Multiwavelength Monitoring of the Supermassive Black Hole in the Galactic Center

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Research Issues

• Supermassive black hole at the Galactic Center: Sagittarius A*
  ▪ Accretion physics
  ▪ Emission mechanism of rapid X-ray/IR flares
  ▪ Evidence for a bipolar outflow
  ▪ Evidence for a possible X-ray jet
• High-mass star formation history in the Nuclear Bulge
• Supernova Remnants
• Colliding stellar winds and other interactions
• Origin of new X-ray structures in the field
X-ray View of the Galactic Center


2 x 0.8 degrees
Zooming into the Galactic Center in X-rays

Animation Credit: NASA/CXC/SAO
Chandra Galactic Center Deep Field

17 x 17 arcmin
590 ks

Red 2–3.7 keV
Green 3.7–4.5 keV
Blue 4.5–8 keV
Chandra Galactic Center Deep Field

17 x 17 arcmin

590 ks

Red 2–3.7 keV
Green 3.7–4.5 keV
Blue 4.5–8 keV
Chandra Galactic Center Deep Field

8.4 x 8.4 arcminutes
E1: Chandra counterpart

$\Gamma = 1.22 \pm 0.20$

$L(0.5-8 \text{ keV}) = 8 \times 10^{34} \text{ ergs/s}$
X-ray Point Sources

- 2287 sources have been resolved.
- 278 are of the foreground in the galactic center.
- About 40 are background AGN
- Sources have $L_X=10^{30}$-$10^{33}$ erg s$^{-1}$ (2-8 keV)

Muno et al. (2003)
Spatial Distribution

- Consistent with an isothermal sphere \((1/R^2)\)
- Similar to spatial density of bright infrared stars in Nuclear Bulge
- Could provide important information about star formation history
X-ray Emission-Line Equivalent-Width Maps

Fe He\(\alpha\)  
(E $\sim$ 6.7 keV)

Fe K\(\alpha\) “neutral”  
(E $\sim$ 6.4 keV)

S He\(\alpha\) + Ly\(\alpha\)  
(E $\sim$ 2.5 keV)

Si He\(\alpha\)  
(E $\sim$ 1.8 keV)

Park et al. (2003), submitted to ApJ
Galactic Center Bipolar Lobes

- Lobe material distributed differently than “hot” (6.7 keV) and fluorescent “neutral” (6.4 keV) Fe
- Emission grows in intensity and size perpendicular to Galactic plane toward lower energies
- $T_e \sim 2 \times 10^7$ K
- $n_e \sim 1$ cm$^{-3}$
- Separate lumps may indicate separate episodes of activity spaced by 2000–5000 yr
- Timescale for outer portions to flow from Sgr A*: $10^4$ yr ($v_{out}/1000$ km s$^{-1}$)
- Mass per blob $\sim 1$ $M_{\odot}$
- Origin: Sgr A* or star formation in central parsec?
X-ray Features in the Vicinity of the Sgr A Radio Complex
The Central Parsec

CXOGC J174539.7-290020

Sgr A*

IRS13

CXOGC J174539.4-290031 (AFNW)

0.25 pc
CXOGC J174539.7-290020

Γ = 1.74 ± 0.11

Γ = 1.55 ± 0.15

Γ = 1.92 ± 0.17

entire structure
1.1 \times 10^{34} \text{ ergs/s}
(0.5 - 8 \text{ keV})
Radio Image of the Sgr A West Minispiral
Superposition of 2-8 keV x-ray contours on the mid-IR image.
Radio Image of Sgr A West and Circumnuclear Disk
X-ray Image and 6 cm Contours of Sgr A West
2000 October 26-27


(Baganoff et al. 2001)

Oct 27 05:42 UT
45x, 4 hr
Some models predict large mm or IR variations during X-ray flares, while others do not.
ADAF Model – Narayan 2002
Observatories Participating in Sgr A* Monitoring Campaign

- Chandra (12–62 nm)
- Keck (2 & 10 μm)
- Very Large Telescope (3–5 μm)
- Magellan (10 μm)
- Submillimeter Array (1.3 mm)
- Caltech OVRO Millimeter Array (3 mm)
- Australia Telescope Compact Array (3 mm)
- Very Large Baseline Array (7 mm)
- Very Large Array (7mm, 1.3 cm, 2 cm)
2002 May 22-23 – Orbit 1, Part 1

2002 May 24 – Orbit 1, Part 2

OBSID 3663 – 2002:05:24:12:17:02.9 (UT)

