Exposing Star Formation in our Galaxy's Center: A Window into the Distant Universe

Cara Battersby (CfA)

NSF fellow
Harvard Smithsonian Center for Astrophysics

Eric Keto, Qizhou Zhang, Thushara Pillai, Steve Longmore, Jens Kauffmann, Diederik Kruijssen, Daniel Walker, Xing 'Walker' Lu, Adam Ginsburg, Katharina Immer, Jonny Henshaw, Betsy Mills, Nimesh Patel, Mark Graham, Volker Tolls, John Bally, Katharine Johnston, Luis C. Ho, Andrew Walsh
Tracing the rise of dust & metals in galaxies and the path of water across cosmic time to Earth and other habitable planets.
NASA Mission concept for 2020 Decadal review; launch 2030ish

7 μm – 800 μm (ish), Large aperture 8-15 m

**Study Chairs:** Margaret Meixner & Asantha Cooray

**Comes from the NASA Astrophysics Roadmap, Enduring Quests, Daring Visions: Improvements from *Herschel***

- large gain in sensitivity
- angular resolution sufficient to overcome spatial confusion in deep cosmic surveys
- new spectroscopic capability
Actively-Cooled Large Aperture

Will attain sensitivities 100–1000x greater than any previous far-infrared telescope
ORIGINS
Space Telescope

Tracing the rise of dust & metals in galaxies and the path of water across cosmic time to Earth and other habitable planets.

Tracing the signatures of life and the ingredients of habitable worlds
Origins will trace the trail of water from interstellar clouds, to proto-planetary disks, to Earth itself facilitating understanding of the abundance and availability of water for habitable planets.

Unveiling the Growth of Black Holes and Galaxies over Cosmic Time
Origins will reveal the co-evolution of super-massive black holes and galaxies, energetic feedback, and the dynamic interstellar medium from which stars are born.

Charting the Rise of Metals, Dust, and the First Galaxies
Origins will trace the metal enrichment history of the Universe, probe the first cosmic sources of dust, the earliest star formation, and the birth of galaxies.

Characterizing Small Bodies in the Solar System
Origins will chart the role of comets in delivering water to the early Earth, and conduct a survey of thousands of ancient Trans Neptunian Objects (TNOs) in the outer reaches of the Solar System.
We want your input!
Please contact, if interested in contributing:
cbattersby@cfa.harvard.edu
The Milky Way Laboratory

Extreme SF in our Galactic Center

Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)
Central Molecular Zone

24 μm (Carey+ 2009.), 8 μm
and 4.5 μm (Benjamin+20003)
Central Molecular Zone

$N(H_2)$ (Battersby+ in prep.), 70 $\mu$m (Hi-GAL, Molinari +2011),
8 $\mu$m (GLIMPSE, Benjamin+20003)
Star Formation over cosmic time

- Afterglow Light Pattern 380,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy Accelerated Expansion
- Inflation
- Quantum Fluctuations
- 1st Stars about 400 million yrs.

Big Bang Expansion
13.7 billion years
Star Formation over cosmic time

The peak of star formation was $z \sim 1-3$. 

Big Bang Expansion
13.7 billion years
The peak of star formation was $z \sim 1-3$. 

- Dark Energy Accelerated Expansion
- Development of Galaxies, Planets, etc.
- Quantum Fluctuations
- 1st Stars about 400 million yrs.
- Inflation
- Afterglow Light 380,000 yrs.
- Big Bang Expansion 13.7 billion years
Star Formation over cosmic time

The peak of star formation was $z \approx 1 - 3$.

