

SOFIA FEEDBACK survey: exploring the dynamics of the stellar wind-driven shell of RCW49

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FEEDBACK consortium

Massive stars

What is the role of massive stars in driving various physical and chemical processes in the ISM?

- Injection of mechanical energy is through the stellar winds.
- Injection of radiative energy is through the heating of gas by EUV ($h\nu > 13.6$ eV) and FUV ($13.6 > h\nu > 6$ eV) photons.

Giving rise to these beautiful structures!



SOFIA legacy program: FEEDBACK

PIs: Dr. N. Schneider (Univ. of Cologne)

Prof. Dr. A.G.G.M. Tielens (UMD)

(Schneider et al, 2020, Luisi et al, 2021, Tiwari et al, 2021)



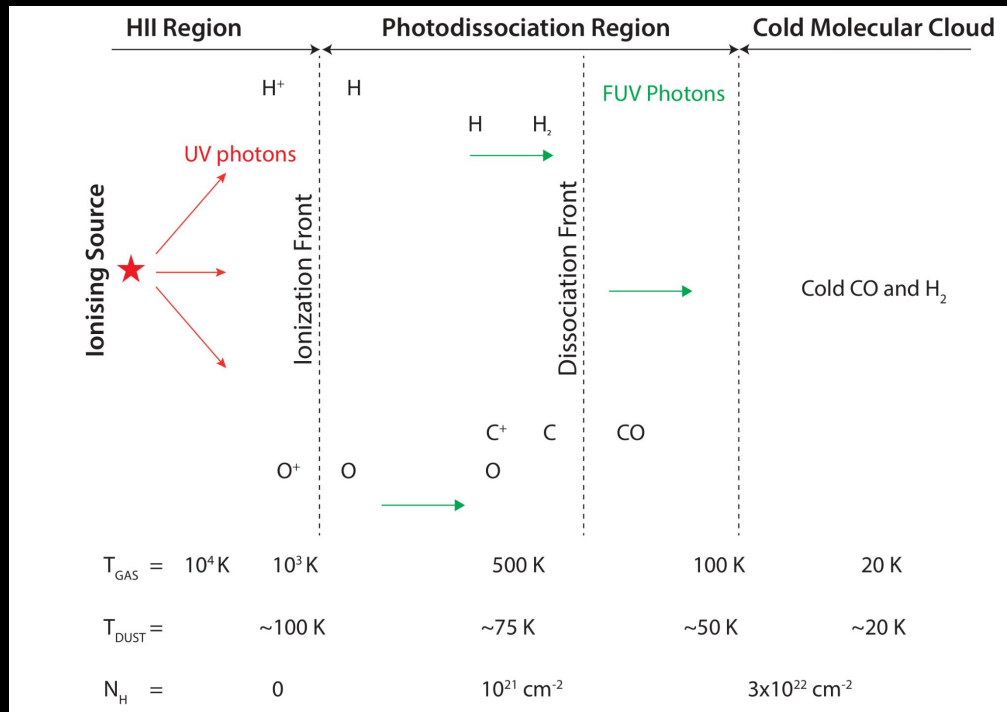
Goals

We have started observing the C^+ ([CII]) 1.9 THz line towards a number of massive star-forming regions in our Galaxy to measure the mechanical and radiative response of the ISM surrounding massive stars.

- Study the **processes of feedback** in the local Universe.
- **Quantify the kinetic energy input** by massive stars into the ISM.
- **Quantify the radiative energy input** by massive stars into the ISM.
- Find a link between the different feedback mechanisms to **star formation activity**.

The GREAT [CII]...

Major coolant of the ISM.



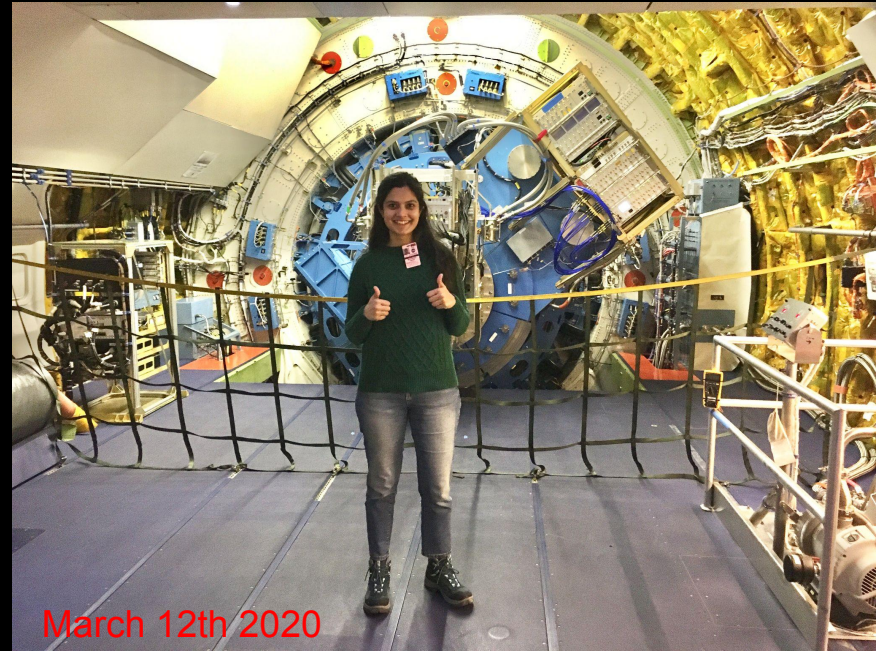
Adapted from Hollenbach & Tielens (1999) and Goicoechea et al. (2016)

- One of the brightest lines in PDR.
- $I_C (11.3 \text{ eV}) < I_H (13.6 \text{ eV})$
- [CII] traces the transition from H⁺ to H and H₂.
- Dominates C budget.
- Trace star formation in the Universe.

Method: The upGREAT receiver

High spatial (14") and spectral (sub km/s) resolution to map [CII] line over large areas (Risacher et al. 2018).

- spectral resolution will allow us to disentangle different gas components allowing us to study the kinematics. Thus, quantifying the mechanical energy input.
- Since [CII] is the dominant cooling line for low to moderate densities and UV fields, it will directly measure the radiative energy injection.



Source Sample

- **Wide range in star formation activity:** Single or group of O-type stars, clusters, etc.
- **Wide range in evolutionary stages.**
- **Different morphology:** expanding HII regions (almost perfect spheres), broken shells, pillars and more.



Source Sample

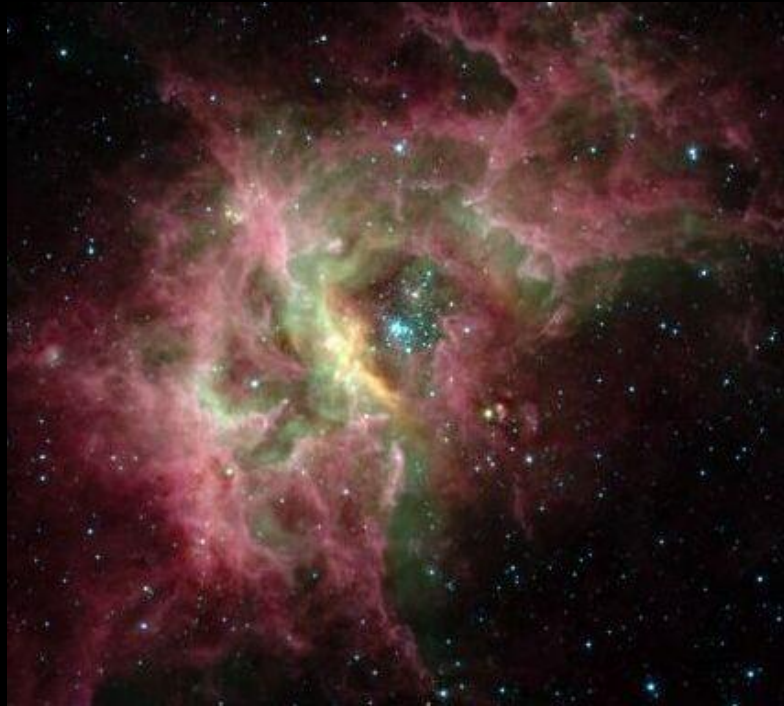
Source	d (kpc)	SF activity	Area (')
RCW 36	0.7	O8, B-cluster	15 x 15
RCW 76	4.3	2 O4, 10 late O	20 x 20
RCW 49	4.2	Comp. cluster, 2 WR	20 x 30
RCW 120	1.3	1 O7	15 x 15
NGC 6334	1.3	O8, mini starburst	20 x 35
M17	1.9	2 O4, 10 late O	20 x 30
M16	2	O4, 10 late O	20 x 30
W40	0.26	1 O, 2 B	20 x 30
W43	5.5	mini starburst	15 x 15
Cygnus X	1.4	2 OB, 3 WR, ~50 O	20 x 35
NGC 7538	2.8	O3	15 x 15

