The Supermassive Black Hole at the Center of Our Galaxy – Sagittarius A*

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Optical View of the Galactic Center

30 magnitudes of optical extinction => optical diminished by factor of a trillion!

80 degrees. Courtesy of Dr. Axel Mellinger. Used with permission.
How Do We Study a Supermassive Black Hole That We Cannot “See”?

• Imaging or Photometry
• Spectroscopy
• Timing
• Multiwaveband
Annotated Radio View of the Galactic Center

Produced at the U.S. Naval Research Laboratory by Dr. N.E. Kassim and collaborators from data obtained with the National Radio Astronomy’s Very Large Array Telescope, a facility of the National Science Foundation operated under cooperative agreement with Associated Universities, Inc. Basic research in radio astronomy at the Naval Research Laboratory is supported by the U.S. Office of Naval Research.
Radio View of the Galactic Center

2.8 x 0.8 degrees

Credit: VLA
Mid-Infrared View of the Galactic Center

2 x 0.8 degrees

Credit: MSX
X-ray View of the Galactic Center

2 x 0.8 degrees

Credit: NASA/UMass/D. Wang et al.
Radio/Mid-Infrared/X-ray View of the Galactic Center

2 x 0.8 degrees

Credit: (X-ray) NASA/UMass/D. Wang et al., (Mid-IR) MSX, (Radio) VLA
Chandra X-ray Observatory

Credit: NASA/CXC/SAO

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Light Path Through Chandra

Credit: NASA/CXC/SAO
Advanced CCD Imaging Spectrometer (ACIS)

Credit: NASA/CXC/SAO

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Zooming into the Galactic Center in X-rays

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

8.4 x 8.4 arcmin

Credit: NASA/CXC/MIT/F.K. Baganoff et al.
Sagittarius A* – Milky Way’s Central Black Hole

Courtesy of Max Planck Society for the Advancement of Science/R. Genzel et al. Used with permission.
Credit: NASA/CXC/MIT/F.K. Baganoff et al.
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)


Credit: NASA/CXC/MIT/F.K. Baganoff et al.
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 Features in the Vicinity of the Sgr A Radio Complex

Courtesy of Max Planck Society for the Advancement of Science/R. Genzel et al. Used with permission.
Credit: NASA/MIT/F.K. Baganoff et al.
Three-color X-ray View of Sgr A West and Sgr A*

Courtesy of Max Planck Society for the Advancement of Science/R. Genzel et al. Used with permission.
Credit: NASA/MIT/F.K. Baganoff et al.
Radio Image of the Sgr A West Minispiral

Credit: F. Yusef-Zadeh
Superposition of 2-8 keV x-ray contours on the mid-IR image.

Credit:
(X-ray) NASA/MIT/F.K. Baganoff et al., (mid-IR) UCLA/M. Morris et al.
Near-Infrared View of the Galactic Center

Credit:Courtesy of Peter Michaud, Gemini Observatory/NSF/University of Hawaii Adaptive Optics Group. Used with permission.
Proper Motions of Infrared Stars Around Sgr A*
Star in a 15.2-year Orbit Around Sgr A*  

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Enclosed Mass vs. Radius Around Sgr A*


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Mass Densities vs. Dark Object Masses in Nearby Galactic Nuclei


- $\tau_{\text{max}} =$ maximum lifetime of a cluster of dark objects (e.g., brown dwarfs, stellar remnants, or elementary particles)

- Current estimate for mass density in our Galactic center is $1 \times 10^{17}$ Msun/pc$^3$

- Maximum lifetime for clusters of dark objects implausibly short only for Milky Way and NGC 42
2000 October 26-27


(Baganoff et al. 2001)

Oct 27 05:42 UT
45x, 4 hr
Jet Models - Markoff et al. 2001

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Multiwavelength Monitoring of Sgr A* During Chandra Observations of Multiple X-ray Flares

F.K. Baganoff


1MIT, 2UCLA, 3Penn State, 4Steward Obs., 5U. Cologne, 6MPE, 7CfA, 8U. Groningen, 9ISAS, 10ATNF, 11NRAO, 12Caltech

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Observatories Participating in Sgr A* Monitoring Campaign

- Chandra (12−62 nm)
- Keck (2 & 10 μm)
- Very Large Telescope (2 & 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 (1.3 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 18:33 UT
13x, 0.5 hr

May 29 06:03 UT
12x, 1.5 hr
2002 June 3-4 – Orbit 5

OBSID 3665 – 2002:06:03:01:46:30.4 (UT)
Sgr A* Multiwavelength Monitoring Campaign

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Three Large X-ray Flares from Sgr A*
Integrated X-ray Spectrum of Sgr A* During Flares

Model: Absorbed, Dust-Scattered Power Law

\[
N_H = 6.0 \times 10^{22} \text{ cm}^{-2}
\]
\[
\Gamma = 1.3
\]
\[
F_X = 1.6 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}
\]
\[
L_X = 2.0 \times 10^{34} \text{ erg s}^{-1}
\]
\[
D = 8 \text{ kpc}
\]
Integrated X-ray Spectrum of Sgr A* in Quiescence

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

\[ N_H = 5.9 \times 10^{22} \text{ cm}^{-2} \]
\[ \Gamma = 2.4 \]

\[ E_{Fe} = 6.59 (6.54-6.64) \text{ keV} \]
Line is narrow and NIE

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

\[ \frac{<L_F>}{<L_Q>} = 14.0 \]
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 3x10^6 solar-mass black hole

Adapted from Baganoff et al., CHANDRA X-RAY SPECTROSCOPIC IMAGING OF SAGITTARIUS A* AND THE CENTRAL PARSEC OF THE GALAXY. Astrophysical Journal, Vol. 591, p. 901, Fig. 6 (2003). Used with permission.
Summary

- 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 (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
Courtesy of Max Planck Society for the Advancement of Science/R. Genzel et al. Used with permission.

Credit: NASA/MIT/F.K. Baganoff et al.
Spectrum of Possible Jet-like Feature Near Sgr A*

Gamma = 1.8
\[ N_H = 8.0 \times 10^{22} \text{ cm}^{-2} \]
Summary – X-ray Jet

- Discovery of an apparent X-ray jet from the Milky Way’s central black hole
- Never before seen in any other waveband!
- 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
- Strongly suggests we are seeing “fingerprints” of activity over the past few thousand years
- X-ray flares tell us about the current activity