- $\Sigma_{\text{gas}} \sim 10^3 \, M_{\odot}/\text{pc}^2$
- $\sigma \sim 20 - 50 \, \text{km/s}$
- $P/k \sim 10^7 \, \text{K/cm}^3$

- $\Sigma_{\text{gas}} \sim 10^2 \, M_{\odot}/\text{pc}^2$
- $\sigma \sim 10 \, \text{km/s}$
- $P/k \sim 10^4 \, \text{K/cm}^3$

1st Stars about 400 million years after the Big Bang
Star Formation over cosmic time

![Graph showing星系生成随时间变化]

Kruijssen & Longmore 2013
Star Formation over cosmic time

Kruijssen & Longmore 2013
Central Molecular Zone

- $\Delta v \sim 10x$ higher
- $n \sim 10^{-100x}$ higher
- High temperatures, ubiquitous exotic molecules

$N(H_2)$ (Battersby+ in prep.), 70 $\mu$m (Hi-GAL, Molinari +2011), 8 $\mu$m (GLIMPSE, Benjamin+20003)
Central Molecular Zone

No signs of active star formation
$10^5 \, M_{\odot}$ in $< 3$ pc
$T \sim 20 \, K$, $\Sigma_{H_2} \sim 1 \, g \, cm^{-2}$

$N(H_2)$ (Battersby+ in prep.), 70 $\mu$m (Hi-GAL, Molinari +2011), 8 $\mu$m (GLIMPSE, Benjamin+20003)
SMA Legacy Survey of the Central Molecular Zone

- Large primary beam + wide bandwidth + long wavelength + high angular resolution → detect early star formation across a large area
- First survey of the CMZ ever to be able to do so
SMA Legacy Survey of the Central Molecular Zone

- Large primary beam + wide bandwidth + long wavelength + high angular resolution → detect early star formation across a large area
- First survey of the CMZ ever to be able to do so
CMZoom

- 230 GHz (1.3 mm)
- 240 arcmin² (above N(H₂) = 10²³ cm⁻² or 3x10²² cm⁻²)
- 4'' (0.2 pc) resolution, Δv~1.1 km/s
- dust continuum + spectral lines (H₂CO, ¹²CO, ¹³CO, C¹⁸O, SiO, CH₃OH, CH₃CN, etc.): 8+ GHz bandwidth
- 3 mJy RMS continuum, 0.4 K
- 500 hours (60 tracks; 15 tracks subcompact, 45 tracks compact) over 3 yrs
- Complement with single-dish (APEX, CSO) observations
The image shows a map of the Galactic region with various features labeled, including:

- 1.6° cloud
- Sgr B2
- The "Brick"
- Sgr A*
- Sgr C
- Cloud "d"
- The Three Little Pigs

The map is marked with CMZoom Mosaic Pointings and a scale of 100 pc.
CMZoom

- 230 GHz (1.3 mm)
- 240 arcmin$^2$ (above $N(H_2) = 10^{23}$ cm$^{-2}$ or $3 \times 10^{22}$ cm$^{-2}$)
- 4'' (0.2 pc) resolution, $\Delta v \sim 1.1$ km/s
- Dust continuum + spectral lines ($H_2CO$, $^{12}CO$, $^{13}CO$, $C^{18}O$, SiO, CH$_3$OH, CH$_3$CN, etc.): 8+ GHz bandwidth
- 3 mJy RMS continuum, 0.4 K
- 500 hours (60 tracks; 15 tracks subcompact, 45 tracks compact) over 3 yrs
- Complement with single-dish (APEX, CSO) observations
CMZoom

Find embedded star formation

- 230 GHz (1.3 mm)
- 240 arcmin$^2$ (above N(H$_2$) = 10$^{23}$ cm$^{-2}$ or 3x10$^{22}$ cm$^{-2}$)
- 4'' (0.2 pc) resolution, Δν~1.1 km/s
- Dust continuum + spectral lines (H$_2$CO, $^{12}$CO, $^{13}$CO, C$^{18}$O, SiO, CH$_3$OH, CH$_3$CN, etc.): 8+ GHz bandwidth
- 3 mJy RMS continuum, 0.4 K
- 500 hours (50 subcompact, 450 compact/custom) over 3 yrs
- Complement with single-dish (APEX, CSO) observations
Central Molecular Zone