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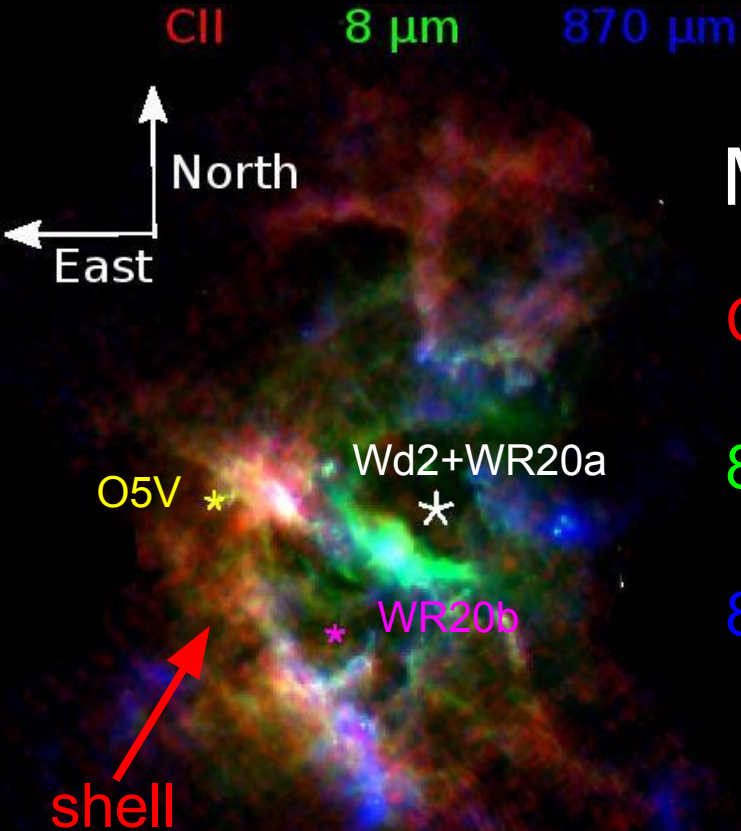
RCW 49 (Tiwari et al, 2021)

One of the most luminous massive star-forming regions in our Galaxy.



- It is 4.16 kpc away from us.
- It has a compact stellar cluster Wd2: 37 OB stars and 30 early type OB star candidates
- It has 2 Wolf Rayet stars + O5V star east of Wd2.

What are the effects of stellar FEEDBACK in RCW49 ?



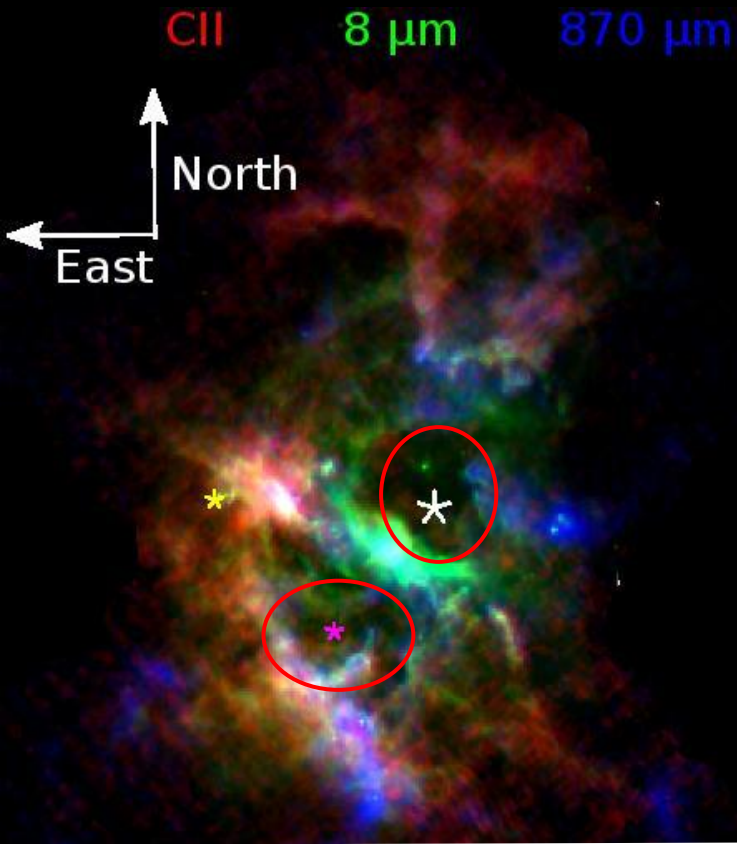
Multiwavelength overview:

CII traces the warm PDR shell

8 μm traces the warm dust

870 μm traces the cold and dense clumps

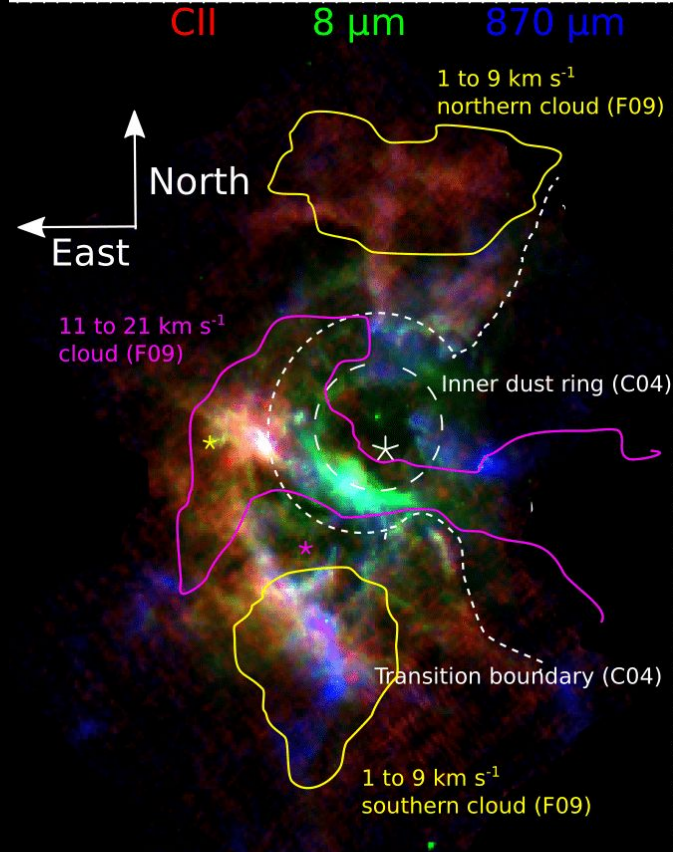
RCW 49: Previous studies



- Whiteoak & Uchida 1997 reported radio data (1-2 GHz) towards RCW 49.
- Identified two shells separated by a bridge.
- Spatial resolution = $43'' \times 51''$.
- Not spectrally resolved.

