The Milky Way Laboratory

Cara Battersby
Harvard-Smithsonian Center for Astrophysics
The Milky Way Laboratory

Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)
1. What is the large-scale structure of our Galaxy?
2. How do the most massive stars form in our Galaxy?
3. How do they form in the distant Universe?
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Stop 1: The Skeleton of the Milky Way

"Nessie"

Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)
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1. What is the large-scale structure of our Galaxy?
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Stop 2: Massive star and cluster formation
1. What is the large-scale structure of our Galaxy?
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Stop 3: Extreme SF in our Galactic Center

Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)
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Stop 1: The Skeleton of the Milky Way
The Skeleton of the Milky Way
M51: the Whirlpool Galaxy
From the Hubble Space Telescope. NASA / JPL-Caltech / R. Kennicutt (U. Arizona)
Spitzer's infrared array camera (IRAC) are shown in blue (3.6 and 4.5 microns) and green (5.8 and 8.0 microns), while the multiband imaging photometer (MIPS) observation is red (24 microns).

IC 342 Infrared image
Spitzer's infrared array camera (IRAC) are shown in blue (3.6 and 4.5 microns) and green (5.8 and 8.0 microns), while the multiband imaging photometer (MIPS) observation is red (24 microns).
The Milky Way

“Galactic Plane”
Nessie – Bone of the Milky Way?

Goodman et al. 2014

Red: 24 μm, Green: 8 μm, Blue: 4.5 μm, MIPSGAL (Carey et al. 2009) and GLIMPSE (Benjamin et al. 2003)
Nessie – Bone of the Milky Way?

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Nessie – Bone of the Milky Way?

Goodman et al. 2014

Dame & Thaddeus 2011
Nessie traces out the Scutum-Centaurus Arm. Are there others?
Nessie traces out the Scutum-Centaurus Arm. Are there others?

Yes!
Search for more Bones of the Milky Way

Catherine Zucker
2014 SAO REU from Virginia
Just started Harvard PhD program!

Zucker, Battersby, & Goodman 2015
Red: 24 μm, Green: 8 μm, Blue: 4.5 μm, MIPSGAL (Carey et al. 2009) and GLIMPSE (Benjamin et al. 2003)
Search for more Bones of the Milky Way

- Mid-infrared extinction feature
- Roughly parallel to the Galactic plane
- Within 20 pc of the physical Galactic mid-plane
- Within 10 km/s of the global-log spiral fit to any MW arm
- Projected aspect ratio greater than or equal to 50:1

Zucker, Battersby, & Goodman 2015

Red: 24 μm, Green: 8 μm, Blue: 4.5 μm, MIPSGAL (Carey et al. 2009) and GLIMPSE (Benjamin et al. 2003)
6/10 candidates are excellent tracers of spiral arm in 3-D (position-position-velocity space)

We are now working to assemble a full ‘Skeleton’

Zucker, Battersby, & Goodman 2015
Working to characterize their physical properties and kinematics with Harvard undergraduate, Amy Cohn

Zucker, Battersby, & Goodman 2015
Next Steps: The Skeleton of the Milky Way
Next Steps: The Skeleton of the Milky Way

- Identify more Bones of the Milky Way. Combine with other tracers (e.g. CO, HI, dense gas) to develop a model of Galactic structure.
Next Steps: The Skeleton of the Milky Way

• Identify more Bones of the Milky Way. Combine with other tracers (e.g. CO, HI, dense gas) to develop a model of Galactic structure

• Measure physical properties and kinematics of Bones – compare directly with simulations. Develop improved Galactic-scale simulations
Next Steps: The Skeleton of the Milky Way

- Identify more Bones of the Milky Way. Combine with other tracers (e.g. CO, HI, dense gas) to develop a model of Galactic structure
- Measure physical properties and kinematics of Bones – compare directly with simulations. Develop improved Galactic-scale simulations
- Preliminary $\text{^{18}C}O$ contours on 8μm image
- 60 hour IRAM Project (PI: Battersby) to map our best Northern “Bone candidate”
• Measure physical properties and kinematics of Bones – compare directly with simulations. Develop improved Galactic-scale simulations
Next Steps: The Skeleton of the Milky Way

- Identify more Bones of the Milky Way. Combine with other tracers (e.g. CO, HI, dense gas) to develop a model of Galactic structure.