“Bricklet” D

Cold dust – submillimeter
Central Molecular Zone

100 pc

“Bricklet” D

Cold dust – submillimeter
CMZoom

Team:
CfA: Cara Battersby, Eric Keto, Qizhou Zhang, Xing ‘Walker’ Lu (Nanjing), Mark Graham (Oxford), Nimesh Patel, Volker Tolls, Dennis Lee, Jimmy Castaño, Liz Gehret, Irene Vargas-Salzar
Bonn: Jens Kauffmann, Thushara Pillai
Liverpool: Steve Longmore, Daniel Walker (CfA), Jonny Henshaw
University of Colorado, Boulder: John Bally
Heidelberg: Diederik Kruijssen, NRAO: Betsy Mills
ESO: Adam Ginsburg, Katharina Immer, Leeds: Katharine Johnston
Peking University: Luis C. Ho, Perth: Andrew Walsh
Driving Science Questions:

1) What is the cause of the extremely low star formation efficiency (given the reservoir of dense gas) in the CMZ?

2) Is there an energy and SF cycle in the CMZ? Where does gas enter the CMZ?

3) Is SF induced by tidal compression by SgrA*?

4) Can we find precursors to the most massive stars in the Galaxy?
Driving Science Questions:

1) What is the cause of the extremely low star formation efficiency (given the reservoir of dense gas) in the CMZ?

2) Is there an energy and SF cycle in the CMZ? Where does gas enter the CMZ?

3) Is SF induced by tidal compression by SgrA*?

4) Can we find precursors to the most massive stars in the Galaxy?
The "Molinari Ring" (Molinari+2011)
New orbital models (Kruijssen, Dale, & Longmore 2015)
Tidal compression of clouds

\[ N(\text{H}_2) \] from HiGAL Battersby+, in prep., 70 \( \mu \text{m} \) from HiGAL, Molinari+ 2011, 8 \( \mu \text{m} \) from GLIMPSE (Benjamin+ 2003)
Tidal compression of clouds

$N(H_2)$ from HiGAL Battersby+, in prep., 70 μm from HiGAL, Molinari+ 2011, 8 μm from GLIMPSE (Benjamin+ 2003)
Tidal compression of clouds

Kruijssen, Dale, Longmore 2015

$N(H_2)$ from HiGAL Battersby+, in prep., 70 $\mu$m from HiGAL, Molinari+ 2011, 8 $\mu$m from GLIMPSE (Benjamin+ 2003)
Tidal compression of clouds

Dan Walker – PhD student in Liverpool
SAO Pre-doc

$N(H_2)$ from HiGAL Battersby+ in prep., 70 $\mu$m from HiGAL, Molinari+ 2011, 8 $\mu$m from GLIMPSE (Benjamin+ 2003)
ALMA 3mm contours, Rathborne et al. 2014; 2015

SMA 1.3mm contours

Cloud 'a' ('the Brick')

Cloud 'd'

Cloud 'c'

Cloud 'e'

Cloud 'b'

Cloud 'f'

N(H$_2$)

5 pc

70 μm

8 μm

CMZzoom
N_{ff} = 0.61
No SF tracers

N_{ff} = 0.65
H$_2$O maser

N_{ff} = 1.28
H$_2$O and CH$_3$OH masers

N_{ff} = 1.76
H$_2$O, CH$_3$OH, SiO, H$_2$CO masers + 70 \mu m
Warm dust column density
Cold dust column density

Barnes, Longmore, Battersby, & Bally in prep.
Driving Science Questions:

1) What is the cause of the extremely low star formation efficiency (given the reservoir of dense gas) in the CMZ?

2) Is there an energy and SF cycle in the CMZ? Where does gas enter the CMZ?

3) Is SF induced by tidal compression by SgrA*?

4) Can we find precursors to the most massive stars in the Galaxy?
Why is the SFR low in the CMZ?

\( N(H_2) \) from HiGAL Battersby+, in prep., 70 \( \mu \text{m} \) from HiGAL, Molinari+ 2011, 8 \( \mu \text{m} \) from GLIMPSE (Benjamin+ 2003)
Why is the SFR low in the CMZ?

\[ N(\text{H}_2) \] from HiGAL Battersby+, in prep., 70 \( \mu \text{m} \) from HiGAL, Molinari+ 2011, 8 \( \mu \text{m} \) from GLIMPSE (Benjamin+ 2003)
Why is the SFR low in the CMZ?