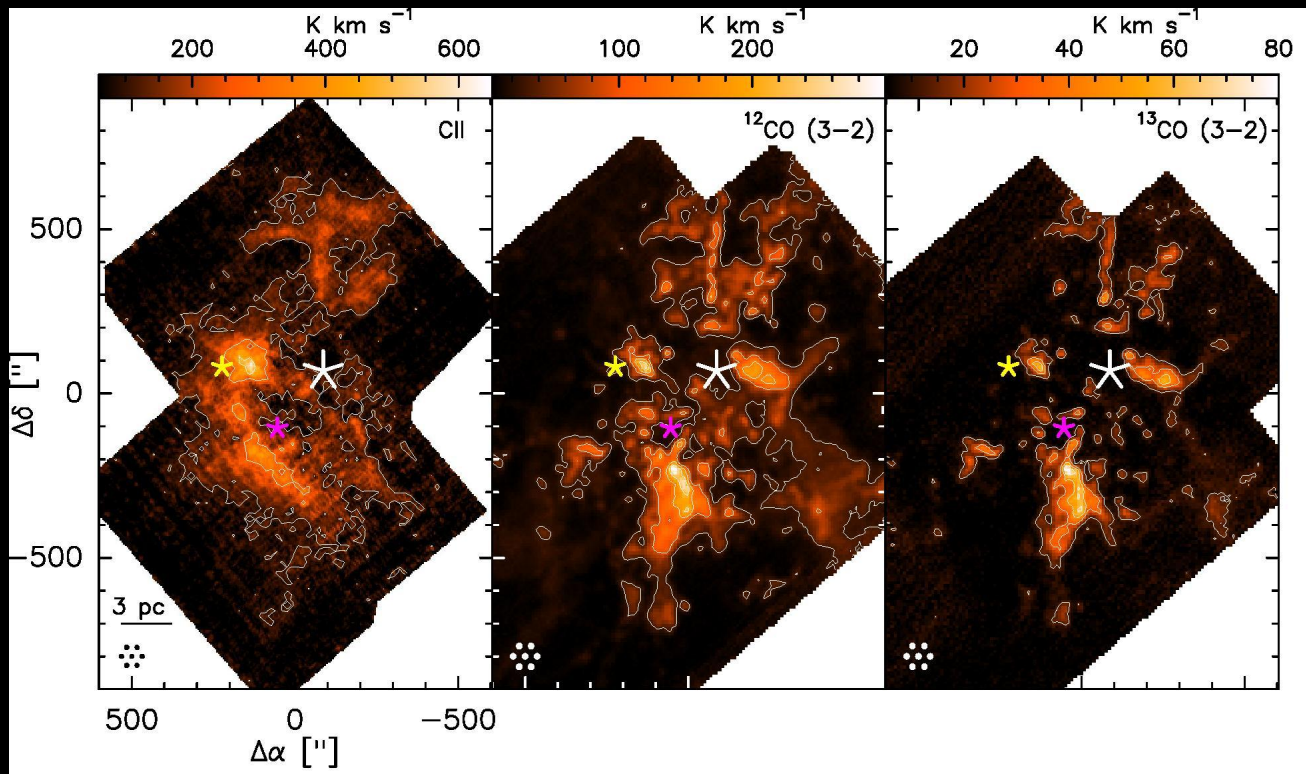
RCW 49: Previous studies

- Churchwell et al. 2004 (C04) studied mid-IR data.
- Identified distinct regions as a function of the angular radius with respect to Wd2.
- Furukawa et al. 2009 studied CO 2-1 data.
- Identified two large scale molecular clouds.



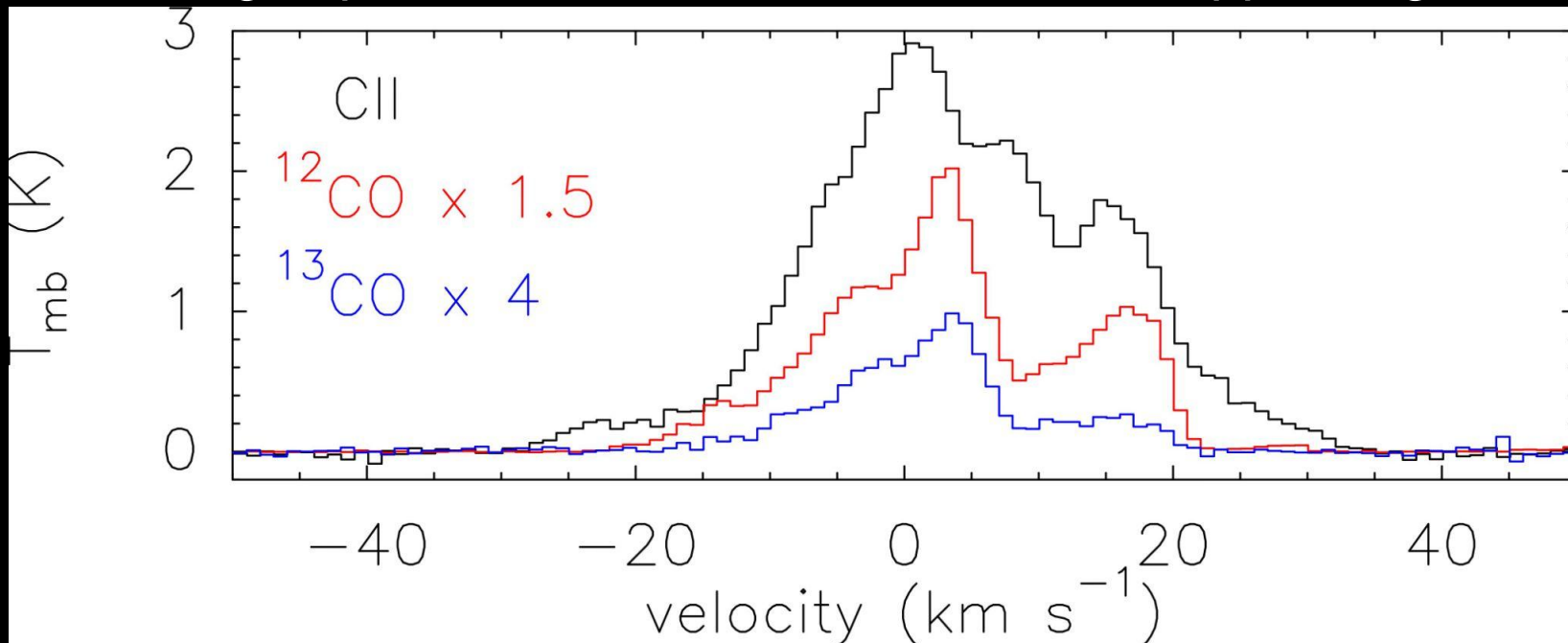
RCW 49 observed with SOFIA and APEX

Maps in the entire velocity range of -25 to 30 km/s.



Average spectra

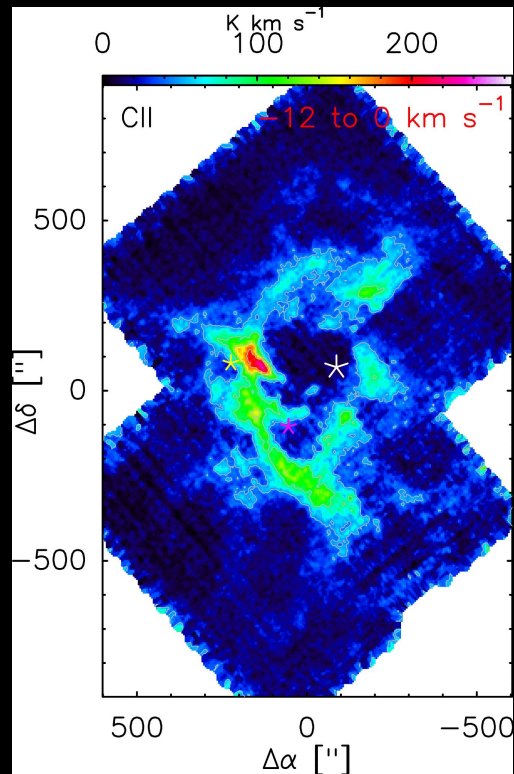
Average spectra over the entire observed mapped region



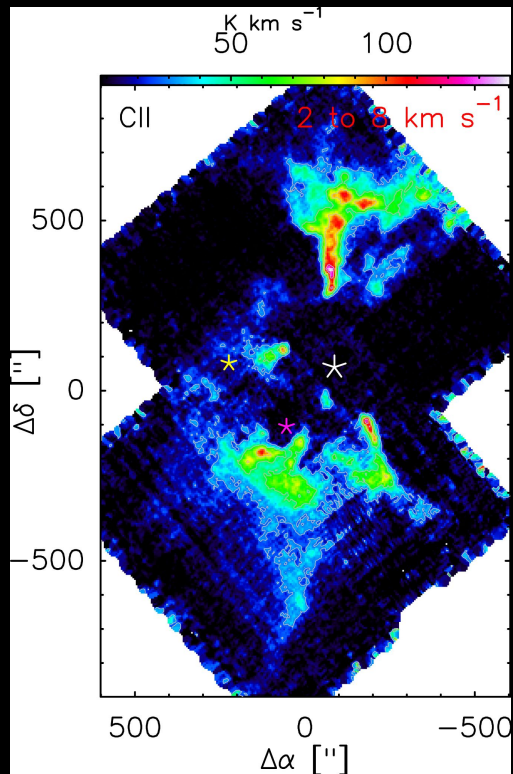
A complex set of gas components!