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- Detect Bones in nearby face-on spiral galaxies to understand their role in Galactic structure.
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Stop 2: Massive star and cluster formation

Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)
Evolution

Starless proto-cluster

Star-forming proto-cluster

Star-forming proto-cluster

Embedded cluster

Battersby et al. 2010; 2011
Search for Starless Proto-Clusters
Search for Starless Proto-Clusters

Embedded cluster
Search for Starless Proto-Clusters

First ever complete search for massive, compact starless proto-clusters (BGPS: Ginsburg, Battersby, et al. 2012)

- Massive, Tightly Bound: $3 \times 10^4 \, \text{M}_\odot \quad (1 \times 10^4 \, \text{M}_\odot) \quad r < 2.5 \, \text{pc}$
Search for Starless Proto-Clusters

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Search for Starless Proto-Clusters

Starless clumps are *less massive* overall
→ corresponds to mass accretion rate of \( \sim 1000 \, M_\odot / \text{Myr} \)

Svoboda, Shirley, Battersby, et al. 2015
Search for Starless Proto-Clusters

Starless clumps are *less massive* overall → corresponds to mass accretion rate of ~1000 $M_\odot$ / Myr

Svoboda, Shirley, Battersby, et al. 2015

Follow-up SMA and ALMA surveys toward most massive starless clumps → initial structure before disruption by stellar feedback
70 μm, 24 μm, 8 μm

From Battersby et al. 2014b; Hi-GAL: Molinari et al. (2011), MIPSGAL: Carey et al. (2009), GLIMPSE: Benjamin et al. (2003),
→ look for evidence of infall in line asymmetries

70 μm, 24 μm, 8 μm, Herschel N(H₂) contours

G32.03+0.05, Battersby+ in prep
Infall Signature

Diffuse

Dense

Emits

Absorbs

Intensity

Blue-shifted

Red-shifted

Pink – optically thin → sees the entire cloud
Cyan – optically thick → only sees envelope
HCO$^+$ (1-0) and H$^{13}$CO$^+$ (1-0) on the ARO 12m

G32.03+0.05, Battersby, Myers, Keto, et al. in prep
Clear evidence of infall

HCO$^+$ (1-0) and H$^{13}$CO$^+$ (1-0) on the ARO 12m

70″ FWHM
1.8 pc at 5.5 kpc

G32.03+0.05, Battersby, Myers, Keto, et al. in prep
Perform modified blackbody fitting of Herschel data to derive $N(\text{H}_2)$ and dust temperature.

70 $\mu$m, 24 $\mu$m, 8 $\mu$m, Herschel $N(\text{H}_2)$ contours

G32.03+0.05, Battersby, Myers, Keto, et al. in prep
Add the density and temperature profiles

70 µm, 24 µm, 8 µm, Herschel N(H₂) contours
Use our knowledge of the physical structure to inform the radiative transfer model (MOLLIE).

- Plummer profile, $p = 2$, $r_{flat} = 0.5$ pc
- Flat temperature profile, $T = 16$ K

---

Battersby, Myers, Keto, et al. in prep
Calculate infall rates

\[ \dot{M} = \rho \sigma v = \left[ \frac{n}{10^4 \text{ cm}^{-3}} \right] \left[ \frac{\sigma}{\text{pc}^2} \right] \left[ \frac{v}{\text{km/s}} \right] \cdot 700 \text{ M}_\odot/\text{Myr} \]

- Density from Plummer fit
- Surface area of cylinder
- HCO\(^+\) line profile fit

\[ V_{\text{in}} = 2 \text{ km/s} \]
\[ \dot{M} = \rho \sigma v = \left[ \frac{n}{10^4 \text{ cm}^{-3}} \right] \left[ \frac{\sigma}{\text{pc}^2} \right] \left[ \frac{v}{\text{km s}^{-1}} \right] 700 \, M_\odot / \text{Myr} \]

- Density from Plummer fit
- Surface area of cylinder
- HCO$^+$ line profile fit
Infall Rates

Battersby et al., in prep. See also Peretto et al. (2013), SDC335 Mass infall rate of 700 $M_\odot$ / Myr.
Infall Rates

Region can double its mass in a Myr!

