TOWARDS EVENT HORIZON SCALE PHYSICS FROM MOVIES AND POLARIZATION MAPS

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PRESENTATION AT NSBP INNOVATIVE SEMINAR SERIES
TALK OUTLINE

• A Brief Introduction to Relativity
  • Electromagnetism
  • Special Relativity
  • General Relativity

• Observing Jet/Accretion Flow/Black Hole (JAB) Simulations
  • Terminology and Definitions
  • Application: M87
    • Observing JAB Simulations of M87
      • Comparison of images with VLBA (43 GHz) and polarized EHT (230 GHz) observations

• Future Horizons: Sgr A*
  • Observing JAB Simulations of Sgr A*
    • Comparison of images with EHT constraints
    • Classification of model parameter space movies
ELECTROMAGNETISM – MAXWELL’S EQUATIONS

- Maxwell’s equations describe the dynamics of electric and magnetic fields

**Gauss’s Law**

\[ \oint E \cdot dA = \frac{Q_{enc}}{\varepsilon_0} \]

**Gauss’s Law for Magnetism**

\[ \iiint B \cdot d\vec{A} = 0 \]

**Faraday’s Law**

\[ \int E \cdot d\vec{l} = -\frac{\partial \Phi_B}{\partial t} \]

**Ampère Law**

\[ \int B \cdot d\vec{l} = \mu_0 I_{enc} + \mu_0 \varepsilon_0 \frac{\partial \Phi_E}{\partial t} \]

Now that we know these basic relationships between \( \vec{E} \) and \( \vec{B} \) ... Let there be light!

Poynting flux (power per unit area):

\[ \vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B} \]

Let’s also see Maxwell’s Eqs. in integral form
SPECIAL THEORY OF RELATIVITY – ON THE ELECTRODYNAMICS OF MOVING BODIES

• In 1905 Albert Einstein (1879-1955) wrote observations from a series of thought experiments and observations in *On the Electrodynamics of Moving Bodies*:
  
  • Relative, not absolute motion, establishes current in magnet-conductor system
  • Simultaneity depends on an observer’s state of motion, or reference frame
  • Clocks synchronize if the difference in times (measured locally) from when light is emitted at A to when light arrives at B equals the corresponding difference for the reverse journey
In the frame of the conductor, the moving magnet creates a changing magnetic flux that results in an electric field in the conductor, and subsequently a current.

\[ \oint \vec{E} \cdot d\vec{l} = -\frac{\partial \Phi_B}{\partial t} \]

In the frame of the magnet...?
In the frame of the conductor, the moving magnet creates a changing magnetic flux that results in an electric field in the conductor, and subsequently a current.

In the frame of the magnet, the moving conductor’s free charges are deflected by the magnetic field.

\[
\oint \vec{E} \cdot d\vec{l} = -\frac{\partial \Phi_B}{\partial t}
\]

\[
\vec{F}_B = q\vec{v} \times \vec{B}
\]
POSTULATES OF SPECIAL RELATIVITY

• Postulate 1: “The laws by which the states of physical systems undergo change are not affected, whether these changes of state be referred to the one or the other of two systems of co-ordinates in uniform translatory motion” (Einstein, 1905, p.4).

The laws of physics are the same in any two inertial frames

• Postulate 2: “Any ray of light moves in the ‘stationary’ system of co-ordinates with the determined velocity c, whether the ray be emitted by a stationary or by a moving body” (Einstein, 1905, p.4).

The speed of light in a vacuum is the constant c regardless of the motion of the emitting frame

\[ c = 299,792,458 \text{ m/s} \]
• Inertial frames move relative to each other at constant speed, without acceleration
• In relativity, space and time coordinates of an event observed in different inertial frames are related by Lorentz transformations $t \rightarrow t'(t,x,y,z)$, $x \rightarrow x'(t,x,y,z)$, $y \rightarrow y'(t,x,y,z)$, $z \rightarrow z'(t,x,y,z)$
• Frame $S'$ is said to be “boosted” with velocity $(v,0,0)$ with respect to $S$, and has Origin $O'$ at $(t',vt',0,0)$.