Disentangling different regions in RCW 49

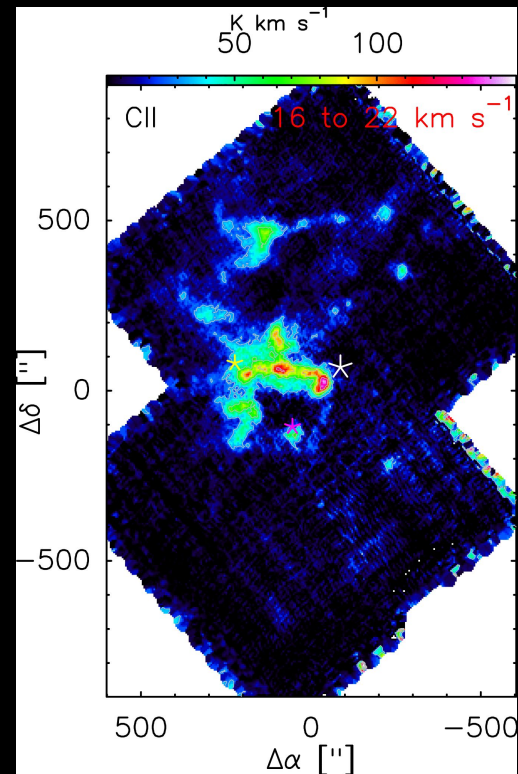
Shell



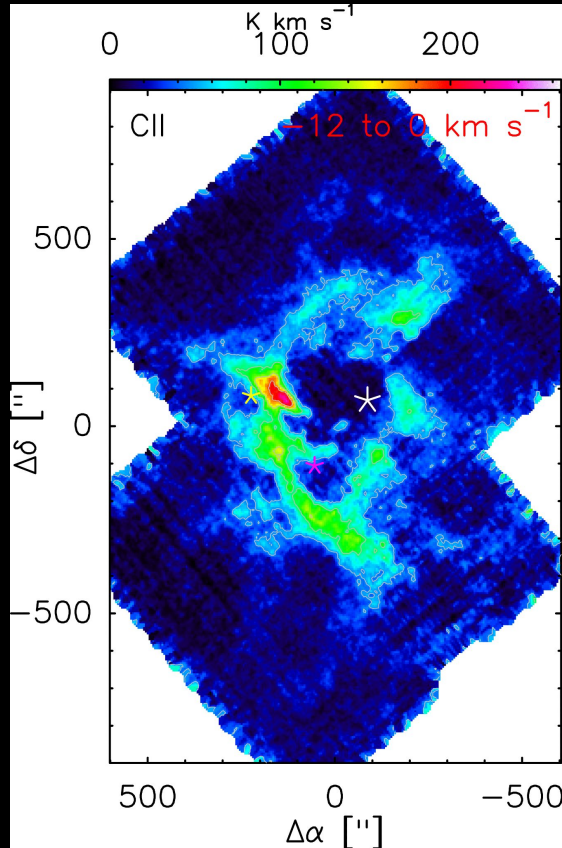
Northern and southern clouds



Ridge



Specific goals of this project

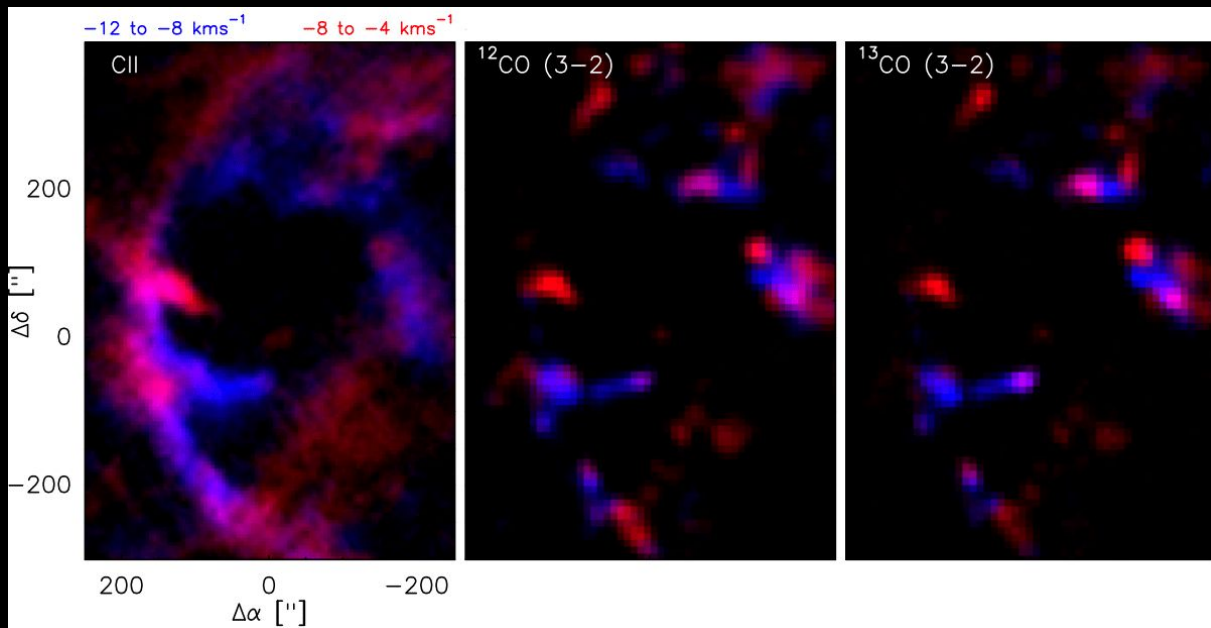


- Characterization of the shell
radius ?
speed ?
mass ?
- What's the driving force ?
- Physical conditions?
- Morphology ?
- What is the future of star formation?

The expanding shell of RCW 49

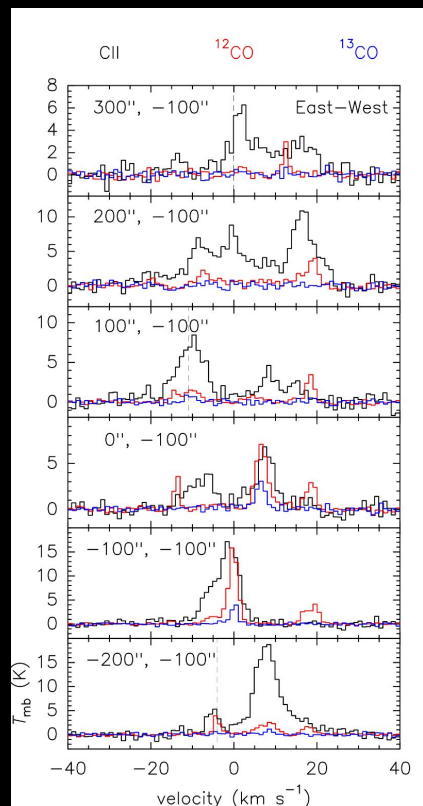
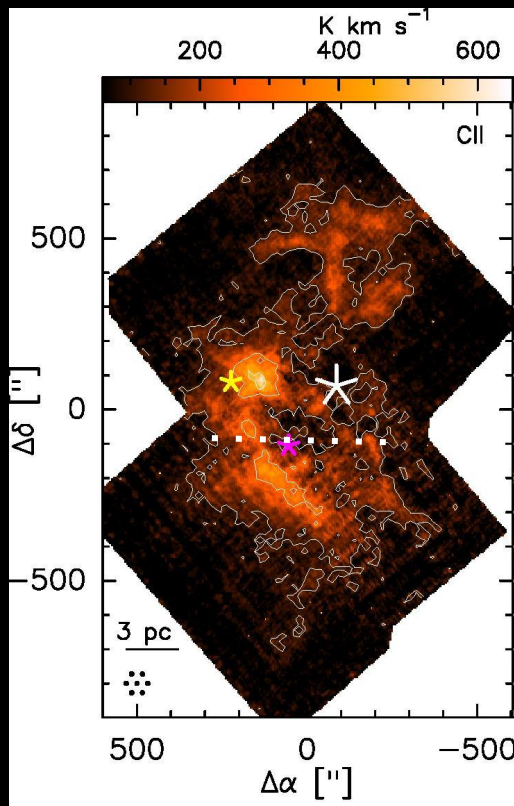
The shell can be disentangled from a complex set of gas components!