Mark Graham
SAO Pre-doc, now a PhD student at Oxford
Why is the SFR low in the CMZ?

\[ N(\text{H}_2), \ 70 \, \mu \text{m}, \ 8 \, \mu \text{m} \]
Why is the SFR low in the CMZ?

\[ \text{N}(\text{H}_2), \ 70 \mu \text{m}, \ 8 \mu \text{m} \]  
SMA 1.3 mm continuum
Why is the SFR low in the CMZ?

$N(H_2)$, 70 $\mu$m, 8 $\mu$m
SMA 1.3 mm continuum
Why is the SFR low in the CMZ?

N(H$_2$), 70 μm, 8 μm
SMA 1.3 mm continuum
Why is the SFR low in the CMZ?
Why is the SFR low in the CMZ?

Is it star forming?
- Dense gas
- Shocked, highly excited gas
- Virial ratio < 2
- Power-law tail in N-PDF
- Outflow or localized hot-core chemistry

SMA 1.3 mm dust continuum
Why is the SFR low in the CMZ?

- Dense gas
- Shocked, highly excited gas
- Virial ratio < 2
- Power-law tail in N-PDF
- Outflow or localized hot core chemistry
Why is the SFR low in the CMZ?

Is it star forming?
✓ Dense gas
✓ Shocked, highly excited gas
☐ Virial ratio < 2
☐ Power-law tail in N-PDF
☐ Outflow or localized hot-core chemistry
Why is the SFR low in the CMZ?

Is it star forming?
- Dense gas
- Shocked, highly excited gas
- Virial ratio < 2
- Power-law tail in N-PDF
- Outflow or localized hot-core chemistry

Gravity vs. pressure (thermal and turbulence)
Why is the SFR low in the CMZ?

Dendrograms, e.g. Shetty et al. 2012, Rosolowsky et al. 2008

Liz Gehret
SAO REU student
Why is the SFR low in the CMZ?

