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

SOFIA Tele Talk, June 16, 2021

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Ramsey Karim, Marc Pound, Mark Wolfire, Xander Tielens, Nicola Schneider & the 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)
Goals

We have started observing the $\text{C}^+ ([\text{CII}])$ 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.

- 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 $H_2$.
- Dominates C budget.
- Trace star formation in the Universe.

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

March 12th 2020
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

<table>
<thead>
<tr>
<th>Source</th>
<th>d (kpc)</th>
<th>SF activity</th>
<th>Area ('')</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCW 36</td>
<td>0.7</td>
<td>O8, B-cluster</td>
<td>15 x 15</td>
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<td>4.3</td>
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<td>20 x 20</td>
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<td>2</td>
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<tr>
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<td>0.26</td>
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<tr>
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<td>5.5</td>
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<tr>
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<td>1.4</td>
<td>2 OB, 3 WR, ~50 O</td>
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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
Whiteoak & Uchida 1997 reported radio data (1-2 Ghz) towards RCW 49.

- Identified two shells separated by a bridge.
- Spatial resolution = 43” x 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

12 to 6 km s$^{-1}$

2 to 8 km s$^{-1}$

16 to 22 km s$^{-1}$
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 $\tau$, 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 $\tau$, which estimates $N(\text{HI}) + N(\text{H}_2)$.
Mass estimation

Method 2: Using CII ($T_{ex} = 100$K) to get $N(H)$ for the same mask as used for dust. Optical depths are important! Using $^{13}$CII 1900.95 Ghz line to determine CII opacity.


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

Spectra towards a bright region. $\alpha = ^{12}$C/$^{13}$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.
Mass estimation

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

- Pixel-by-pixel determination of $T_{\text{ex}}$ using $^{12}\text{CO}$ and estimating $N\left(^{13}\text{CO}\right)$.
- Estimating $\text{H}_2$ mass from $N\left(^{13}\text{CO}\right)$.
Mass estimation and errors

<table>
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<tr>
<th>Method</th>
<th>Mass</th>
</tr>
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<tr>
<td>Dust SEDs</td>
<td>$8 \times 10^3$ solar mass</td>
</tr>
<tr>
<td>CII</td>
<td>$4.6 \times 10^3$ solar mass</td>
</tr>
<tr>
<td>$^{12}$CO</td>
<td>$1.5 \times 10^3$ solar mass</td>
</tr>
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Compare the mass obtained from dust with the combined mass obtained from CII and CO

Errors in dust mass estimation:
- line-of-sight contribution: ~ 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 = $2.4 \times 10^4$ 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

- Ionized gas traced by H109 α line
- Hot plasma traced by 0.5-7 keV
- PDR traced by CII and CO

Maitrayee Tiwari, UMD
Physical conditions

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]) using PDR ToolBox (Kaufman et al. 2006, Pound & Wolfire et al. 2008): PDR

<table>
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<tr>
<th>Region</th>
<th>n (cm⁻³)</th>
<th>T (K)</th>
<th>p(th)/k</th>
<th>p(rad)/k</th>
<th>p(turb)/k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma</td>
<td>0.71</td>
<td>3.13 x 10⁶</td>
<td>4.9 x 10⁶</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ionised gas</td>
<td>317</td>
<td>7.7 x 10³</td>
<td>4.9 x 10⁶</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PDR</td>
<td>7.5 x 10³</td>
<td>400</td>
<td>1.2 x 10⁶</td>
<td>2.6 x 10⁶</td>
<td>5.9 x 10⁶</td>
</tr>
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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!
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 significantly more momentum than the ensemble of OB stars...
Timescales

WR stars do not inject significantly more momentum 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


- 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 \( \sim 6 \) pc and thickness of 1 pc is expanding toward us at 13 km/s. The shell mass is \( 2.4 \times 10^4 \) 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!!!