The Shadow of the Supermassive Black Hole

First M87 Event Horizon Telescope Results

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Introduction

• Astronomical Black Holes
  • Stellar mass BHs (up to 100 $M_{\text{Sun}}$)
    • Made from Supernova explosion and consequent mergers
    • Keplerian motion + X-ray (Webster & Murdin 1972; Remillard & McClintock 2006)
    • Gravitational-wave measurements (Abbott et al. 2016)
  
• Supermassive Black holes (SMBHs; from $10^6 M_{\text{Sun}}$)
  • Seeds? Stellar mass BH or heavier seeds (IMBH)?
  • exist in the centers of nearly all galaxies (Lynden-Bell 1969; Kormendy & Richstone 1995; Miyoshi et al. 1995)
  • Our Galactic center, Sgr A* (Eckart & Genzel 1997; Ghez et al. 1998; Gravity Collaboration et al. 2018)
  • M87 (Gebhardt et al. 2011; Walsh et al. 2013)

• Strong evidence of Micro BHs or Intermediate mass BHs is yet to be found
Introduction

• Observational Evidences of BHs
  • Cyg X-1 Radiation from very compact objects
    • Stellar BH - X-ray binary
      • e.g. [Black body radiation] power of $10^{37}$ erg/s, $L = 4\pi R^2 \sigma T_e^4$
    • [X-ray] Peak around 1 keV ($10^7$ K),
      • $r \sim 10^7$ km (Sun $\sim 7 \times 10^5$km, Earth $\sim 6 \times 10^3$ km)
    • If it radiates at optical-UV,
      • $r \sim 10^7$ km (a giant star) for given Luminosity
  • Cyg X-1 (Webster & Murdin 1972) > a few solar mass
    • Keplerian motion of companion from spectroscopy

Cyg X-1 X-ray light curve (Agrawal+ 1971)
Introduction

• Observational Evidences
  • Keplerian motion around compact objects (mass function)
    • Stars around SMBH (e.g. Sgr A*)
    • Gas disk around SMBH (e.g. NGC4258(M107))
    • Velocity dispersion (e.g. M87)
  • Gravitational redshift from center of galaxies
    • Star (GRAVITY collaboration 2018), gas
  • Optical, IR, Radio (VLBI), X-ray, ...
  • Photometry, spectroscopy, Astrometry, ...

[Graphs and plots related to gravitational redshift and data analysis]
Galactic Center Sgr A*  
(Eckart & Genzel 1997; Ghez+ 1998; ESO & UCLA GC group)

- Long-term monitoring of star’s positions
- In a volume with radius of 60 AU
  - \(\sim 0.3 \text{ mPC} \sim 0.00095 \text{ ly} \sim 8.3 \text{ lhr}\)
- \(M \sim 4.1 \pm 0.6 \times 10^6 M_{\odot}\)
  - 0.1 arcsec \(\sim 850 \text{ AU at 8.5 kpc}\)
  - \(R_{\text{sch}} \sim 0.08 \text{ AU (0.39 \mu pc)}\)
- Full phase coverage measured for two stars
  - S0-2 with an orbital period of 15.56 years
  - S0-102 with 11.5 years
  - At the closest approach, S0-2 is only 17 light hours
Looking for Best objects for Black Hole Shadow Image

M_BH should be massive ➔ large photon capture ring (BH shadow)
Object should be as close as possible from us ➔ large angular size
Should be compact and bright Synchrotron source ➔ Radio Interferometer
Photon Capture Radius (Black Hole Shadow Size)

\[ R_c = 1.5 \sqrt{3} \, R_{sch} = 3 \sqrt{3} \frac{GM_{BH}}{c^2} \]
Apparent Size of Photon Capture Radius

- **Apparent Size of Photo Ring**
  \[ \Theta_c = \frac{R_c}{\text{distance}} \]

- **Stellar Mass BHs**
  - Cygnus X-1
    - \( M \sim 15 \, M_{\odot} \)
    - Distance 1,900 pc
  - SS433 (Stellare BH with Jet)
    - \( M < 30 \, M_{\odot} \)
    - \( D \sim 5,500 \, \text{pc} \)