<table>
<thead>
<tr>
<th>Structure ID</th>
<th>H$_2$CO Flux (Jy)</th>
<th>Dust Flux (Jy)</th>
<th>Central Velocity (km/s)</th>
<th>$\Delta v_{FWHM}$ (km/s)</th>
<th>$M_{dust}$ (M$_\odot$)</th>
<th>$M_{vir}$ (M$_\odot$)</th>
<th>Virial Ratio $M_{vir}/M_{dust}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.085</td>
<td>4.224</td>
<td>49.66</td>
<td>20.63</td>
<td>7.15E+03</td>
<td>6.22E+04</td>
<td>8.70</td>
</tr>
<tr>
<td>1</td>
<td>1.012</td>
<td>4.197</td>
<td>49.34</td>
<td>20.03</td>
<td>7.10E+03</td>
<td>5.83E+04</td>
<td>8.23</td>
</tr>
<tr>
<td>2</td>
<td>0.879</td>
<td>3.997</td>
<td>49.36</td>
<td>19.96</td>
<td>6.71E+03</td>
<td>5.04E+04</td>
<td>8.42</td>
</tr>
<tr>
<td>3</td>
<td>0.837</td>
<td>3.868</td>
<td>49.54</td>
<td>19.95</td>
<td>6.58E+03</td>
<td>4.92E+04</td>
<td>8.53</td>
</tr>
<tr>
<td>4</td>
<td>0.719</td>
<td>3.725</td>
<td>49.43</td>
<td>19.85</td>
<td>6.31E+03</td>
<td>4.41E+04</td>
<td>8.58</td>
</tr>
<tr>
<td>5</td>
<td>0.359</td>
<td>1.501</td>
<td>45.46</td>
<td>16.65</td>
<td>2.54E+03</td>
<td>2.36E+04</td>
<td>9.28</td>
</tr>
<tr>
<td>6</td>
<td>0.233</td>
<td>0.943</td>
<td>46.03</td>
<td>17.06</td>
<td>1.60E+03</td>
<td>1.90E+04</td>
<td>11.91</td>
</tr>
<tr>
<td>7</td>
<td>0.154</td>
<td>0.656</td>
<td>45.17</td>
<td>16.30</td>
<td>1.11E+03</td>
<td>1.46E+04</td>
<td>13.18</td>
</tr>
<tr>
<td>8</td>
<td>0.54</td>
<td>2.899</td>
<td>49.28</td>
<td>20.43</td>
<td>4.91E+03</td>
<td>5.04E+04</td>
<td>10.26</td>
</tr>
<tr>
<td>9</td>
<td>0.288</td>
<td>1.153</td>
<td>46.09</td>
<td>16.86</td>
<td>1.95E+03</td>
<td>2.11E+04</td>
<td>10.80</td>
</tr>
<tr>
<td>10</td>
<td>0.075</td>
<td>0.339</td>
<td>43.52</td>
<td>12.44</td>
<td>5.74E+02</td>
<td>6.05E+03</td>
<td>10.55</td>
</tr>
<tr>
<td>11</td>
<td>0.035</td>
<td>0.100</td>
<td>39.86</td>
<td>7.01</td>
<td>1.69E+02</td>
<td>1.27E+03</td>
<td>7.54</td>
</tr>
<tr>
<td>12</td>
<td>0.008</td>
<td>0.045</td>
<td>42.00</td>
<td>9.13</td>
<td>7.57E+01</td>
<td>1.11E+03</td>
<td>14.68</td>
</tr>
<tr>
<td>13</td>
<td>0.053</td>
<td>0.171</td>
<td>55.23</td>
<td>15.23</td>
<td>2.90E+02</td>
<td>8.20E+03</td>
<td>28.26</td>
</tr>
<tr>
<td>14</td>
<td>0.02</td>
<td>0.068</td>
<td>41.35</td>
<td>7.51</td>
<td>1.16E+02</td>
<td>1.20E+03</td>
<td>10.31</td>
</tr>
<tr>
<td>15</td>
<td>0.083</td>
<td>0.363</td>
<td>51.82</td>
<td>12.31</td>
<td>6.14E+02</td>
<td>6.64E+03</td>
<td>10.82</td>
</tr>
<tr>
<td>16</td>
<td>0.154</td>
<td>0.723</td>
<td>58.80</td>
<td>12.03</td>
<td>1.22E+03</td>
<td>6.94E+03</td>
<td>5.67</td>
</tr>
<tr>
<td>17</td>
<td>0.017</td>
<td>0.131</td>
<td>54.87</td>
<td>6.12</td>
<td>2.22E+02</td>
<td>9.80E+02</td>
<td>4.41</td>
</tr>
<tr>
<td>18</td>
<td>0.012</td>
<td>0.109</td>
<td>49.58</td>
<td>2.77</td>
<td>1.85E+02</td>
<td>1.85E+02</td>
<td>1.00</td>
</tr>
<tr>
<td>19</td>
<td>0.008</td>
<td>0.031</td>
<td>50.85</td>
<td>4.58</td>
<td>3.03E+01</td>
<td>4.37E+02</td>
<td>8.24</td>
</tr>
<tr>
<td>20</td>
<td>0.024</td>
<td>0.090</td>
<td>53.91</td>
<td>6.05</td>
<td>1.52E+02</td>
<td>7.76E+02</td>
<td>5.11</td>
</tr>
<tr>
<td>21</td>
<td>0.018</td>
<td>0.122</td>
<td>57.90</td>
<td>7.65</td>
<td>2.07E+02</td>
<td>1.87E+03</td>
<td>9.05</td>
</tr>
<tr>
<td>22</td>
<td>0.008</td>
<td>0.067</td>
<td>55.09</td>
<td>6.40</td>
<td>1.13E+02</td>
<td>8.48E+02</td>
<td>7.51</td>
</tr>
<tr>
<td>23</td>
<td>0.011</td>
<td>0.081</td>
<td>57.67</td>
<td>6.99</td>
<td>1.37E+02</td>
<td>1.13E+03</td>
<td>8.23</td>
</tr>
<tr>
<td>24</td>
<td>0.02</td>
<td>0.197</td>
<td>65.77</td>
<td>10.39</td>
<td>3.33E+02</td>
<td>3.16E+03</td>
<td>9.48</td>
</tr>
</tbody>
</table>
### SMA 1.3 mm dust continuum

#### Why is the SFR low in the CMZ?

High levels of turbulence are preventing star formation.

