-1}) observed by SOFIA/upGREAT in 2015 (Pabst+2017, Bally+2018).

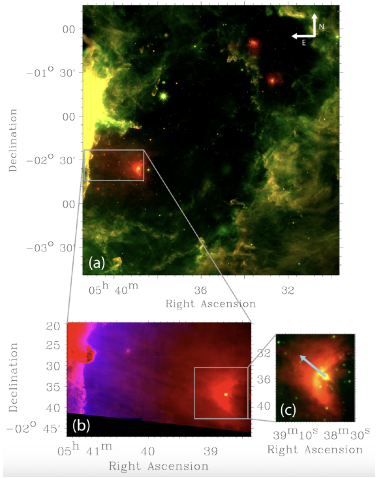
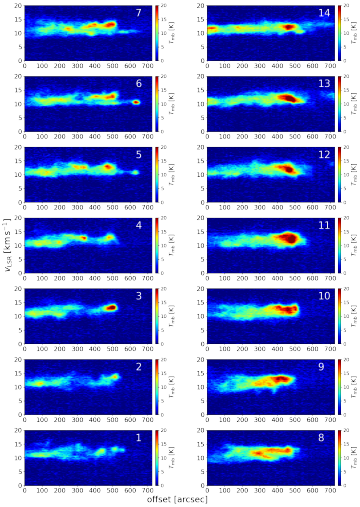
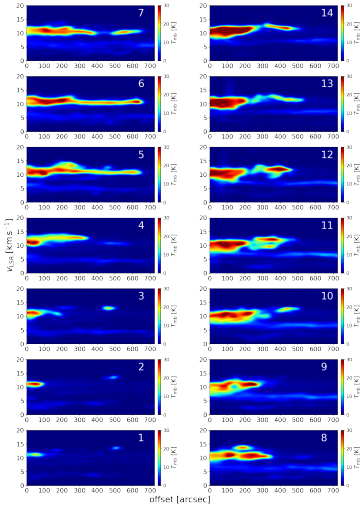


Figure 2: WISE view on Orion B (Ochsendorf+2014).

PV diagrams of L1630

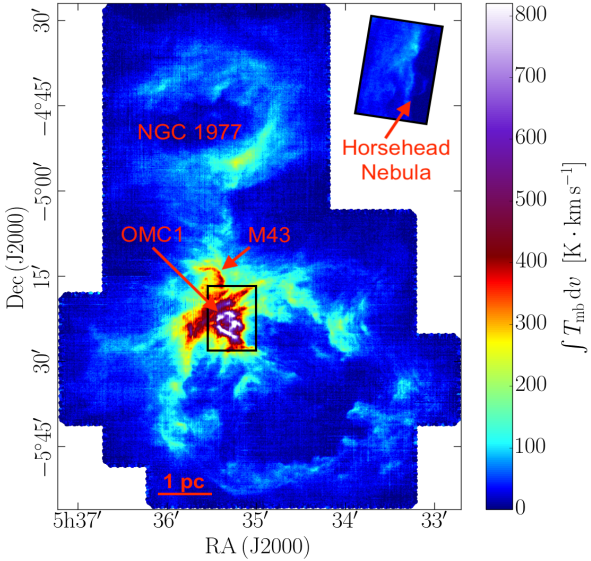


[C II]



^{12}CO(1-0)

From small to large...



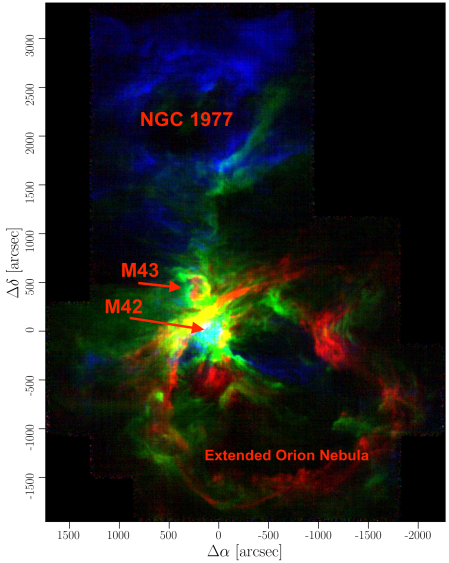
[C II] line-integrated intensity
from the Orion Nebula complex

black box:
$\sim$ 9h with *Herschel*/HIFI,
$\sim$ 35min with SOFIA/upGREAT

Orion's Dragon

Figure 3: A screenshot from the rotating [C II] data cube observed by SOFIA/upGREAT with artist's impression (image credit: NASA/SOFIA; AIP, A. Malate).