- **Supermassive BHs**
  - Sgr A*
    - \( M \sim 4 \times 10^6 \, M_{\odot} \)
    - \( d \sim 8.5 \, \text{kpc} \)
  - M87* (Vir A*)
    - \( M \sim 6 \times 10^9 \, M_{\odot} \)
    - \( d \sim 16.7 \, \text{Mpc} \)
  - Cen A
    - \( M \sim 5 \times 10^7 \, M_{\odot} \)
    - \( d \sim 4 \, \text{Mpc} \)

\[ \Theta_c \text{ of Sgr A*, M87* } \sim 40 \, \mu\text{arcsec} \]

> 10^4 times larger than stellar BH candidates
Synchrotron radiation around Black Holes

• Synchrotron radiation from SMBH
  • Power law distribution of flux density ($S_\nu \propto \nu^{-\alpha}$, $\alpha$: 0.5 ~ 0.8)
  • Relatively interstellar extinction free
  • But synchrotron absorption
    • significant in compact region (e.g. near BH)
    • Synchrotron self-absorption (jet)
    • Blandford-Koenigl jet (1979)
      • $S_\nu \propto \nu^{5/2}$
• Radio frequency $\rightarrow$ Radio interferometry
• mm wavelength $\rightarrow$ higher angular resolution
• mm wavelength $\rightarrow$ low synchrotron self-absorption
Active Galactic Nuclei (AGNs)

• NGC1068 first discovered by Fath in 1908
• Central bright regions that can outshine the entire stellar population of their host galaxy
• Mass-accreting SMBH and surrounding regions
• Simplified classification
  • High accretion rate Quasars
    • Optically thick, geometrically thin accretion disk (Shakura & Sunyaev 1973; Sun & Malkan 1989)
  • Low accretion rate LLAGN
    • fed by hot, tenuous accretion flows with much lower accretion rates (Ichimaru 1977; Narayan & Yi 1995; Blandford & Begelman 1999; Yuan & Narayan 2014)
• All together ~10% of whole SMBHs (~90% are not active)
Seyfert Galaxy NGC 5548 (AGN in Spiral Galaxy) versus normal galaxy NGC 3277
Radio core in M87

- Linear feature found in M87 by Curtis in 1918
  - Called “jet” by Baade and Minkowski (1954)
  - 65kpc; 40 Myr
    - Power close to $10^{45}$ erg/s (de Gasperin+, 2012)
  - Compact (unresolved) source at the upstream end of the jet – LLAGN

And ~10% of ‘Active’ SMBHs are ‘radio loud’ (bright synchrotron sources)
Radio core in M87

• Blandford-Koenigl (1979) jet
  • Synchrotron self-absorption
  • Confirm (Hada+ 2011)
  • Quasi-parabolic limb shape
    • From $10^5 \, r_g$ to $20 \, r_g$ (Hada+ 2013)
    • Further to $10^7 \, r_g$ (Asada+ 2012)
• A global millimeter VLBI experiment
  • Baseline 160 m to 10,700 km
  • 230GHz; 1.3mm → resolution ~25 μas
  • 6 locations, 8 stations (2017)
  • Sensitivity increase by a factor of ~30 increased over last ten years (ALMA and high performance recorders)

Best targets

Sgr A* : $$M_{BH} \sim 4 \times 10^6 M_{\odot}$$
  $$d \sim 8.5 \text{kpc}$$

M87* : $$M_{BH} \sim 4-6 \times 10^9 M_{\odot}$$
  $$d \sim 16.5 \text{Mpc}$$
First radio telescope was an interferometer.
Radio interferometer

• Interferometer sees ‘visibility’ (e.g. fringes of Young’s experiment)
• Visibility ($v_x$, $v_y$) FT Image ($x$, $y$); FT ‘Fourier Transformation’
• In imaging, transformation between Spatial Frequency and position

\[
E(\xi) = \int_{-\infty}^{\infty} E(x) e^{-i 2\pi x \xi} \, dx \\
E(x) = \int_{-\infty}^{\infty} E(\xi) e^{i 2\pi x \xi} \, d\xi
\]

