The Galactic Center: From the Black Hole to the Minispiral

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The Galactic Center on Three Size Scales

1. Circumnuclear (molecular) Disk (CND) and Minispiral (ionized streamers)
   120 arcs / 5 pc
   Zhao, Blundell, Downes, Schuster, Marrone

2. Black hole accretion envelope (100 R_s)
   1 mas / 0.3 micro pc
   Marrone, Munoz, Rao

3. SgrA* radio source
   37 microarcseconds / 0.01 microparsec
   Doeleman et al.
Submillimeter Valley,
Mauna Kea, HI

- **CSO**
  - 10 m single dish (79 m²)
  - (aggregate area 482 m² equivalent of 25 m aperture)

- **JCMT**
  - 15 m single dish (177 m²)

- **SMA**
  - Eight 6 m dishes (compact configuration) (226 m²)
Nine-Field Mosaic Image of Circumnuclear Disk in Galactic Center

CN
H$_2$CO
SiO

SMA Data
Sergio Martin Ruiz

5 arcmin field
3 arcs resolution
1.3 mm wavelength
Galactic Center CND with 230 GHz Continuum from Ionized Minispiral
H30α Recombination Line at Prominent Locations
Velocity Distribution of Gas Traced by H30α Emission
Keplerian Radial Velocity Model
Three-Dimensional Geometry of Minispiral Arms

Observer above

Gray image is in the sky projection
Some Scales in the Galactic Center

$r_s = 1.3 \times 10^{12}\text{cm} \ (\text{for } 4.3 \times 10^6 \text{ solar masses}) = 10\mu\text{as at 8.3 kpc}$
A Hungry Black Hole
Polarization Images at Various Wavelengths from the SMA
2005 SMA Measurements of Faraday Rotation in Sgr A*
Accretion Rate and Faraday Rotation

\[ \chi(\lambda,t) = \chi_0(t) + \lambda^2 \, RM(t) \]

\[ RM = 8.1 \times 10^5 \int n_e B \cdot dl \]

\[ RM = -5.1 \times 10^5 \text{ rad/m}^2 \]

Assumptions
- equipartition
- density power law
- inner radius cutoff of Faraday screen

Accretion rate = \(10^{-9} - 10^{-7} \, M_{\text{Sun}}/\text{yr}\)
Polarization of Sgr A* at 230 GHz (1.3 mm) (SMA)
Polarization Track for 3/31/07 Observation of SgrA∗
Circular Polarization of Sgr A*
Emission Models for SgrA*

Free Fall onto Rotating BH

Orbiting Gas and Nonrotating BH

GR Code 0.6mm VLBI 1.3mm VLBI

Falcke et al.
Hot Spot Models ($P = 27$ min)

230 GHz, ISM scattered

Spin = 0, orbit = ISCO

Spin = 0.9, orbit = 2.5 x ISCO

Models: Broderick & Loeb
1.3mmλ Observations of SgrA*

VLBI program led by a large consortium led by Shep Doeleman, MIT/Haystack
Fits to Visibility Data

14 Rsch (140μas)

Gammie et al.
Days 96 and 97 (2009)
Observations of Cygnus A with the Jodrell Bank Intensity Interferometer at 125 MHz before 1952 by Jennison and das Gupta

Preferred model!
The Synchrotron Emission from Cygnus A Imaged with the VLA at 6 cm Wavelength
The Minimum Apparent Size

Event Horizon

![Graph showing apparent diameter vs. object diameter (Rsch)]

![Image of event horizon and black hole]

Broderick & Loeb
Noble & Gammie
Seeing Through the Scattering

$\theta_{OBS}$ deviates from scattering for $\lambda < 1.35$ cm

$\theta_{INT} \ll \theta_{SCAT}$ for $\lambda > 1.3$ mm

$\theta_{INT} \propto \lambda^{1.4}$
Hot Spot Model \((a = 0, i = 30)\)

Scattering at 230 GHz

\(a = 0, \text{ISCO} (3 \, r_{\text{Sch}}), \, i = 30^\circ, \, M = 4 \times 10^6 M_{\odot}\)
Simulation of Closure Phase for Hot Spot Model
SMTO–Hawaii–CARMA, 8 Gb/s, 230 GHz, 10 sec points
New (sub)mm VLBI Sites

Phase 1: 7 Telescopes (+ IRAM, PdB, LMT, Chile)
Phase 2: 10 Telescopes (+ Spole, SEST, Haystack)
Phase 3: 13 Telescopes (+ NZ, Africa)
EHT Phases

Phase I: 7-station 8Gb/s array
   Phasing ALMA and CARMA
   2010–2014

Phase II: 10-station 32Gb/s dual-pol array
   Activate SEST, equip S.Pole
   move to 0.8mm observations
   2015–2018

Phase III: 12-station array up to 64Gb/s
   New dishes for optimal baseline coverage
   2019–2024
Progression to an Image

GR Model  7 Stations  13 Stations