Tracing expanding bubbles: The Veil Shell



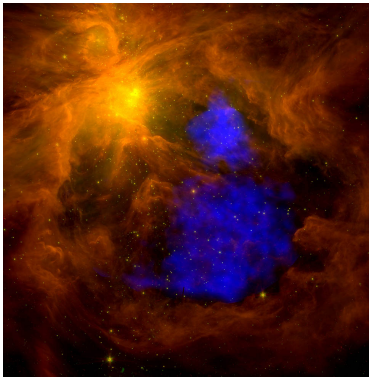


Figure 4: Excess X-ray emission from the cavity of the Orion Nebula (blue). Green and red channel: *Spitzer*/IRAC 4.5 μm and 5.8 μm, respectively (Güdel+2008).

Measuring stellar feedback

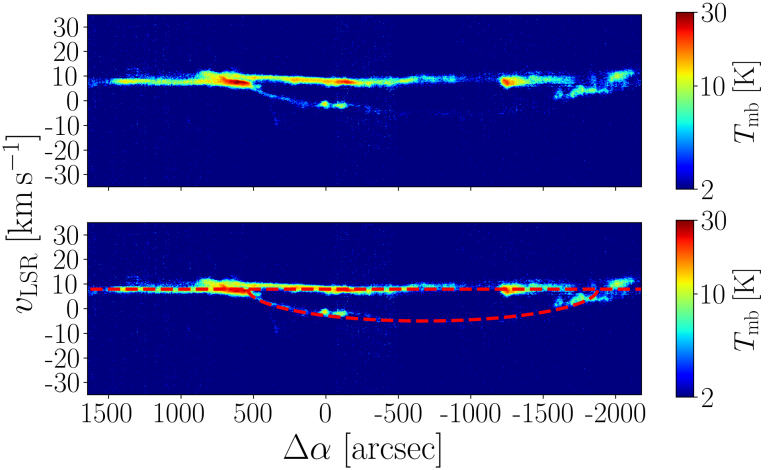
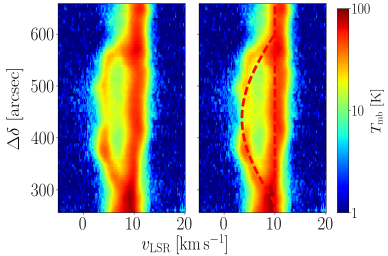
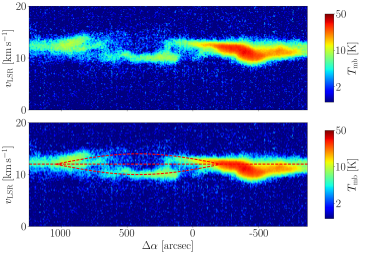


Figure 5: [C II] pv diagram through the Orion Veil shell (Pabst+2019, 2020). Expansion velocity of 13 $\mathrm{km\,s^{-1}}$ on a background velocity of 8 $\mathrm{km\,s^{-1}}$ (red dashed lines) and total mass of 1500 $M_\odot$.

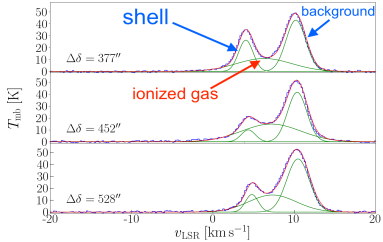
Measuring stellar feedback: M43 and NGC 1977