• Radio interferometer with very long baseline
  • ‘Very long’ means separate freq. time standard and incoherent atmosphere
  • At radio wavelength, arbitrary long baseline is possible
• From IR, frequency standard (H-maser clock) accuracy is not sufficient to record waves
  • Plus interstellar extinction and contamination
Observation, Correlation and Calibration

• M87* observed on 2017 April 5, 6, 10 and 11
• $\tau$ (opacity) $0.03 \sim 0.28$ at 230 GHz
• M87* scans (alias 3C274) interleaved with 3C279
  • A scan 3 to 7 minutes duration
  • Seven scans on April 10, twenty-five scans on April 6
  • Dual circular polarization observation
  • 2GHz BW, centered at 227.1 and 229.1 GHz, digitized and recorded at 32Gbps
  • Typical coherence time $\sim 10$ s
    • mainly due to water vapor
• Correlated at MIT Haystack and at MPIfR Bonn
• ALMA as reference station
  • Amplitude accuracies 5 to 10 %
Earth Synthesis
Observation, Correlation and Calibration

- ALMA baseline SNR > 100, non-ALMA baseline > 10
- 2 bands & 2 polarization, three independent pipelines
  - 1deg phase and 2% amplitude systematic errors
- Visibility distribution (left) resembles a thin ring (middle)
  - Huge improve of UV coverage since 2012 (right)
  - 46 μas diameter, a first null at 3.4 Gλ, but not a simple plain ring
  - 50% flux resolved out, depth of first minima as a function of orientation \(\Rightarrow\) asymmetric

\[\text{EHT collaboration 2019} \quad \text{Thompson+ 2017} \quad \text{Doeleman+ 2012}\]
Images and Features

- EHT baselines sample a (very) limited range of spatial frequencies
  - 25 to 160 μas
- Two algorithms
  - Inverse-modelling – CLEAN & self-calibration
    - Deconvolve PSF from Visibilities
  - Forward-modelling – RML
    - Searching for images
- Four teams independently imaging
  - Common ring feature 38-44 μas diameter
  - With common enhanced brightness to the South
- Position angle 20deg between 5/6 and 10/11
On all four observed days from each of the three imaging pipelines, CLEAN images (from DIFMAP) are shown after convolution and SMILI results have no restoring beam applied. Different selected fiducial imaging parameters (e.g., compact flux) result in fluxes for each method, as indicated by the unique color bars for each row.
After beam-convolution of forward modelling data

Figure 14. Fiducial images of M87 on April 11 from our three separate imaging pipelines after restoring each to an equivalent resolution. The eht-imaging and SMILI images have been restored with 17.1 and 18.6 μas FWHM Gaussian beams, respectively, to match the resolution of the DIFMAP reconstruction restored with a 20 μas beam.
Theoretical Modeling

• General-relativistic magneto-hydrodynamics (GRMHD) simulations
  • A turbulent, hot, magnetized disk orbiting a Kerr black hole
  • Powerful jet and the broad-band SED observed in LLAGN
  • A shadow and an asymmetric emission ring predicted
  • Ring – lensed photon ring rather than ISCO

• Synthetic image library built
  • Magnetized accretion flows onto black holes in GR
  • Coupled to three different general-relativistic ray-tracing and radiative-transfer codes
Simulated images rather model-independent
Theoretical Modeling

- Kerr Black hole with accretion flow
  - Initial: Thermal ion, relativistic electron and weakly magnetized torus, axis aligned
  - Outcome: All Corona with $\beta_p \sim 1$ & strongly magnetized poles ($B^2 / \rho c^2$)
  - Schwarzschild BH disfavored: Accretion rate $\ll$ Jet power
    - Blandford-Payne (1982, accretion disk) not enough
    - Blandford-Znajek (1977, BH spin + B) – Kerr BH

- MAD Highly magnetized
  - Magnetic flux / accretion rate $\sim 15$
    - All strongly magnetized
    - Emission mostly from disk midplane

- SANE Mildly magnetized
  - Magnetic flux / accretion rate $\sim 1$
    - Jet (disk) strongly (weakly) magnetized
    - High (low) $R_{high}$, emission mostly from jet (disk)
Where the lights come from?
## Model Comparison and Parameter Estimation