- The shell is traced by [CII].
- CO emission is fragmented toward it.



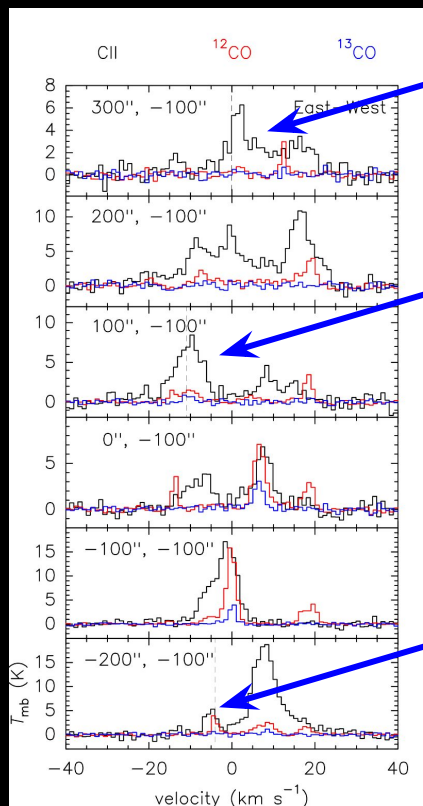
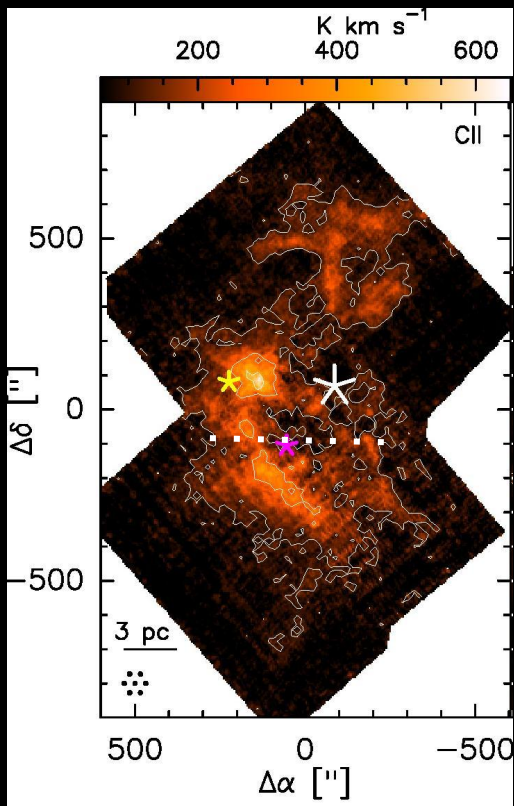
The expanding shell of RCW 49

Spectra along the white dashed line



The expanding shell of RCW 49

Spectra along the white dashed line.



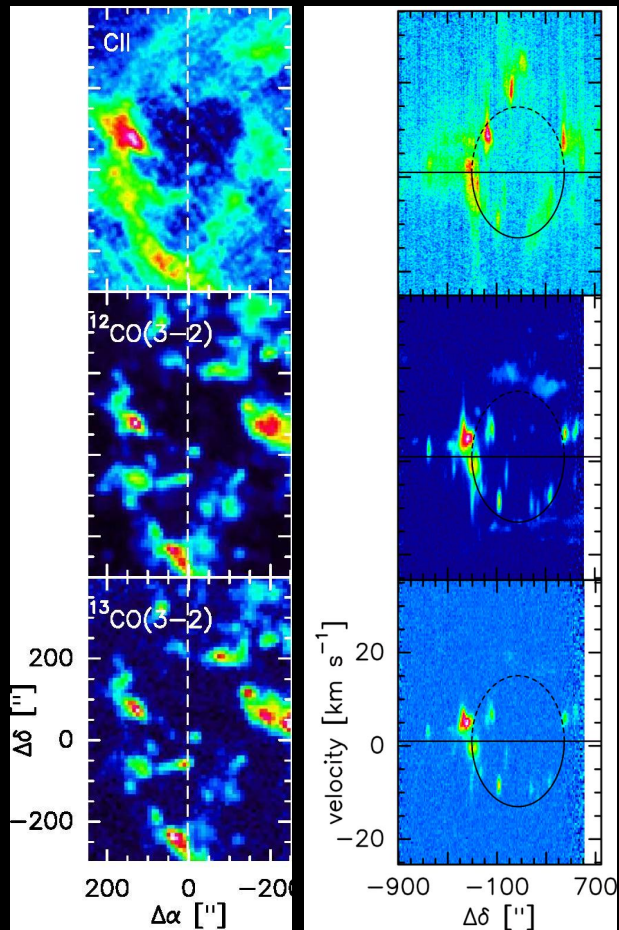
sequential shift in the peak of the blue-shifted velocity component.

Characterization of the shell

Projection of an expanding spherical shell on a p-v space is an ellipse (Butterfield et al 2012).

Shell parameters:

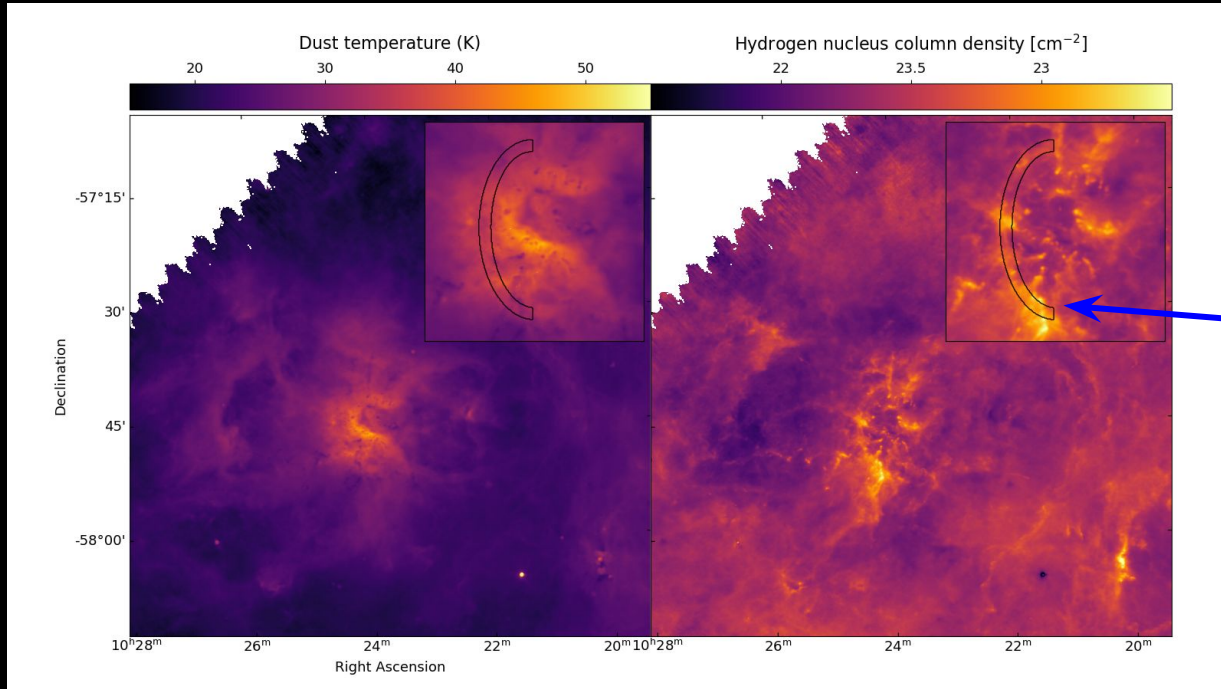
- radius ~ 6 pc
- thickness ~ 1 pc
- velocity ~ 13 km/s