<table>
<thead>
<tr>
<th>Structure ID</th>
<th>H$_2$CO Flux (Jy)</th>
<th>Dust Flux (Jy)</th>
<th>Central Velocity (km/s)</th>
<th>$\Delta v_{FWHM}$ (km/s)</th>
<th>$M_{dust}$ (M$_{\odot}$)</th>
<th>$M_{vir}$ (M$_{\odot}$)</th>
<th>Virial Ratio $M_{vir}/M_{dust}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.085</td>
<td>4.224</td>
<td>49.66</td>
<td>20.63</td>
<td>7.15E+03</td>
<td>6.22E+04</td>
<td>8.70</td>
</tr>
<tr>
<td>1</td>
<td>1.012</td>
<td>4.197</td>
<td>49.34</td>
<td>20.03</td>
<td>7.10E+03</td>
<td>5.85E+04</td>
<td>8.23</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.42</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.53</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.58</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.28</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11.91</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13.18</td>
</tr>
<tr>
<td>8</td>
<td>0.54</td>
<td>2.899</td>
<td>49.28</td>
<td>20.43</td>
<td>4.91E+03</td>
<td>3.05E+04</td>
<td>10.26</td>
</tr>
<tr>
<td>9</td>
<td>0.288</td>
<td>1.153</td>
<td>46.09</td>
<td>16.86</td>
<td>1.95E+03</td>
<td>2.11E+04</td>
<td>10.80</td>
</tr>
<tr>
<td>10</td>
<td>0.075</td>
<td>0.339</td>
<td>43.52</td>
<td>12.44</td>
<td>5.74E+02</td>
<td>6.05E+03</td>
<td>10.55</td>
</tr>
<tr>
<td>11</td>
<td>0.035</td>
<td>0.100</td>
<td>39.86</td>
<td>7.01</td>
<td>1.69E+02</td>
<td>1.27E+03</td>
<td>7.54</td>
</tr>
<tr>
<td>12</td>
<td>0.008</td>
<td>0.045</td>
<td>42.00</td>
<td>9.13</td>
<td>7.57E+01</td>
<td>1.11E+03</td>
<td>14.68</td>
</tr>
<tr>
<td>13</td>
<td>0.053</td>
<td>0.171</td>
<td>55.23</td>
<td>15.23</td>
<td>2.90E+02</td>
<td>8.20E+03</td>
<td>28.26</td>
</tr>
<tr>
<td>14</td>
<td>0.02</td>
<td>0.068</td>
<td>41.35</td>
<td>7.51</td>
<td>1.16E+02</td>
<td>1.20E+03</td>
<td>10.31</td>
</tr>
<tr>
<td>15</td>
<td>0.083</td>
<td>0.363</td>
<td>51.82</td>
<td>12.31</td>
<td>6.14E+02</td>
<td>6.64E+03</td>
<td>10.82</td>
</tr>
<tr>
<td>16</td>
<td>0.154</td>
<td>0.723</td>
<td>58.80</td>
<td>12.03</td>
<td>1.22E+03</td>
<td>6.94E+03</td>
<td>5.67</td>
</tr>
<tr>
<td>17</td>
<td>0.017</td>
<td>0.131</td>
<td>54.87</td>
<td>6.12</td>
<td>2.22E+02</td>
<td>9.80E+02</td>
<td>4.41</td>
</tr>
<tr>
<td>18</td>
<td>0.012</td>
<td>0.109</td>
<td>49.58</td>
<td>2.77</td>
<td>1.85E+02</td>
<td>1.85E+02</td>
<td>1.00</td>
</tr>
<tr>
<td>19</td>
<td>0.008</td>
<td>0.031</td>
<td>50.85</td>
<td>4.58</td>
<td>5.30E+01</td>
<td>4.37E+02</td>
<td>8.24</td>
</tr>
<tr>
<td>20</td>
<td>0.024</td>
<td>0.090</td>
<td>53.91</td>
<td>6.05</td>
<td>1.52E+02</td>
<td>7.76E+02</td>
<td>5.11</td>
</tr>
<tr>
<td>21</td>
<td>0.018</td>
<td>0.122</td>
<td>57.90</td>
<td>7.65</td>
<td>2.07E+02</td>
<td>1.87E+03</td>
<td>9.05</td>
</tr>
<tr>
<td>22</td>
<td>0.008</td>
<td>0.067</td>
<td>55.09</td>
<td>6.40</td>
<td>1.13E+02</td>
<td>8.48E+02</td>
<td>7.51</td>
</tr>
<tr>
<td>23</td>
<td>0.011</td>
<td>0.081</td>
<td>57.67</td>
<td>6.99</td>
<td>1.37E+02</td>
<td>1.13E+03</td>
<td>8.23</td>
</tr>
<tr>
<td>24</td>
<td>0.02</td>
<td>0.197</td>
<td>65.77</td>
<td>10.39</td>
<td>3.33E+02</td>
<td>3.16E+03</td>
<td>9.48</td>
</tr>
</tbody>
</table>
Structure Identification

