Imaging the Structure and Dynamics near the Event Horizon of a Black Hole

Michael Johnson (CfA)
On Behalf of the Event Horizon Telescope Collaboration

NEROC
November 8, 2017
"It is conceptually interesting, if not astrophysically very important, to calculate the precise apparent shape of the black hole... Unfortunately, there seems to be no hope of observing this effect." (Bardeen 1973, 1974)
The Event Horizon Telescope

230 GHz = 1.3 mm
Full Polarization
Resolution: ~20 μas

Image Credit: APEX, IRAM, G. Narayanan, J. McMahon, JCMT/JAC, S. Hostler, D. Harvey, ESO/C. Malin
Past Results with the EHT

Image Credit: APEX, IRAM, G. Narayanan, J. McMahon, JCMT/JAC, S. Hostler, D. Harvey, ESO/C. Malin
Studying Sgr A* with the EHT

- Best-fit Gaussian
- Best-fit Ring

Baseline Length (10^6 wavelengths)

Correlated Flux Density (Jy)

Characteristic Size

43 µas (FWHM) \(\sim 10 r_g\)

Smaller than the apparent
diameter of the photon sphere

Best-fit Gaussian

CA/AZ – HI
The SED of Sgr A*
The SED of Sgr A*

- Energetically dominant emission
- Polarization is expected and traces the magnetic fields
- 7% pol > 100 GHz, but unresolved

Magnetic field order is unknown

Ordered Fields
Low %Pol

Tangled Fields
High %Pol

Unpolarized

EHT

EHT

Low %Pol

High %Pol
Why Study Polarization?

Strong Gravity:
- Parallel Transport
- Relativistic Aberration

BH Accretion and Outflow:
- Field morphology
- Turbulence

Global Accretion:
- Faraday rotation & conversion

The accretion rate of Sgr A* was not determined until submillimeter polarization was detected! (Aitken et al. 2000; Marrone et al. 2007)
Resolving Sgr A* with the EHT

First polarimetric VLBI at 230 GHz;
First resolved polarization of Sgr A* at any wavelength

Johnson et al. (2015)
Resolving Sgr A* with the EHT

Asymmetry is special!
Implies spatial changes in polarization direction

Fractional Polarization

North–South Baseline (Gλ)

East–West Baseline (Gλ)
Ordered Fields Near the Horizon

Increasingly Resolved Image

Ordered Fields

Turbulent Fields

EHT Data

Increasingly Polarization Dominated

(Debiased) Fractional Polarization

(Deblurred) Normalized Visibility

mJy/μas²

(All these models appear identical when unresolved)
Closure Phases of Sgr A*

Non-zero closure phases detected in 2009-2013

Persistent, asymmetric structure (first ever for Sgr A*)

Example of a compatible model

Fish et al. (2016)

Broderick et al. (2016)
Roadmap of the EHT

2008
- 1 GHz BW (4 Gb/s)
- 3 Stations
- Detection of horizon-scale structure in Sgr A*

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<th>Date (UT)</th>
<th>Correlated flux density (Jy)</th>
<th>SNR</th>
<th>Residual delay (ns)</th>
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</table>

Doeleman et al. (2008)
Fish et al. (2011)

Characteristic Size
43 μas (FWHM) ~10 r_g
Smaller than the apparent diameter of the photon sphere

Doeleman et al. (2008)
Roadmap of the EHT

2008
- 1 GHz BW (4 Gb/s)
- 3 Stations
- $\sim 4R_{Sch}$ structure in Sgr A*

2013
- Phased arrays (CARMA, SMA) w/ dual-pol (8 Gb/s)
- Enabled Science: Polarimetry
- Ordered magnetic fields near Sgr A*

Sgr A*, 2013 EHT Data

Best-fit Gaussian

Best-fit Ring

Johnson et al. (2015)
Roadmap of the EHT

2008
- 1 GHz BW (4 Gb/s)
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- ~4R_{Sch} structure in Sgr A*

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- Phased arrays
- Polarimetry
- Ordered fields near Sgr A*

2017
- 4 GHz BW (32 Gb/s)
- ALMA!
- Images of Sgr A* and M87

5 observing nights, 80 hours observing, 18 different sources

The 2017 EHT Campaign was this April
We have already successfully detected fringes to all sites with unprecedented SNR

Details in Kazu Akiyama's talk next!
The 2017 EHT observations prompted a worldwide multiwavelength campaign.
The 2017 EHT observations prompted a worldwide multiwavelength campaign. Two flares were detected during EHT observations with ALMA.

Successful detection of interferometric fringes to all sites.
Roadmap of the EHT

2008
- 1 GHz BW (4 Gb/s)
- 3 Stations
- $\sim 4R_{\text{Sch}}$ structure in Sgr A*

2013
- Phased arrays
- Polarimetry
- Ordered fields near Sgr A*

2017
- 4 GHz BW (32 Gb/s)
- ALMA!
- Images of Sgr A* and M87

2018+
- 8 GHz BW (64 Gb/s)
- Sideband separation: 18 GHz spanned
- New sites: Greenland Telescope and Kitt Peak
- Extension to 345 GHz

Chael et al. (2016)  
Akiyama et al. (2017)

Model Image  
CLEAN  
MEM
Time Variability: Movies of a Black Hole

Earth-rotation synthesis is inapplicable for Sgr A*!

**Simulation:**
- An orbiting “hot spot” (Broderick & Loeb 2006)
- Earth rotates 7° per hot spot orbit (27 minutes)

**Reconstruction:**
- Assumes the sites and sensitivities of the expected 2017 EHT
- Snapshot images (~1 minute of data per frame)
- An entire movie is reconstructed, favoring frame-to-frame continuity
7mm VLBA Observations of M87

Computing Time: ~hours
Framework is flexible
- Irregularly spaced obs.
- Inhomogeneous beam

A calibration/imaging framework
Results can be post-processed; e.g., wavelet analyses (Mertens & Lobanov 2015)

← Equivalent to ~3-hr for Sgr A*

with Craig Walker, Andrew Chael, Katie Bouman, Lindy Blackburn, Shep Doeleman

The EHT Collaboration

Shep Doeleman (EHT Director)
Dimitrios Psaltis (Project Scientist)
Vincent Fish (Research Scientist)
Geoff Crew (APP Software Lead)
Kazu Akiyama (Jansky Fellow)
Summary

The EHT is now enabling science that requires horizon-scale observations

Past discoveries include:

- Compact structure in Sgr A* and M87, only ~5 Schwarzschild radii in size
- Persistent complex structure over several years
- Ordered magnetic fields near the event horizon

2017 observations with EHT+ALMA are expected to lead to the first EHT images of Sgr A*, M87, and many other targets (e.g., 3C279 and OJ287)

Continued EHT Expansion will enable:

- Imaging at 230 & 345 GHz
- New sites (GLT, KP, and more)
- Triggered observing
- Tests of the no-hair theorem
- Polarimetric and RM images of black holes
- Movies of flares, steady dynamics, and jet launching