Mass estimation

Method 1: Using 70 and 160 μm dust emission

I_{70}/I_{160} gives T and τ , which estimates $N(\text{HI}) + N(\text{H}_2)$ (general technique in Lombardi et al, 2004)

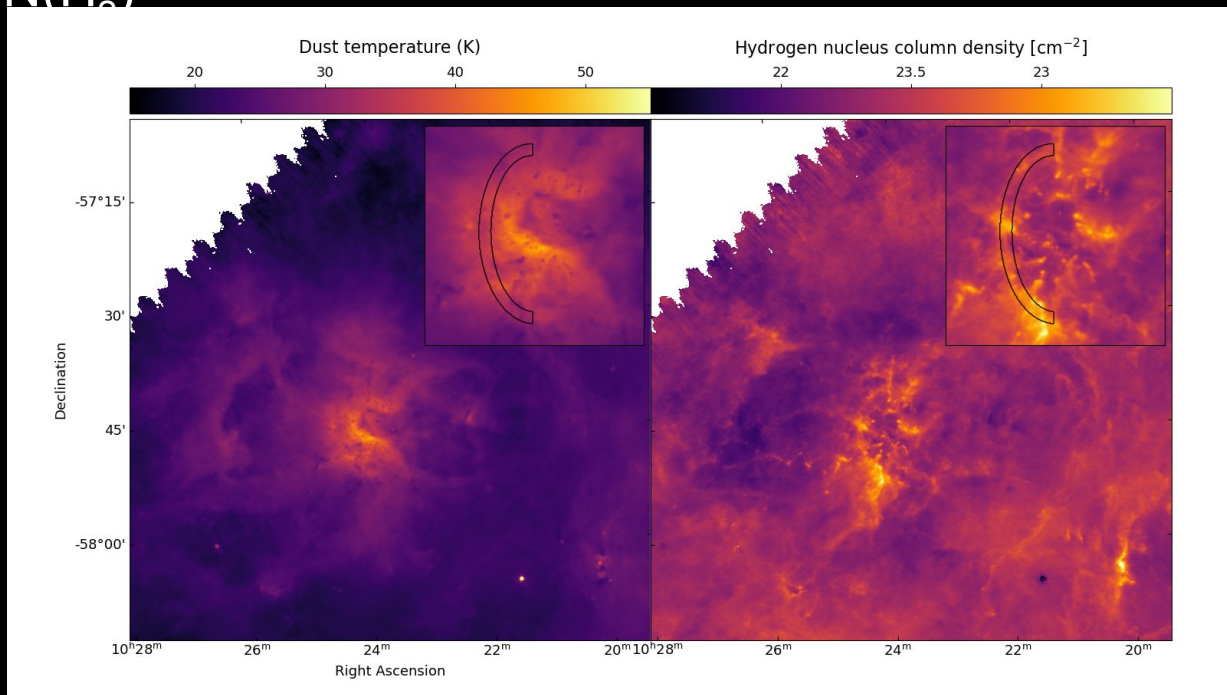


Mass of the masked region

Mass estimation

Method 1: Using 70 and 160 μm dust emission

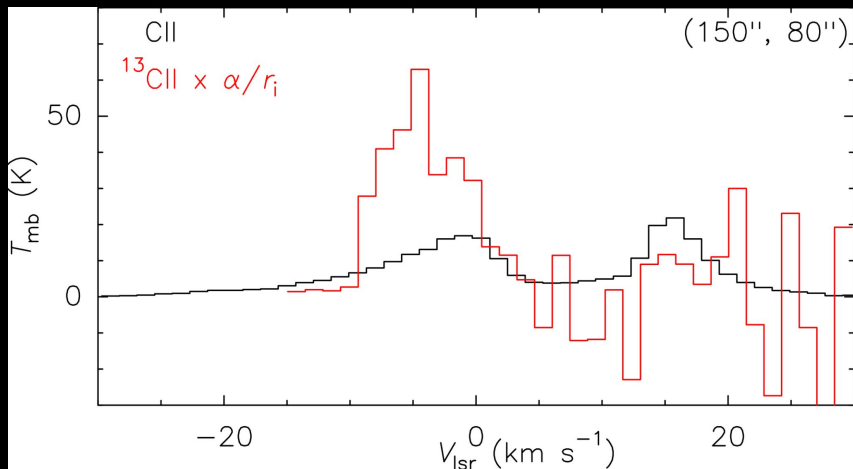
I_{70}/I_{160} gives T and τ , which estimates $N(\text{HI}) + N(\text{H}_2)$



Ramsey Karim
(PhD student, UMD)

Mass estimation

Method 2: Using CII ($T_{\text{ex}} = 100\text{K}$) to get $N(\text{H})$ for the same mask as used for dust.



Spectra towards a bright region.

$\alpha = ^{12}\text{C}/^{13}\text{C} = 52$ (Milam et al, 2004)

$r = 0.25$ (relative intensity of ^{13}CII)

Optical depths are important!

Using ^{13}CII 1900.95 GHz line to determine CII opacity.

Technique mentioned in Guevara et al., (2020). Upper limit: $\tau = 3$.

$\tau = 3$ is only a reference! Very low S/N..

Mass estimation

Method 3: Using ^{13}CO to get $N(\text{H}_2)$ for the same mask as used for dust.

- Pixel-by-pixel determination of T_{ex} using ^{12}CO and estimating $N(^{13}\text{CO})$.
- Estimating H_2 mass from $N(^{13}\text{CO})$.

Mass estimation and errors

Method	Mass
Dust SEDs	8×10^3 solar mass
CII	4.6×10^3 solar mass
^{12}CO	1.5×10^3 solar mass

Compare the mass obtained from dust with the combined mass obtained from CII and CO

Errors in dust mass estimation:

- line-of-sight contribution: $\sim 5\%$
- Diffuse foreground and background: upto 30%

Error in CII mass estimation:

- CII coming from molecular gas: 1.5 times mass

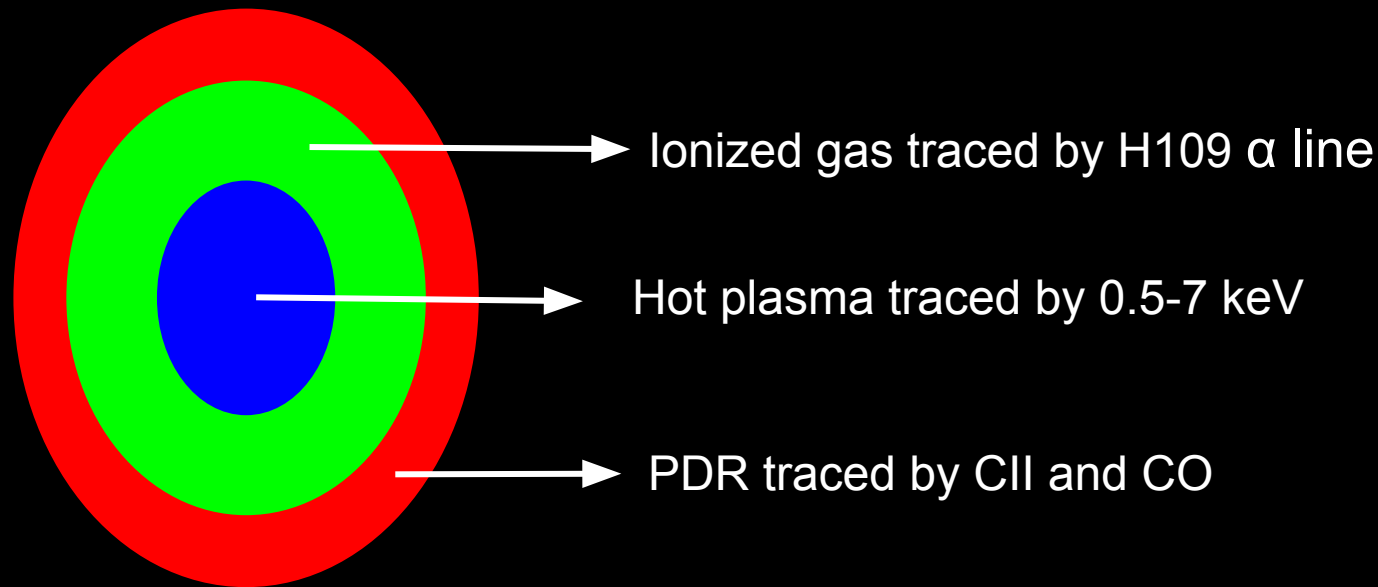
For a 3D structure, **mass = 2.4×10^4 solar mass**