Battersby et al., in prep.  See also Peretto et al. (2013), SDC335 Mass infall rate of 700 $M_\odot$ / Myr.
Evolution

Starless proto-cluster

Star-forming proto-cluster

Star-forming proto-cluster

Embedded cluster

Battersby et al. 2010; 2011
Star-forming proto-cluster

Quiescent -- mid-IR dark

Star-forming proto-cluster

Embedded cluster

(e.g. Battersby et al. in prep., Longmore et al. (2011); Schneider et al. 2010; Barnes et al. 2010; Galván-Madrid et al. 2010; Liu et al. 2012)
Next Steps: Massive Star and Cluster Formation
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• Add more species and improve radiative transfer modeling (JCMT, PI: Kirk).
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• Measure infall rates toward many more regions. Does it correlate with mass or evolutionary stage? What determines the final mass of a cluster?
Next Steps: Massive Star and Cluster Formation

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Stop 3: Extreme SF in our Galactic Center

Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)
Star Formation over cosmic time

- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy Accelerated Expansion
- Afterglow Light Pattern 380,000 yrs.
- 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 $z \sim 1-3$
Star Formation over cosmic time

The peak of star formation was $z \sim 1-3$
Star Formation over cosmic time

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

1st Stars about 400 million years ago

\[ \Sigma_{\text{gas}} \sim 10^2 \, M_{\odot}/\text{pc}^2 \]
\[ \sigma \sim 10 \, \text{km/s} \]
\[ P/k \sim 10^4 \, \text{K/cm}^3 \]
Star Formation over cosmic time

Kruijssen & Longmore 2013
The Milky Way Laboratory

Stop 3: Extreme SF in our Galactic Center

Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)
Extreme Star Formation

24 μm
8 μm
4.5 μm
Extreme Star Formation

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

The Central Molecular Zone: CMZ

$N(H_2)$ from HiGAL Battersby+, in prep., 70 $\mu$m from HiGAL, Molinari+ 2011, 8 $\mu$m from GLIMPSE (Benjamin+ 2003)
Basic 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?
Central Molecular Zone

“Bricklet” D

300 light years

Cold dust – submillimeter
SMA Legacy Survey of the Central Molecular Zone

- Long wavelength + high angular resolution → detect early star formation
- First survey of the CMZ ever to be able to do so!
SMA Legacy Survey of the Central Molecular Zone

- Long wavelength + high angular resolution → detect early star formation
- First survey of the CMZ ever to be able to do so!
• 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 ($H_2CO$, $^{12}CO$, $^{13}CO$, $C^{18}O$, $SiO$, $CH_3OH$, $CH_3CN$, etc.): 8 GHz bandwidth
• 3 mJy RMS continuum, 0.4 K
• 500 hours (50 subcompact, 450 compact/custom)
• Complement with single-dish (APEX, CSO) observations
CMZoom

- 230 GHz (1.3 mm)
- 240 arcmin² (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 ($H_2CO$, $^{12}CO$, $^{13}CO$, $^{18}CO$, 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)
- Complement with single-dish (APEX, CSO) observations

Find star formation!
CMZoom

Team:

CfA: Cara Battersby, Eric Keto, Qizhou Zhang, Xing ‘Walker’ Lu, Mark Graham (Southampton), Nimesh Patel, Volker Tolls, Dennis Lee, Jimmy Castaño, Liz Gehret

Bonn: Jens Kauffmann, Thushara Pillai

University of Colorado, Boulder: John Bally

Liverpool: Steve Longmore, Daniel Walker, Jonny Henshaw

MPA: Diederik Kruijssen

ESO: Adam Ginsburg, Katharina Immer

Peking University: Luis C. Ho, NRAO: Betsy Mills
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The image shows a cosmic scene with various labeled regions:

- 1.3° Cloud
- Sgr B2
- The "Brick"
- Sgr A*
- Sgr C
- 24 micron sources

The scale bar indicates 100 pc. The text includes:

- $N(\text{H}_2)$
- 70 μm
- 8 μm
The "Molinari Ring" (Molinari+2011)
New orbital models (Kruijssen, Dale, & Longmore 2015)
New orbital models (Kruijssen, Dale, & Longmore 2015)

\[ N(\text{H}_2) \]

\[ \sigma \]

\[ \mu_{\text{m}} \]

\[ 100 \text{ pc} \]

\[ 24 \text{ micron sources} \]

\[ N(\text{H}_2) \]

\[ 70 \mu_{\text{m}} \]

\[ 8 \mu_{\text{m}} \]

\[ \text{Sgr A}^* \]

\[ \text{Sgr C} \]

\[ \text{Three Little Pigs} \]

\[ \text{Brick} \]

\[ \text{Stream 1} \]

\[ \text{Stream 2} \]

\[ \text{Stream 3} \]

\[ \text{Stream 4} \]
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

\( N(H_2) \) from HiGAL Battersby+, in prep., 70 \( \mu m \) from HiGAL, Molinari+ 2011, 8 \( \mu m \) from GLIMPSE (Benjamin+ 2003)
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Kruijssen, Dale, Longmore 2015