Battersby, Gehret, et al., in prep.
Structure Identification

35-45 km/s
45-55 km/s
55-65 km/s

H$_2$CO (3-2)

SCOUSE line fitting
Jonny Henshaw
Liverpool
Structure Identification

H$_2$CO (3-2)
Why is the SFR low in the CMZ?

Is it star forming?

- Dense gas
- Shocked, highly excited gas

X Virial ratio < 2

☐ Power-law tail in N-PDF
☐ Outflow or localized hot-core chemistry
Why is the SFR low in the CMZ?

Is it star forming?

- Dense gas
- Shocked, highly excited gas

-X Virial ratio $< 2$

- Power-law tail in N-PDF
- Outflow or localized hot-core chemistry
Why is the SFR low in the CMZ?

- Is it star forming?
  - Yes: Dense gas
  - Yes: Shocked, highly excited gas
  - No: Virial ratio < 2
  - No: Power-law tail in N-PDF
  - No: Outflow or localized hot-core chemistry

![SMA 1.3 mm dust continuum](image)

![Normalised Number](image)

![CMZOOM logo](image)
Why is the SFR low in the CMZ?

Is it star forming?
- Dense gas
- Shocked, highly excited gas

Virial ratio < 2
Power-law tail in N-PDF
Outflow or localized hot-core chemistry

High levels of turbulence (and maybe more) are preventing star formation
Why is the SFR low in the CMZ?
Why is the SFR low in the CMZ?

Is it star forming?
- Dense gas
- Shocked, highly excited gas
- Virial ratio $< 2$
- Power-law tail in N-PDF
- Outflow or localized hot-core chemistry

Lu, et al., 2015
Why is the SFR low in the CMZ?

Is it star forming?
- Dense gas
- Shocked, highly excited gas
- Virial ratio < 2
- Power-law tail in N-PDF
- Outflow or localized hot-core chemistry

Discovered hidden star formation

Lu, et al., 2015
Why is the SFR low in the CMZ?

Xing ‘Walker’ Lu
CfA / Nanjing Univ.
Why is the SFR low in the CMZ?

Lu, et al., in prep.

SMA 1.3 mm

Is it star forming?
- Dense gas
- Shocked, highly excited gas
- Virial ratio < 2
- Power-law tail in N-PDF
- Outflow or localized hot-core chemistry

Lu, et al., in prep.
Why is the SFR low in the CMZ?

Is it star forming?
- Dense gas
- Shocked, highly excited gas
- Virial ratio < 2
- Power-law tail in N-PDF
- Outflow or localized hot-core chemistry

Lu, et al., in prep.