Physical conditions in the shell

X-ray data (0.5–7 keV) from Townsley et al. (2019): Plasma

Radio data (H109 α line) from Paladini et al. (2015): Ionised gas

Submm and FIR data (CO and [CII]): PDR



Physical conditions

X-ray data (0.5–7 keV) from [Townasley et al. \(2019\)](#): Plasma

Radio data (H109 α line) from [Paladini et al. \(2015\)](#): Ionised gas

Submm and FIR data (CO and [CII]) using PDR ToolBox ([Kaufman et al. 2006](#), [Pound & Wolfire et al. 2008](#)): PDR

Region	n (cm ⁻³)	T (K)	p_{th}/k	p_{rad}/k	p_{turb}/k
Plasma	0.71	3.13×10^6	4.9×10^6	-	-
Ionised gas	317	7.7×10^3	4.9×10^6	-	-
PDR	7.5×10^3	400	1.2×10^6	2.6×10^6	5.9×10^6

Energetics

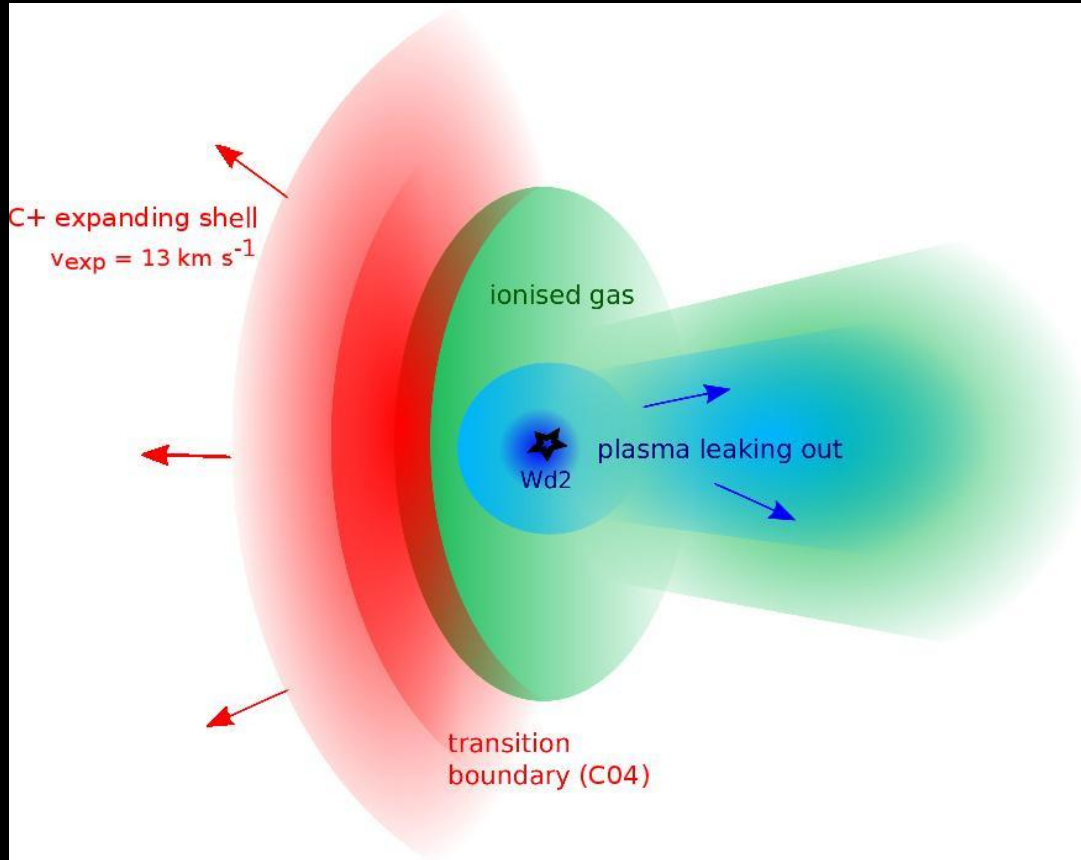
- Kinetic energy of the shell $\sim 2 \times 10^{50}$ ergs.
- Mechanical energy injected by the stellar winds of Wd2: from stellar spectral types (Tsujimoto et al. 2007, Vargas Alvarez et al. 2013 and Mohr-Smith et al. 2015) + STARBURST99: evolutionary spectral synthesis software (Leitherer et al, 2014)
- ME (over its age of 2Myr) $\sim 6 \times 10^{51}$ ergs. More than enough to drive the shell!

Energetics

- Kinetic energy of the shell $\sim 2 \times 10^{50}$ ergs.
- Mechanical energy injected by the stellar winds of Wd2 (over its age of 2Myr) $\sim 6 \times 10^{51}$ ergs. More than enough to drive the shell!
- Plasma's thermal energy $\sim 2.4 \times 10^{48}$ ergs.

Plasma's thermal energy is low!

Morphology



The shell is broken open in the west and the plasma is venting out.

Shell's expansion must be driven by momentum.

Timescales

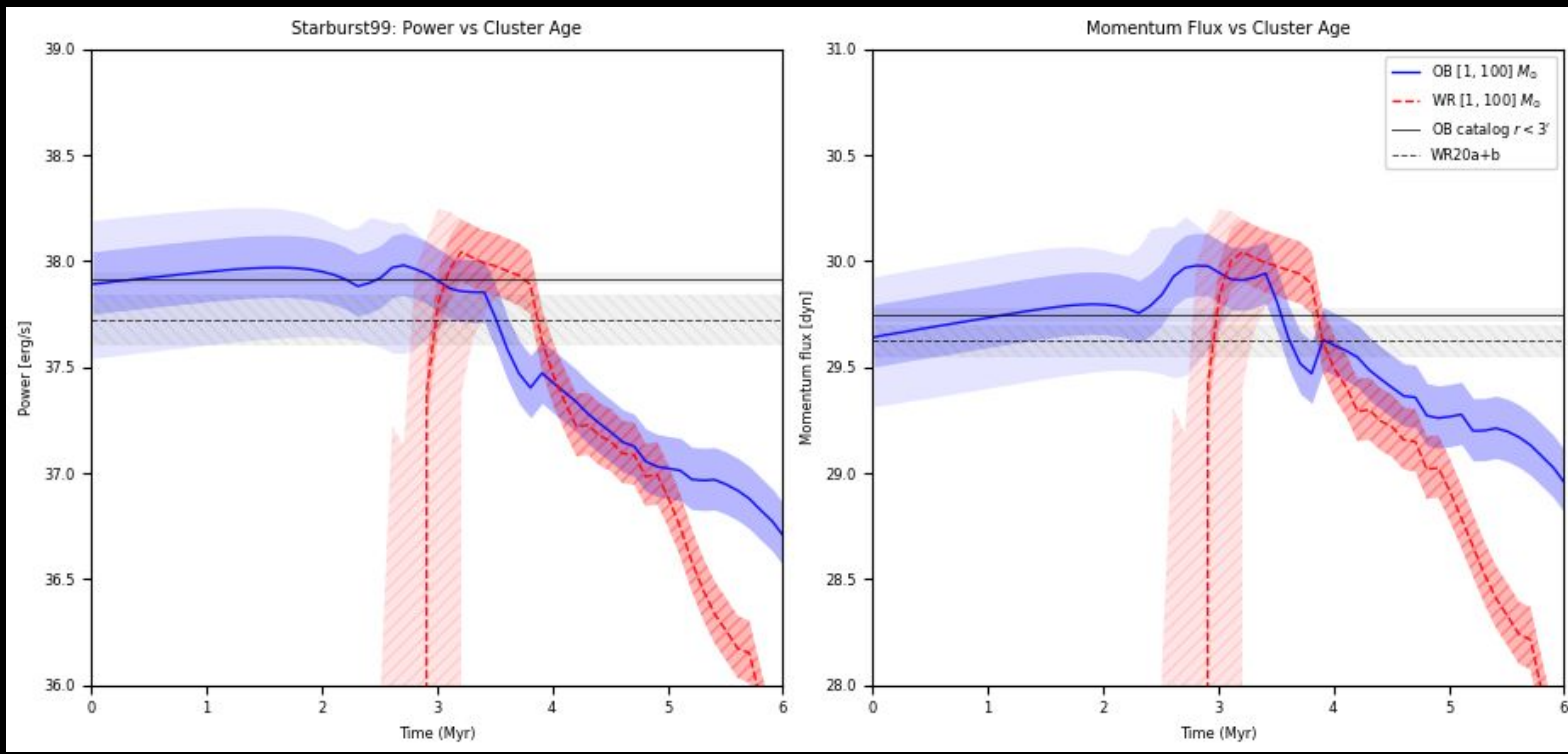
- Stellar wind-driven shell of RCW 49 with radius ~ 6 pc, speed ~ 13 km/s has an expansion timescale of 0.27 Myr (using formalism in [Weaver et al, 1977](#)).
- But the age of Wd2 is 2 Myr ([Ascenso et al. 2007](#) & [Zeidler et al. 2015](#)), such that the shell's speed cannot be > 2 km/s.

