From Low to High Energy: Current frontiers in the Galactic center

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Fermi Symposium
Elisabeth A.C. Mills  (Brandeis University)
Introduction: The Galactic center environment

What are the physics that govern conditions in the ISM?

What is the 3D distribution of the ISM?

What is the magnetic field geometry?
The nearest galaxy nucleus

Galactic Center vs. Seyferts:

Supermassive black hole

$4 \times 10^6 \, M_{\odot}$

Ghez et al. 2008

7-8 orders of magnitude lower

$L_{\text{AGN}} \, (\text{erg/s})$

(range of Seyfert properties from a sample by Diamond-Stanic & Rieke 2012)

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The nearest galaxy nucleus

X-ray light echoes show at least two flares in the past 300 years

Supermassive black hole

$4 \times 10^6 \, M_{\text{SUN}}$

Ghez et al. 2008

Galactic Center vs. Seyferts:

$L_{\text{AGN}}$ (erg/s)

(range of Seyfert properties from a sample by Diamond-Stanic & Rieke 2012)
The nearest galaxy nucleus
The nearest galaxy nucleus

Galactic center: 8.1 kpc away

Optical

Infrared

Radio

300 pc

Credit: NRAO, A. Ginsburg

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The Central Molecular Zone

<table>
<thead>
<tr>
<th>Waveband</th>
<th>Characteristics</th>
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<tr>
<td>Radio</td>
<td>hot gas, plasma</td>
</tr>
<tr>
<td>Infrared</td>
<td>hot dust, stars</td>
</tr>
<tr>
<td>Millimeter</td>
<td>cold dust/gas</td>
</tr>
</tbody>
</table>

Distance: 300 pc

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$1 \times 10^9 \, M_{\text{SUN}}$ of stars
(Launhardt et al. 2002)

$\sim 2\%$ of total Milky Way: $6 \times 10^{10} \, M_{\text{SUN}}$ of stars
(McMillan 2011)

**Infrared**: hot dust, stars

**The Nuclear Stellar Disk**

Fermi Excess

Schonrich et al. 2015 (APOGEE)
0.05-0.15 $M_{\text{SUN}}$ yr$^{-1}$ of new stars
(Launhardt et al. 2002)

3-10\% of total Milky Way:
1.45-2 $M_{\text{SUN}}$ yr$^{-1}$ of new stars

---

**Radio:** hot gas, plasma

**Star formation rate**

- **IRAS:** 0.08 $M_{\text{SUN}}$/yr
  (Crocker et al. 2011)

- **WMAP:** 0.06 $M_{\text{SUN}}$/yr
  (Longmore et al. 2012)

- **24 $\mu$m:** 0.07 $M_{\text{SUN}}$/yr
  (Yusef Zadeh 2009)

- **24 $\mu$m YSOs:** 0.14 $M_{\text{SUN}}$/yr
  (Yusef Zadeh 2009)
  (0.05 $M_{\text{SUN}}$/yr, Koepferl et al. 2015)
3x10^7 M_{\odot} of 

molecular gas 

(Dahmen et al 1998)

~4% of total Milky 

Way: 8x10^8 M_{\odot} of 

stars (Nakanishi & Sofue 2006)

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**Millimeter**: cold dust/gas

**Hot**

T= 50 - 300 K

Galactic Disk: T~10-20 K

Mills + Morris 2013

**Dense**

n > 10^3 - 10^6 cm^{-3}

Galactic Disk: n~10^2 cm^{-3}

Mills et al. 2013, Mills et al. 2018

**Turbulent**

Δv~15-50 km s^{-1}

Galactic Disk: Δv~2-5 km s^{-1}

Mills et al. 2015

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Radio: hot gas, plasma
Infrared: hot dust, stars
Millimeter: cold dust/gas

300 pc
The Galactic Center
d=8.1 kpc

Sgr B2
100 pc

Sgr A

Central Molecular Zone

7 pc

Sgr A East

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The Galactic Center

Sgr B2

Sgr A

100 pc

Sgr A East

Circumnuclear Disk

d=8.1 kpc

Central Molecular Zone

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The Galactic Center

d=8.1 kpc

Central Molecular Zone

Sgr B2

100 pc

Sgr A

7 pc

Sgr A East

0.5 pc

Minispiral

3 pc

Circumnuclear Disk

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The Galactic Center

d = 8.1 kpc

Sgr B2

Sgr A

100 pc

Sgr A East

Circumnuclear Disk

Minispiral

Central lightyear

0.15 pc

0.5 pc

0.15 pc

3 pc

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Central Molecular Zone

100 pc

Sgr A

7 pc

Sgr A East

Circumnuclear Disk
The Galactic Center

$d=8.1$ kpc

Sgr B2

Sgr A

100 pc

Minispiral

Central lightyear

0.5 pc

0.15 pc

Central Molecular Zone

Sgr A East

7 pc

Circumnuclear Disk

3 pc

Central

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The Galactic Center

$\text{d}=8.1$ kpc

Sgr B2

Sgr A

100 pc

Sgr A East

Circumnuclear Disk

Minispiral

Central lightyear

0.15 pc

0.5 pc

0.03 pc

Event Horizon (simulation)

0.0000002 pc

$6 \times 10^6$ km

“S” stars

0.03 pc

$6 \times 10^6$ km

Central Molecular Zone

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What sets the gas properties - the journey or the destination?
Cosmic Ray Heating?

Local CR ionization rate: $\zeta \sim 10^{-16} \text{ s}^{-1}$ (Indriolo et al. 2014)

Galactic center estimates: $\zeta \sim 10^{-16} - 10^{-13} \text{ s}^{-1}$ (Goto et al. 2013, Harada et al. 2013, Yusef Zadeh et al. 2013c)
Cosmic Ray Heating?

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$\text{[Ne III]} / \text{[S III]}$

(Simpson 2018)

Diffuse HESS excess

(Aharonian et al. 2006)
Galactic center clouds are more turbulent than Galactic disk clouds.

Shetty et al. (2012)
A larger fraction of warm H$_2$ is seen in the gas within 3 pc of the black hole, and gas at radii > 30 pc, favors radially-dependent heating driven by shocks.

(Mills et al. 2017b)
What is the 3D distribution of the gas?
Our point of view makes this complicated. what we wish we could see what we actually see

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There are a lot of possibilities.
X-rays may provide strong diagnostics

- **Light echoes** (Ponti et al. 2010)
- **Polarimetry** (Marin 2014)
- **Dust scattering Halos** (Corrales et al. 2017)
What is the magnetic field geometry?
Magnetic fields can trace the gas flow, both inward and outward.
A poloidal field could trace material entrained in a current outflow, and make connections to ‘fossils’ of past events.
Radio: hot gas, plasma

Poloidal field

Yusef-Zadeh and Morris (1987)
Radio: hot gas, plasma

Poloidal field

MeerKAT Pathfinder image (90 cm)
Infrared: polarized starlight
Largely Toroidal field

Nishiyama et al. 2010
Millimeter: cold dust/gas

Toroidal field

Chuss et al. 2003

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NGC 253
Barred Spiral
Total mass: $10^{11} \, M_{\text{sun}}$
Black hole mass: $5 \times 10^6 \, M_{\text{sun}}$
Nuclear Starburst
Star Formation Rate: $2.8 \, M_{\text{sun}}/\text{yr}$

Arp 220
200 $M_{\text{sun}}/\text{yr}$

Milky Way Physics Likely Not Representative

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