May 24 19:42 UT
5x, 1.7 hr
2002 May 25-27 – Orbit 2


May 26 04:24 UT
6x, 0.75 hr

May 24 19:42 UT
5x, 1 hr

May 26 13:47 UT
5x, 0.5 hr
2002 May 28-30 – Orbit 3

OBSID 3393 – 2002:05:28:05:58:08.2 (UT)

May 28 15:36 UT
25x, 1 hr

May 29 06:03 UT
12x, 1.5 hr

May 29 18:33 UT
13x, 0.5 hr
2002 June 3-4 – Orbit 5

OBSID 3665 – 2002:06:03:01:46:30.4 (UT)
Sgr A* Multiwavelength Monitoring Campaign
Three Large X-ray Flares from Sgr A*
Very Long Baseline Array – 7 mm

• No significant flux variability detected
• Upper limit about 30%
• No extended structure appeared
• Upper limit about 10 mJy
Integrated X-ray Spectrum of Sgr A* During Flares

Model: Absorbed, Dust-Scattered Power Law

$N_H = 6.0 \times 10^{22} \text{ cm}^{-2}$
$\Gamma = 1.3 \ (0.9-1.8)$

$F_X = 1.6 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$
$L_X = 2.0 \times 10^{34} \text{ erg s}^{-1}$
$D = 8 \text{ kpc}$
Integrated X-ray Spectrum of Sgr A* in Quiescence

Model: Absorbed, Dust-Scattered, Power Law Plus Line

\[ N_H = 5.9 \times 10^{22} \text{ cm}^{-2} \]
\[ \Gamma = 2.4 (2.3-2.6) \]
\[ E_{Fe} = 6.59 (6.54-6.64) \text{ keV} \]
Line is narrow and NIE

\[ F_X = 1.8 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \]
\[ L_X = 1.4 \times 10^{33} \text{ erg s}^{-1} \]
\[ D = 8 \text{ kpc} \]

\[ <L_F> / <L_Q> = 14.0 \]
X-ray Emission at Sgr A* is Extended

- Intrinsic size of emission at Sgr A* is about 1.4 arcsec (FWHM)
- Consistent with Bondi accretion radius for a $3 \times 10^6$ solar-mass black hole
- Is emission from a hot accretion flow or from stars in the central cluster?
Summary - Sgr A* Flares

- Chandra observed Sgr A* for 139 hr over a two-week period in late May to early June 2002
- 3 X-ray flares with amplitudes >10x detected in a 28-hr period!
- 4 X-ray flares with amplitudes ~5x detected in addition
- “Factor-of-10” flares occur about once every other day, on average
- Typical flare duration is about 1 hr (0.5-4 hr)
- Frequent, large-amplitude, short-duration flaring behavior of Sgr A* is unique among supermassive black holes!
- Probably selection effect: flares too faint to detect in other galaxies
- Behavior inconsistent with X-ray binaries and not seen from any of the other >2,300 X-ray point sources in the field
- Strong evidence that X-ray flaring source is the Milky Way’s central, supermassive black hole!
Summary – Sgr A* Flares (continued)

• No factor-of-2 or larger flares seen at longer wavelengths
• Some evidence for variations at tens of percent level in millimeter band on timescales of hours to days seen – **upper limit currently about 50%**
• Efforts to improved calibration of millimeter data underway
Keck L’ (3.8 μm) Lightcurves of Sgr A*
Spectral Energy Distribution of Sgr A*
Spectrum of Possible Jet-like Feature Near Sgr A*

Absorbed Power-law Model – Dust Corrected

Gamma = 1.8
\( N_H = 8.0 \times 10^{22} \text{ cm}^{-2} \)
\( L_X = 3.4 \times 10^{32} \text{ erg s}^{-1} \)
Summary – X-ray Jet

• Discovery of an apparent X-ray jet from the Milky Way’s central black hole
• Not seen in other wavebands
• Jet is 1 light-year long and located 1.5 light-years from the black hole
• Jet aligned with large-scale bipolar X-ray lobes
• Lobes may be due to past ejections or outflows from the supermassive black hole
• Suggests we are seeing “fingerprints” of activity over the past few thousand years
• X-ray flares tell us about the current activity
Conclusions

• Rapid, large-amplitude X-ray flares are not accompanied by significant radio and mm-band variations
• Sgr A* has now been detected in IR, and is variable on timescales of ~1 hr
• Future efforts
  – Continue coordinated multiwavelength monitoring to detect simultaneous X-ray and IR flares
    • Identify emission mechanism and constrain physical parameters (e.g., mag field strength, Lorentz factor, particle density near event horizon)
  – Push multiwavelength monitoring to sub-mm and MIR/FIR