What is driving the shell at its current speed of 13 km/s ?

- We infer that the cluster initially drove the shell but then it broke venting plasma, reducing the shell's speed.
- The recent re-acceleration of the shell might be due to the evolution of the most massive WR star WR20a, which formed after 2 Myr.

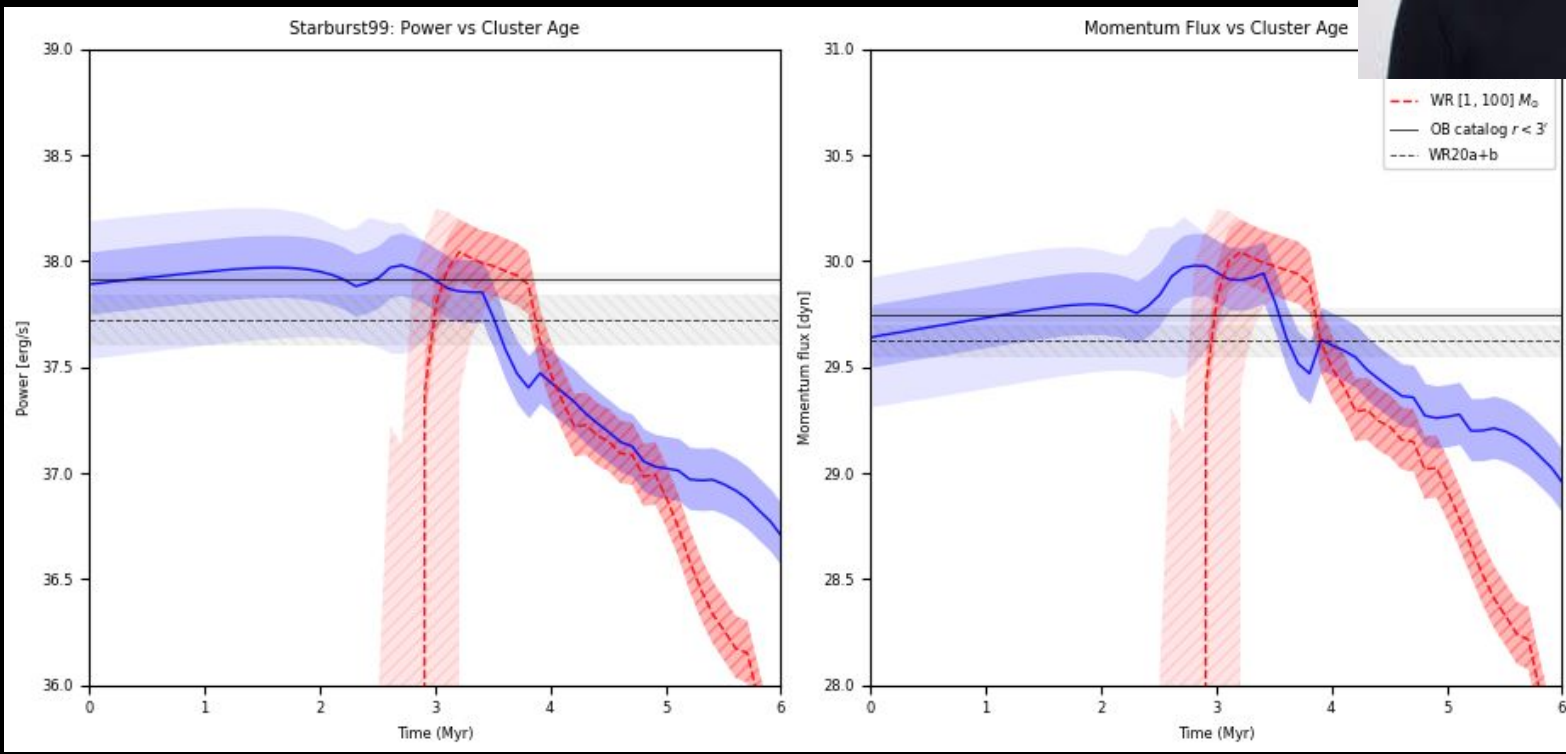
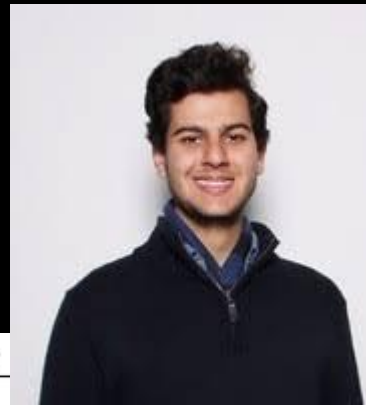
Timescales

WR stars do not inject do not seem to inject significantly more momentum than the ensemble of OB stars...



Timescales

WR stars do not inject do not seem to inject significantly more than the ensemble of OB stars...



Future of star formation

- [Whitney et al, 2004](#) detected 7000 YSOs in RCW 49 with a total mass of 4500 solar mass. Comparing with the shell mass, we get an upper limit on the star formation efficiency $\sim 3.75\%$ (typical in GMCs).
- Most massive YSO in RCW 49 is < 6 solar mass, thus next generation stars will be lower in mass than those in Wd2.
- Feedback from next generation of stars is expected to be limited.

Comparison with the shell of Orion

Studied in detail by Pabst et al 2017, 2019, 2020.

- Similar speeds ~ 13 km/s
- RCW 49 shell is 9 x more massive
- RCW 49 shell driven by a stellar cluster, Orion shell driven by one O7V star
- RCW 49 is broken venting plasma, Orion shell is intact
- CO detected towards RCW 49 shell, no CO detection toward Orion shell.

Larger statistical study initiated by FEEDBACK needed to characterize more shells.



Conclusions

Characterization of the shell

radius ~ 6 pc and thickness of 1 pc is expanding toward us at 13 km/s.
The shell mass is 2.4×10^4 solar mass.

Driving force

The shell was initially powered by the stellar winds of Wd2, broke open in the west releasing the hot plasma.

The shell's observed re-acceleration is most likely driven by the Wolf-Rayet star, WR20a.

Fate of ongoing star formation

A secondary generation of star formation is occurring in the shell but the new generation of stars being formed are relatively lower in mass than those existing in Wd2.

Outlook

- 35% of the data observed as of April 2021. Further observations planned.
- Role of **magnetic fields** in the expansion of shells.
- A **larger statistical study** to investigate the impact of FEEDBACK on massive star formation.
- Stay tuned for the talk by **Matteo Luisi**, “**Stellar FEEDBACK in RCW 120**” on **August 11th**.

Thank you!!!