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

SMA 1.3mm contours

Cloud 'd'

Cloud 'b'

Cloud 'c'

Cloud 'a' ('the Brick')

Cloud 'e'

Cloud 'i'

70 μm

8 μm

N(H₂)
70 μm
8 μm
N(H₂)

A 3mm contours, Rathborne+ 2014; 2015

SMA 1.3mm contours
$N_{\text{H}_2} = 0.61$

No SF tracers

$N_{\text{ff}} = 0.65$

H$_2$O maser

$N_{\text{ff}} = 1.28$

H$_2$O and CH$_3$OH masers

$N_{\text{ff}} = 1.76$

H$_2$O and CH$_3$OH masers + 70 $\mu$m

ALMA 3mm contours, Rathborne+ 2014; 2015

SMA 1.3mm contours

70 $\mu$m

8 $\mu$m

N(H$_2$)
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Where is the Galactic Center?

Map of Galaxy in a Star Formation Tracer (water maser)
Where is the Galactic Center?

Map of Galaxy in a Star Formation Tracer (water maser)

Map of Galaxy in Dense Gas (HC$_3$N)
Why is the SFR low in the CMZ?

Krumholz & Kruijssen 2015

Torrey et al., submitted
Why is the SFR low in the CMZ?

$N(H_2)$ 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?

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

\[ N(\text{H}_2), \ 70 \mu\text{m}, \ 8 \mu\text{m} \]

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?

The Three Little Pigs: Very similar global properties but vastly different substructure

Mass $\sim 3 \times 10^4 M_\odot$

$T_{dust} \sim 20K$

$N(H_2)_{peak} \sim 2 \times 10^{23} \text{ cm}^{-2}$

$\Delta v \sim 10 \text{ km/s}$

Battersby, Bally, Longmore, in prep.
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?

- 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?

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☐ Power-law tail in N-PDF
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<tr>
<th>Core</th>
<th>Mass ($M_\odot$)</th>
<th>$M_{\text{vir}}/M$</th>
<th>Mean Radius (pc)</th>
<th>Number Density ($\times 10^5$ cm$^{-3}$)</th>
<th>Significance ($\sigma^{-1}$)</th>
<th>$\Delta v_{\text{H}_2\text{CO}}$ (km s$^{-1}$)</th>
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Why is the SFR low in the CMZ?

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

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Why is the SFR low in the CMZ?

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<th>Structure ID</th>
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<th>Dust Flux (Jy)</th>
<th>Central Velocity (km/s)</th>
<th>$\Delta\nu_{FWHM}$ (km/s)</th>
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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
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Precursors to Massive Stars

Preliminary Core mass estimates, assuming 20 K

A: 550 $M_\odot$
B: 340 $M_\odot$
C: 140 $M_\odot$
D: 130 $M_\odot$

Battersby, Graham, et al., in prep.
Precursors to Massive Stars

Is it star forming?
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SMA 1.3 mm dust continuum

Battersby, Graham, et al., in prep.
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<th>Mean Radius (pc)</th>
<th>Number Density ($\times 10^5$ cm$^{-3}$)</th>
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Battersby, Graham, et al., 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?
   → High levels of turbulence are important

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 are consistent with this scenario

4) Can we find precursors to the most massive stars in the Galaxy?
   → We have some good candidates
Lu, Zhang, et al. 2015
The Milky Way Laboratory

Stop 1: The Skeleton of the Milky Way

Stop 2: Massive star and cluster formation

Stop 3: Extreme SF in our Galactic Center
The Milky Way Laboratory

Stop 1: The Skeleton of the Milky Way: We are tracing our Galaxy with long, skinny clouds called the Bones of the Milky Way.

Stop 2: Massive star and cluster formation: clusters grow as the stars form!

Stop 3: Extreme SF in our Galactic Center: new, large survey shows turbulence can prevent SF, tidal compression can trigger it, and it can happen where we least expect it.