SMA 1.3 mm
Why is the SFR low in the CMZ?

- SMA 1.3 mm

Is it star forming?
- Dense gas
- Shocked, highly excited gas
- Virial ratio < 2
- Power-law tail in N-PDF
- Outflow or localized hot-core chemistry

Previously known very active star formation

Lu, et al., in prep.
Why is the SFR low in the CMZ?

$N(H_2)$ from HiGAL Battersby+, in prep., 70 μm from HiGAL, Molinari+ 2011, 8 μm from GLIMPSE (Benjamin+ 2003)
Pre-cursors to high-mass stars

Is it star forming?
- Dense gas
- Shocked, highly excited gas
- Virial ratio < 2
- Power-law tail in N-PDF
- Outflow or localized hot-core chemistry

Preliminary Core mass estimates, assuming 20 K
Core 1: 550 M☉
Core 2: 340 M☉

Battersby, Graham, et al., in prep.
Pre-cursors to high-mass stars

Is it star forming?
✓ Dense gas
✓ Shocked, highly excited gas
✓ Virial ratio < 2
✓ Power-law tail in N-PDF
✓ Outflow or localized hot-core chemistry

Preliminary Core mass estimates, assuming 20 K
Core 1: 550 M_☉
Core 2: 340 M_☉

Battersby, Graham, et al., in prep.
Pre-cursors to high-mass stars

Is it star forming?
✓ Dense gas
✓ Shocked, highly excited gas
✓ Virial ratio < 2
✓ Power-law tail in N-PDF
✓ Outflow or localized hot-core chemistry

Low-level isolated star formation

Battersby, Graham, et al., in prep.
Pre-cursors to high-mass stars

Is it star forming?
✓ Dense gas
✓ Shocked, highly excited gas
✓ Virial ratio < 2
✓ Power-law tail in N-PDF
✓ Outflow or localized hot-core chemistry

Battersby, Graham, et al., in prep.
Why is the SFR low in the CMZ?

Low-level isolated star formation

Previously known very active star formation

High levels of turbulence (and maybe more) are preventing star formation

Discovered hidden star formation

\(N(H_2)\) from HiGAL Battersby+, in prep., 70 \(\mu m\) from HiGAL, Molinari+ 2011, 8 \(\mu m\) from GLIMPSE (Benjamin+ 2003)
Why is the SFR low in the CMZ?

- Low-level isolated star formation
- Previously known very active star formation
- High levels of turbulence (and maybe more) are preventing star formation
- Discovered hidden star formation

- High turbulence inhibits SF
- Some SF was missed

$N(H_2)$ from HiGAL Battersby+, in prep., 70 μm from HiGAL, Molinari+ 2011, 8 μm from GLIMPSE (Benjamin+ 2003)
Driving Science Questions:

1) What is the cause of the extremely low star formation efficiency (given the reservoir of dense gas) in the CMZ?

2) Is there an energy and SF cycle in the CMZ? Where does gas enter the CMZ?

3) Is SF induced by tidal compression by SgrA*?

4) Can we find precursors to the most massive stars in the Galaxy?
Driving Science Questions:

1) What is the cause of the extremely low star formation efficiency (given the reservoir of dense gas) in the CMZ?
   → Some places are *very* active, in others, high levels of turbulence are important in inhibiting star formation

2) Is there an energy and SF cycle in the CMZ?  Where does gas enter the CMZ?

3) Is SF induced by tidal compression by SgrA*?
   → Observations consistent

4) Can we find precursors to the most massive stars in the Galaxy?
   → We have some good candidates
Extreme SF in our Galactic Center: new, large survey shows turbulence can inhibit SF, tidal compression can (maybe) trigger it, and it can happen where we least expect it.

Our infinite thanks to the many many people at the SMA who made this survey possible!
Bally et al. 2010
from Binney et al. 1991
Why is the SFR low in the CMZ?

Krumholz & Kruijssen 2015

Torrey et al., 2016
Compact only
Compact + subcompact
Compact + subcompact + single dish