NuSTAR Observation of Galactic Center Molecular Clouds: Reconstructing Sgr A* X-ray Outbursts
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GC Molecular Clouds in X-rays: 
Fe Kα line + Continuum emission

- GCMCs emit 6.4 keV line + continuum emission up to 100 keV.
- Previous studies focused on the 6.4 keV line emission.
- The continuum emission > 10 keV was not resolved by Integral.
X-ray Reflection Nebula (XRN) vs. Low Energy Cosmic Ray Electrons (LECre) or protons (LECRp)?

**Model Signature:**
1. Variability on timescale of ~1-10 yrs
2. Fe Kα equivalent width ~ 1 keV
3. 7.1 keV Fe K absorption edge
4. Compton reflection hump

**Cosmic rays from**
1. A power-law spectrum
2. Variability over electron cooling/diffusion time (LECre) or proton cooling time of >100 yrs (LECRp)

Reflecting a giant Sgr A* X-ray flare

Photo-ionization \(\rightarrow\) fluorescence

X-ray Source

Collisional ionization \(\rightarrow\) fluorescence

Incoming CR

Non-thermal bremsstrahlung \(\rightarrow\) continuum

Compton-scattering \(\rightarrow\) continuum
Sgr B2 is the densest and most massive GMC in CMZ.
-- The Fe Kα emission is fading since ~2001.
-- Still decreasing or has reached background level?
-- G0.66-0.13 is a newly emerging cloud feature with maximum flux observed in 2012, and quickly diminished in 2013.

Sgr B2 Fe Kα emission variability (Zhang+ 2015)
First time to resolve Sgr B2 on sub-arcmin scales > 10 keV by NuSTAR

- Two prominent features detected:
  G0.66-0.13 + central 90” radius region of Sgr B2
- Substructures of 90” region:
  Compact cores Sgr B2(M) and Sgr B2(N) + diffuse emission
- G0.66-0.13:
  Newly emerged cloud feature with a maximum $L_x$ obtained in 2012

INTEGRAL/IBIS 20-40 keV image of GC (Terrier+ 2010)

NuSTAR 10-40 keV image of the Sgr B2 region (Zhang+ 2015)
**Sgr B2 3-79 keV Spectroscopy**

The 3-79 keV spectrum of the Sgr B2 90" region fitted with three models (Zhang+ 2015)

**XRN scenario**
Sgr A* Outburst spectrum:
\[ \Gamma = 2.2 \pm 0.4 \]
Required luminosity:
\[ L_{3-79\text{keV}} \sim 5 \times 10^{38} (d/100\text{pc})^2 \text{ erg s}^{-1} \]
Favored if X-ray emission keeps decreasing.

**LECRE scenario**
Requires
1) \( Z_{\text{Fe}} \sim 4 \) solar  
   ➔ Unphysically high
2) \( E_{\text{min}} \) of \( e^- < 100 \) keV  
   ➔ Unable to penetrate cloud
Excluded to be a major contributor to the remaining level of Sgr B2 X-ray emission

**LECRp scenario**
CRp spectrum:
\[ s = 1.9 \pm 0.7 \]
Required power:
\[ \frac{dW}{dt} \sim 1 \times 10^{39} \text{ erg s}^{-1} \]
Favored if X-ray emission has reached constant background level.

Zhang+ 2015
Role of G0.66-0.13
NuSTAR detected hard X-ray emission, associated with Fe K fluorescence line, from molecular clouds in the Sgr A region.
Molecular cloud MC1 and the Bridge spectra are well fitted with the XRN model. The measured intrinsic nH ~ $10^{23}$ cm$^{-2}$ indicates these clouds are optically thin → No Compton hump observed.
→ Primary source spectrum shape is nearly unchanged.

[Note: the superluminal propagation of Fe K emission observed by XMM rules out LECR and internal source scenario (Ponti 2010)].

1.5-20 keV XMM-Newton and NuSTAR spectra of MC1 and the “bridge” fitted with the XRN model (Mori+ 2015)
Multiple Sgr A* flaring stages in the past a few hundred years?

- MC1, the Bridge and Sgr B2 spectra require consistent source photon indices but different Sgr A* flare luminosities.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>MC1</th>
<th>Bridge</th>
<th>Sgr B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projected distance from Sgr A* [pc]</td>
<td>~ 12</td>
<td>~20</td>
<td>~ 100</td>
</tr>
<tr>
<td>Column density N_H [10^{23} cm^{-2}]</td>
<td>2.3±1.1</td>
<td>1.5±0.8</td>
<td>10±4</td>
</tr>
<tr>
<td>Source photon index</td>
<td>2.1±0.3</td>
<td>1.8±0.1</td>
<td>2.2±0.4</td>
</tr>
<tr>
<td>L_{2-20 keV} [erg s^{-1}]</td>
<td>(1.1±0.5)×10^{38}</td>
<td>(0.9±0.2)×10^{38}</td>
<td>(3.5±1.5)×10^{38}</td>
</tr>
</tbody>
</table>

- XMM+Chandra observations of Sgr A clouds and their Fe K line emission indicate multiple Sgr A* flares (Capelli 2012, Clavel 2013, 2014)
- NuSTAR monitoring of Sgr A clouds with broadband X-ray spectroscopy will be useful to further constrain Sgr A* outburst stages.

<table>
<thead>
<tr>
<th>When?</th>
<th>PL index</th>
<th>Lx [ergs^{-1}]</th>
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<tbody>
<tr>
<td>Bright Sgr A* flares</td>
<td>Γ~2</td>
<td>~5×10^{35}</td>
</tr>
<tr>
<td>Sgr A clouds</td>
<td>Γ=1.8-2.4</td>
<td>~1×10^{38}</td>
</tr>
<tr>
<td>Sgr B2</td>
<td>Γ~2.2</td>
<td>~4×10^{38}</td>
</tr>
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</table>
Observation of the GC molecular clouds reveals past giant X-ray outbursts from Sgr A* and can reconstruct the Sgr A* outburst history.

- Hard X-ray emission (>10 keV) from Sgr B2 is resolved by NuSTAR in 2013,
- The 2013 Sgr B2 X-ray emission is best explained by XRN if the flux is still decreasing, or by LECRp if it has reached the constant background level.
- G0.66-0.13 could be a clump located in the Sgr B2 envelope and reflected the same Sgr A* X-ray outburst.
- Molecular clouds in the Sgr A region are also detected and resolved >10 keV by NuSTAR. Their spectra require a less luminous and more recent Sgr A* outburst.
- Future observations of GCMCs can reveal their hard X-ray emission evolution and help constrain past Sgr A* X-ray outbursts.
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