Vector $r'$ in $S'$ is related to $r$ in $S$ via Lorentz transformation
TIME DILATION

- Compare a light clock that undergoes a tick (round trip of a photon) in Frames S and S’
- Special relativity postulates the speed of light is the same in both stationary and moving clock
- During a tick $\Delta t'$ of the moving clock, the path length of light’s worldline is longer in S’ than in S

\[ \Delta t' = \frac{2\sqrt{1 + \left(\frac{\gamma\Delta t}{2}\right)^2}}{c} \]

\[ \Rightarrow \Delta t' = \gamma \Delta t, \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \]
LENGTH CONTRACTION

• Now consider Events A, B and C for light bouncing parallel to the motion of a light clock in Frames S'.

\[
\begin{align*}
t'_{AB} &= \frac{L' + vt'_{AB}}{c} \Rightarrow t'_{AB} = \frac{L'}{c-v} \\
t'_{BC} &= \frac{L' - vt'_{BC}}{c} \Rightarrow t'_{BC} = \frac{L'}{c+v}
\end{align*}
\]

\[
\begin{align*}
\Delta t' &= t'_{AB} + t'_{BC} = \frac{2L'}{c(1-\frac{v^2}{c^2})} = \frac{2\gamma^2 L'}{c} \\
\Delta t' &= \gamma \Delta t = \gamma \frac{2L}{c} \\
\Rightarrow L' &= \frac{L}{\gamma}
\end{align*}
\]
GENERAL THEORY OF RELATIVITY

• Einstein sought to extend his 1905 special theory of relativity to include non-inertial (accelerating) frames

• In strong gravitational fields, such as near black holes or neutron stars, classical+special relativistic predictions for lengths, times, frequencies, energy, etc. fail

• In a 1915 lecture at the Prussian Academy of Sciences in Berlin, Einstein unified gravity with special relativity in the general theory of relativity
EQUIVALENCE PRINCIPLE

• Consider two labs: GraviLab and AccLab
• Is there any experiment in either lab that can distinguish the black hole from the piston?
EQUVALENCE PRINCIPLE - TIDAL FORCES

- Consider two labs: GraviLab and AccLab
- Tidal forces would affect only the person in GraviLab:

\[ T \approx \frac{MH}{r^3} \]
EQUIVALENCE PRINCIPLE

• Consider two labs: GraviLab and AccLab
• For sufficiently small labs, there is no experiment to distinguish them

Equivalence Principle:
Local properties of curved spacetime are indistinguishable from flat spacetime
POP QUIZ - RELATIVITY OF SIMULTANEITY

- A spaceship-bound individual synchronizes flashing lights for the spaceship. You are a reference frame in which the spaceship is moving at velocity $v$. Which source do you think the person in the spaceship first sees?
  
  a) Source A
  b) Source B
  c) Both Sources A and B
• In 1783 John Mitchell theorized that if a star’s radius is $>500R_{\text{Sun}}$, light could not escape it.
• In 1916, Karl Schwarzschild solved the Einstein field equations for the geometry outside a spherically symmetric, non-rotating mass.
• In 1963, Roy Kerr solved the Einstein field equations for the geometry outside a spherically symmetric, rotating mass.
• In the 1970’s, black hole temperature was theorized by Hawking, among others.
STRONG GRAVITY AND BLACK HOLES

• We have seen that Einstein’s special relativity postulates can warp space and time.
• Can gravity warp spacetime as well?
  • Yes! Dense objects change the spacetime distance formula from flat space.