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Prior Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring diameter $^a$ $^d$</td>
<td>$42 \pm 3 , \mu\text{as}$</td>
<td></td>
</tr>
<tr>
<td>Ring width $^a$</td>
<td>$&lt;20 , \mu\text{as}$</td>
<td></td>
</tr>
<tr>
<td>Crescent contrast $^b$</td>
<td>$&gt;10:1$</td>
<td></td>
</tr>
<tr>
<td>Axial ratio $^a$</td>
<td>$&lt;4:3$</td>
<td></td>
</tr>
<tr>
<td>Orientation PA</td>
<td>$150^\circ$–$200^\circ$ east of north</td>
<td>$150^\circ$–$200^\circ$ east of north</td>
</tr>
<tr>
<td>$\theta_g = GM/DC^2$ $^c$</td>
<td>$3.8 \pm 0.4 , \mu\text{as}$</td>
<td></td>
</tr>
<tr>
<td>$\alpha = d/\theta_g$ $^d$</td>
<td>$11^{+0.5}_{-0.3}$</td>
<td></td>
</tr>
<tr>
<td>$M$ $^c$</td>
<td>$(6.5 \pm 0.7) \times 10^9 M_\odot$</td>
<td></td>
</tr>
<tr>
<td>$D$ $^e$</td>
<td>$(16.8 \pm 0.8) , \text{Mpc}$</td>
<td></td>
</tr>
<tr>
<td>$M(\text{stars})$ $^e$</td>
<td>$6.2^{+1.1}<em>{-0.6} \times 10^9 M</em>\odot$</td>
<td></td>
</tr>
<tr>
<td>$M(\text{gas})$ $^e$</td>
<td>$3.5^{+0.9}<em>{-0.3} \times 10^9 M</em>\odot$</td>
<td></td>
</tr>
</tbody>
</table>
Conclusion and Outlook

• EHT, VLBI at a wavelength of 1.3 mm imaged horizon-scale structures around SMBH candidate in M87
• The image to be dominated by a ring structure of $42\pm3\,\mu\text{as}$ diameter brighter in the south
• Central brightness depression with a contrast of $>10:1$, which we identify with the black hole shadow
• Extensive library of synthetic images obtained from GRMHD simulations
  • Basic features of our image are relatively independent of the detailed astrophysical model
  • Black hole mass of $6.5\pm0.7\times10^{9}\text{M}$
• Rotation of the black hole in the clockwise direction
  • The brightness excess in the south explained as relativistic beaming of material rotating in the clockwise

▪ To come: Polarization (RM $\rightarrow$ accretion rate), ... Sgr A*! And other jetted AGNs
▪ And more stations (a KVN?) and higher frequency
Where is M87?
(binary) Mass function

• Keplerian 3\textsuperscript{rd} law
  • the centripetal force equal to the gravitational force: \( mr\omega^2 = G\frac{mM}{r^2} \)
  • \( mr\left(\frac{2\pi}{P}\right)^2 = G\frac{mM}{r^2} \Rightarrow P^2 = \frac{(2\pi)^2}{GM} r^3 \Rightarrow \frac{a^3}{P^2} = \text{constant} \ (7.5 \times 10^{-6} \text{ AU}^3/\text{day}^2) \)

• When \( m \) is non-negligible, then \( M \mapsto M_1 \text{ & } m \mapsto M_2 \), \( M = (M_1 + M_2) \)
  • Then, \( a = a_1 + a_2, M_1 a_1 = M_2 a_2 \) (the center of the mass location)

• \( a = a_1 \frac{M}{M_2}; K = \left(\frac{2\pi}{P}\right) a_1 \sin i; \)

• \( \frac{M^3}{M^2} = \frac{P K^3}{2\pi G} \sin^{-3} i; \) mass function \( f = \frac{M^3}{M^2} \sin^3 i = \frac{P K^3}{2\pi G}; \)

• From spectroscopy \( v \sin i \)
  • For \( M_1 \ll M_2 \), \( f \sim \frac{M^3}{M^2} \sin^3 i \)
  • For \( M_1 \gg M_2 \), \( f \sim \frac{M^3}{M^2} \sin^3 i \)