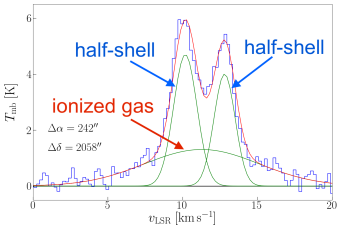


[C II] pv diagram through M43: $6.5\,\mathrm{km\,s^{-1}}$



[C II] pv diagram through NGC 1977: $\pm 2\,\mathrm{km\,s^{-1}}$





Orion's Dragon versus the Tarantula

Figure 6: 1 O7V star, less than 1 Myr old

Figure 7: 300 O stars and 17 WR stars, 1-2 Myr old

The starburst region 30 Doradus

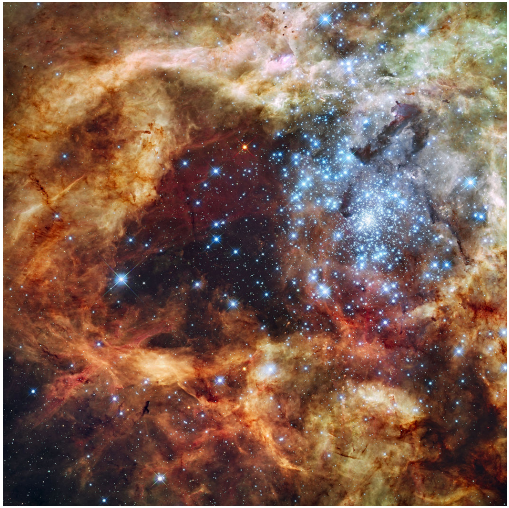


Figure 8: Hubble's view of 30 Dor. *Right*: close-up of R136 in NGC 2070.

The starburst region 30 Doradus

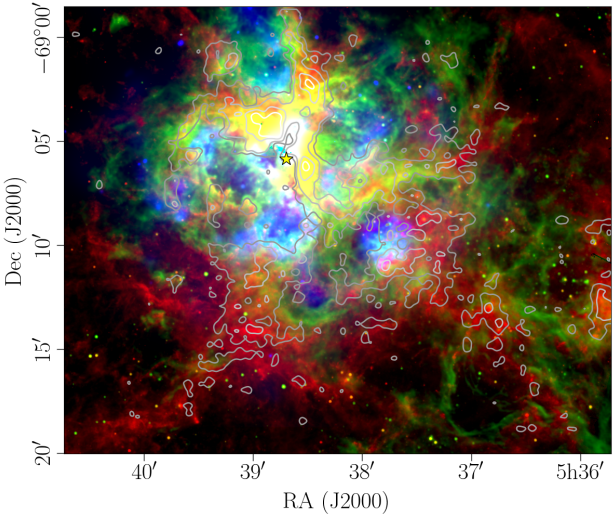


Figure 9: IRAC 8 μm (red), MCELS Hα (green), Chandra X-rays (blue), and [C II] emission (contours).

Stellar feedback on different scales

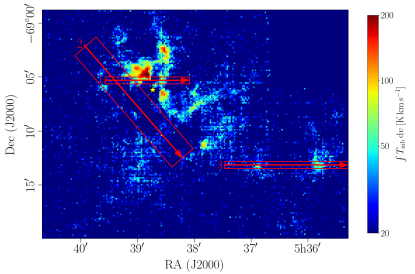


Figure 10: Line-integrated [C II] emission from 30 Dor

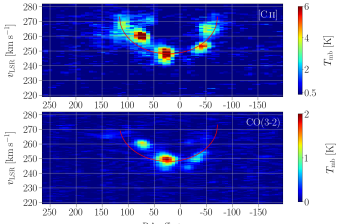


Figure 11: 1: Small-scale bubble

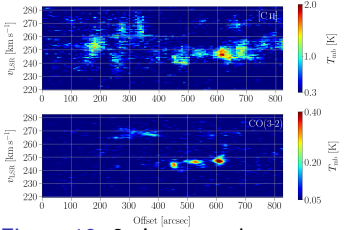


Figure 12: 2: Large-scale feedback

Stellar feedback on different scales

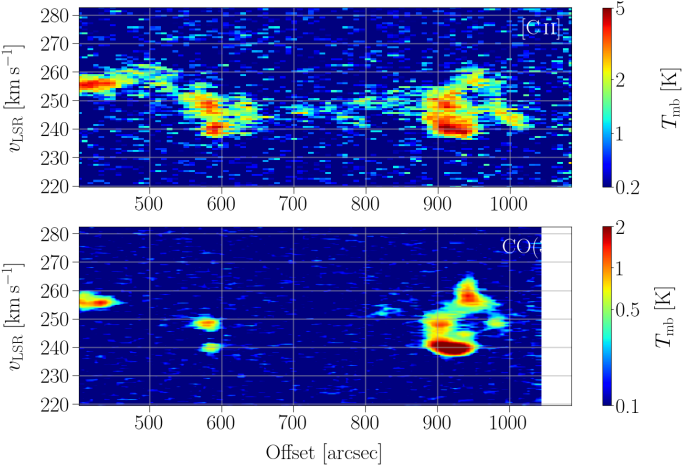


Figure 13: 3: 30 Dor C's bubble

Input stellar energy is largely dissipated in smaller structures (see Chu&Kennicutt 1994).