• STRONG gravity as one approaches singularity of infinite spacetime curvature.
BLACK HOLES - CONCEPT

- Objects launched from massive bodies will fall back unless their kinetic energy is at least the magnitude of the potential energy binding them to the object:

\[
\frac{mv_{\text{esc}}^2}{2} = \frac{GMm}{R}
\]

\[\Rightarrow v_{\text{esc}} = \sqrt{\frac{2GM}{R}}\]

- Note: The object’s mass \(m\) does not enter the escape speed

- **Exercise:** Apply the escape speed condition to a massless photon traveling at the speed of light \(c\) to find the Schwarzschild radius \(r_S\), i.e., the radius in which \(M\) would have to be contained so that light cannot escape.
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\[ c = \sqrt{\frac{2GM}{R}} \]

\[ r_S \equiv R = \frac{2GM}{c^2} \]
1. Start with general relativistic magnetohydrodynamic (GRMHD) simulation or semi-analytic model of jet (or outflow)/accretion flow/black hole (JAB) system

2. Convert GRMHD variables to radiation prescriptions for emission, absorption, polarization, particle acceleration and/or dissipation to emulate sources

3. Add “observer” viewing sources, e.g., Event Horizon Telescope (EHT) targets:

   I. M87

   II. Sgr A*
TERMINOLOGY AND DEFINITIONS

• Active Galactic Nucleus (AGN) – emitting region around a supermassive black hole (SMBH) appearing as a discrete source

• Accretion disk – inflowing, typically magnetized, plasma gravitationally bound to a central massive object
  • Magnetically Arrested Disk (MAD) – inflow inhibited by magnetic pressure near a black hole (contrast Standard and Normal Evolution (SANE))

• Stokes Parameters – total intensity I, two independent linear polarizations Q and U and circular polarization V

• Jet – a relativistic polar outflow emanating from about 10% of AGN SMBHs
  • Blandford-Znajek jets are powered by the interplay of black hole spin with magnetic fields yielding Poynting flux of electromagnetic energy

• Synchrotron radiation – polarized radiation occurring when relativistic charged particles gyrate around magnetic fieldlines
BLACK HOLES - OBSERVATIONS

• The Event Horizon Telescope is a collection of radio antennae forming a network of intercontinental baselines to form mm-images

• Exercise: Can you explain why baselines of radio telescopes are so long in view of the angular resolution limit below?
  • The ability to distinguish two sources at smaller angular separation increases with aperture diameter

\[
\Delta \theta_{\text{min}} = 1.22 \frac{\lambda}{D_{\text{aperture}}}
\]
Zooming towards M87’s Jet and Central Black Hole

Courtesy of European Southern Observatory (ESO)
Emission Prescriptions for Radiative Transfer

• Critical Beta Electron Temperature Model (Anantua et al. 2020b (ARQ20)) – Turbulent Heating Physics (Howes 2010):
  1) Constant $T_e/T_p$ at $\beta \ll \beta_c$
  2) $T_e$ suppressed at $\beta \gg \beta_c$

\[
\frac{T_e}{T_p + T_e} = f \ \text{Exp}[\frac{-\beta}{\beta_c}]
\]

\[
0 < f < 1, \quad \beta = \frac{P_g}{P_B}, \quad T_e = \frac{P_e}{\rho}
\]

• R-Beta Model (EHTC Papers I-VIII)

\[
R = \frac{T_i}{T_e} = \frac{1}{1 + \beta^2} R_{\text{low}} + \frac{\beta^2}{1 + \beta^2} R_{\text{high}}
\]

• Constant $\beta_e$ Model – Magnetic-to-Particle Energy Conversion:

\[
\beta_e = \frac{P_e}{P_B} = \beta_{e0}
\]

\[
P_B = \frac{B^2}{2}
\]

Equi-partition for $P_e \sim P_B$

• Magnetic Bias Model

\[
P_e = K_n P_B^n = K_N \left(\frac{B}{\sqrt{2}}\right)^N, \quad n = N/2
\]
JETS AND RELATIVISTIC BEAMING

• Features moving with apparent speed 6c in M87 observed by Hubble (Biretta, J. A., Sparks, W. B., & Macchetto, F., 1999, ApJ 520, 621)

• Projection/finite c effect:

\[
\theta = \left( \frac{\theta_{\text{Obs}}}{\sin \tau} \right) \left( \frac{c}{V(t_f - t_i)} \right) \\
\tau = \frac{(t_f - t_i) \cos \theta}{c}
\]

Emissivity: \[j' \sim b'^{1.5}\]

