Dissecting X-ray Emitting Gas Around the Center of the Galaxy

Based on the 0th-order ACIS-S data of the 3 Ms Chandra Sgr A* XVP

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Q. Daniel Wang (University of Massachusetts/Nanjing University)

Most SMBHs are undergoing the radiatively inefficient accretion: NGC 3115 as an example

Containing a SMBH of $\sim 10^9 M_\odot$, but no point-like X-ray counterpart.

$R_B \sim 38 \text{ pc}(10^7 \text{K/T})$
$\sim 1''$ at 10 Mpc for NGC 3115
$\sim 0.3^\circ$ at 8 kpc

K. Wong et al, (2011)
Sgr A* and its vicinity: 1-9 keV image

- $M_{BH} = 4 \times 10^6 M_\odot$
- $L_x = 3 \times 10^{33}$ erg/s, or $\sim 10^{-11} L_E$
- $L_{bol} = \text{a few } 10^{36}$ erg/s, mostly in radio to submm.
- What is the mode of the accretion, and what determines the luminosity?

If we have answers to these questions, we may understand a large class of ultra-dim galactic nuclei.
Temporal decomposition of the Sgr A* X-ray data

Detected flares account for ~1/3 of the total X-ray flux of Sgr A* (J. Neilsen et al. 2013).
No sign of line emission in detected flare spectrum.
Flare and quiescent emissions: timing and spatial properties

- Contamination from flares is insignificant (< 10%).
- The flare emission is point-like.
- The quiescent emission is extended on 1"-5" scales.
Spatial decomposition of the Sgr A* quiescent X-ray emission

- Point-like component accounting for < 20% of the total flux within 1.5” radius.
- Extended component with an elongated morphology on 1” scales.
- Elongation direction consistent with the orientation of the clockwise massive stellar disk.
X-ray emission line spectroscopy

Energy (keV)

Counts s⁻¹keV⁻¹

X-ray emission line spectroscopy

Energy (keV)

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halo
Major Classes of Radiatively Inefficient Accretion Flow (RIAF)

- Advection-dominated accretion flow (ADAF; Narayan & Yi 1994)
- Convection-dominated accretion flow (CDAF; Quataert & Gruzinov 2000)

These self-similar solutions are partly consistent with various HD and MHD simulations (e.g., Radiating Rotating Inflow-Outflow Solutions, RRIOS; Ostriker’s talk).
This component applies for $r > 10^2 R_s$.

A bremsstrahlung continuum with fixed $kT_i=100$ keV is added for electrons with an saturated energy.

The two component model is used to fit the observed spectrum with the key parameters: $\gamma$, abundance, and the two normalizations; weak dependence on $T_o$. 

\[
T = T_0 \left(\frac{r_0}{r}\right)^\theta \\
n = n_0 \left(\frac{r_0}{r}\right)^{3/2-s} \\
\dot{M} = \dot{M}_0 \left(\frac{r}{r_0}\right)^s \\
dE \dot{M}/d\log(T) \propto (T_0/T)^\gamma \\
(\text{where } \gamma = 2s/\theta)
\]

$s$ varies from 0 (ADAF) to 1 (ADIOS).
• The best-fit $s=1.0(0.7-1.2)$ (for $\theta\sim1$) is consistent with the exact prediction of ADIOS; both the fitted abundance and $N_H$ are also as expected.

• Smaller $s$ would give a too large FeXXVI/FeXXV Kα ratio and a too flat spectral shape to be consistent with obs.
The X-ray spectrum is consistent with the ADIOS

- \( T_0 \sim 10^7 \text{K} \) at the outer radius \( r_o \sim 10^5 R_s \).
- \( n = 160 \text{ cm}^{-3} \left( \frac{r_o}{r} \right)^{1/2} \xi^{-1/2} \).
- Combining the above with the mass rate limits from the Faraday rotation measure \( \rightarrow \)
  \( \dot{M} \sim 10^{-4} \left( \frac{r_o}{r} \right)^{-1} M_\odot/\text{yr} \) all the way down to \( r \sim 10-10^2 R_s \).
- The 100 keV bremsstrahlung component accounts for \( \sim 20\% \) of the total flux.
Summary

• Detection of Ka line emission from hot S, Ar, and Ca, as well as Fe known previously, in the quiescent spectrum.
• >99% of the initially captured matter is ejected in the r~10^4 - 10^5 r_s range, as inferred from the global spectral fit, as well as Fe XXVI/FeXXV K ratio (< 0.06).
• The bulk of the X-ray emission arises from this outer radial range, in sharp contrast to AGNs, in which the innermost region dominates.
• Extended emission with the morphology and orientation consistent with a known tilted disk of massive stars on ~1" scales. On larger scales, diffuse X-ray emission appears lumpy.
Outstanding Questions and Approaches to Answer Them

• How does the angular distributions of the temperature and density affect the results? (A: e.g., spatially-resolved spectroscopy + Ostriker’s model)

• What are the nature and energetics of the outflow and how does it affect the circumnuclear environment? (A: spectroscopy of the Sgr A* halo region and beyond)

• How may the results be scaled up to explain observations of other low-L SMBHs? (A: new simulations from Ostriker et al. + data on M81* etc.)
Other ways to probe the accretion flow: G2 cloud

Only 20 light hours from the BH and has now been stretched over more than $1.5 \times 10^4 R_s$ around the pericenter (Gillessen et al. 2013).

The orbit has shown no hydrodynamic effect yet; no enhanced emission has been detected, consistent with the extreme low density of the accretion flow at a few $10^3 R_s$!

What is the long-term forecast? What is the best wavelength band to monitor the change?
Other ways to probe the accretion flow: Transient magnetar

- < 1 ly away from Sgr A*
- RM = \(-5 \times 10^5\) rad m\(^{-2}\) for Sgr A*
  \(-6.7 \times 10^4\) rad m\(^{-2}\) for the magnetar
- Dispersion measure (DM) = 1778 cm\(^{-3}\) pc
- If the density prescription has a \(r^{-1}\) scaling (roughly estimated), then \(B \geq 8\) mG, higher than the equipartition field (~2.5 mG) in the hot phase on this scale.

What can all these tell us about the accretion flow?

Kennea et al. 2013,
Mori et al. 2013,
Rea et al. 2013

\(P = 3.76\) s
Variability: Monitoring at ~1 mm

- Emission from Sgr A* peaks at ~1 mm and arises from the innermost region around the SMBH.
- The peak is due to the transition from being optically thick to thin.
- Variability in (sub)mm likely leads to the change of the size of Sgr A*, which can be detected with mm-VLBI (Event Horizon Telescope).
- Present programs with LMT:
  - Long-term “daily” monitoring
  - Intraday monitoring with coordinated X-ray and JVLA observations.

Yuan et al. (2003)

If the (sub)mm flux changes by a factor of 2, what can we infer?

Does the SED represent an extreme case of the LLBH?

When do we expect to see such a distinct (sub-)mm bump?
The LMT is a 50m diameter millimeter-wave telescope at the summit of Volcan Sierra Negra at an elevation of 4600m.