Stellar feedback on different scales

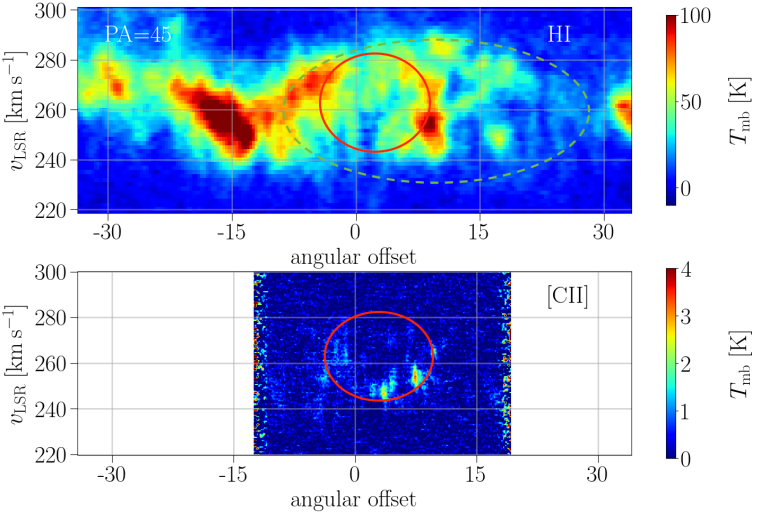
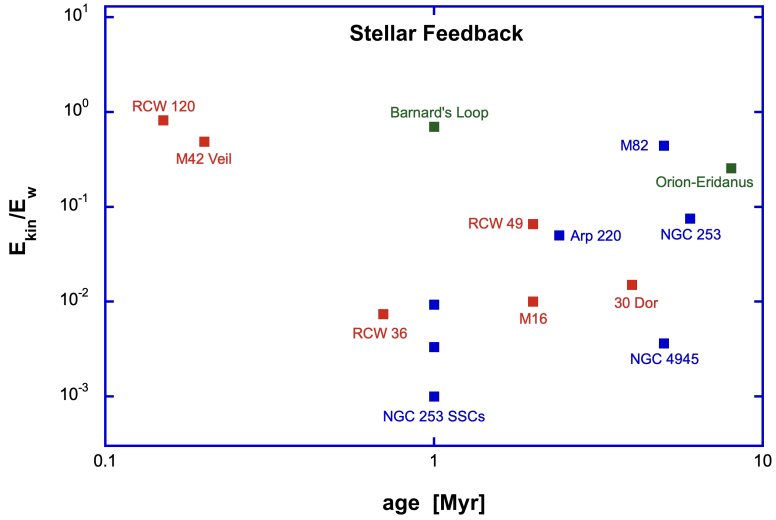


Figure 14: Large H I bubble (Kim+2005)

Stellar feedback on different scales



Conclusions

- [C II] map of Orion is an incredibly rich data set, many as yet unexplored features
- [C II] observations of the Orion Nebula discovered a young expanding spherical bubble
- [C II] observations of 30 Dor show fragmented feedback
- while we do see X-ray bubbles, [C II] emission in shells is very faint: why?
- at upGREAT's angular (and spectral) resolution 30 Dor looks highly turbulent
- each pixel is one Orion Nebula
- energy dissipates at smaller (ionized gas) and larger scales (H I halo)
- does R136 heat most of the plasma or do single massive stars heat the plasma locally?

What's next?

- We only began to understand the **Local Truth**, i.e. the complexity of local star-forming regions ...
- ... but the demise of SOFIA shouldn't stop us.
- many papers on FEEDBACK sources still in the pipeline (c.f. Simon Dannhauer's talk)
- higher-resolution, higher-sensitivity [C II] and [O I] observations: space mission?
- carbon radio-recombination lines: trace similar gas, but are very faint
- simulations of entire H II regions: but real life is much more complex (chaotic!?)
- Therefore, we need more observations to improve our knowledge: molecular lines, CRRLs, and far-infrared lines!