Disk subtraction: \[b_\mu b'^{\mu}/p > 10\]

\[(\theta_{\text{Obs}}, \Phi_{\text{Obs}}) = (20^\circ, 0^\circ), T_{\text{Obs}} = 2000M, 2056M, ..., 2560M\]
CONNECTING WITH OBSERVATIONS:
M87 43 GHZ RADIO MAP TIME SERIES
VS. CURRENT DENSITY MODEL

- Current density model based on having particles accelerated at current layers

\[ j_v \propto \tilde{P}_e \propto j^2 \]

\[(\theta_{\text{Obs}}, \Phi_{\text{Obs}}) = (20^\circ, 0^\circ), T_{\text{Obs}} = 2000\text{M}, 2056\text{M}, ..., 2560\text{M} \]

Emissivity: Current Density Model
Disk subtraction: \(|z| > 35\text{M} \)
\(L_{Jzq} = 1e4 \text{ M}\)

M87 43GHz (7mm) VLA maps
21-Day frame rate, Epochs A,B,D-L

Anantua, Blandford and
tchekhovskoy (2018) Galaxies 6, 31

VLA 3C274 EpochA 43GHz

(Mapping credit to the Hubble Heritage Team, STScI/AURA, NASA, and APL/UA (C. Steidel, M.; Rix, D. L.); Bill Junker (Los Alamos), Phil Hardree (J.))
Using a HARM GRMHD simulation and adding e+/e- pairs so \( n = n_p + (n_{e^-})_0 + n_{\text{pairs}} \) in ray tracing at 230 GHz results in

- Magnetically Arrested Disk (MAD) simulations with decreasing V/I with increasing \( n_{e^+} = \frac{n_{\text{pairs}}}{2} \) due to positrons cancelling intrinsic circular polarization
- MAD simulation models have lower Faraday depth than Standard and Normal Evolution (SANE), resulting in slower rates of EVPA rotation

MAD \( R_{\text{high}}=20, a/M=-0.5 \)

SANE \( R_{\text{high}}=20, a/M=-0.5 \)
Interstellar - Photon Rings

- Interstellar 2:13:24 – Shuttle approaches Gargantua with visible Einstein rings
- Quiz: What’s missing?
  - A: Relativistic beaming
Zooming in on Milky Way’s Sgr A* Region

Courtesy of European Southern Observatory (ESO)
SGR A* IMAGE OBSERVATIONS

- Event Horizon Telescope (EHT) 230 GHz emitting region size constraints
  - Intrinsic size: \((\Delta \theta)_{\text{FWHM}} = 37^{+16}_{-10} \mu\text{as} \) (isotropic); \((\Delta \theta_{\text{max}})_{\text{FWHM}} = 56^{+7}_{-3} \mu\text{as} \) (anisotropic)
  - Scattering size: \(43^{+14}_{-8} \mu\text{as} \) (isotropic)

Non-point symmetric (Fish et al. 2016; Johnson et al. 2018) ring more likely than circular Gaussian
EHT Intrinsic Size Constraint for $|I| > 0.2 \times |I_{\text{Max}}| : 8.2M < D < 16.2M$

$M = \frac{G M_{\text{BH}}}{c^2} \leftrightarrow 5\mu\text{as}$

$\beta_{e0} = 0.01$

$\beta_{e0} = 0.1$

$\beta_{e0} = 0.1$

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SGR A* MODEL CLASSIFICATION

ARQ20 Model Movies

Tobs=10,000M, 10,100M,..., 11,000M

Type I a or b - Thin, Compact, Asymmetric Photon Ring/Crescent; best fit spectrum or flat spectrum

Type II - Inflow-Outflow Boundary + Thin Photon Ring; steep spectrum

Type III - Thick Photon Torus; spectral excesses at low and high frequency

Type IV - Extended Outflow; spectral excesses at low and high frequency and flat low frequency knee
CONCLUSIONS

• Special relativity unifies physical quantities classically thought distinct and independent
  • Electric and magnetic fields transform together as a tensor
  • Space and time transform as a 4-vector
• General relativity continues the unification by incorporating accelerating frames through the equivalence principle
  • Gravity can be identified with spacetime curvature, including for black holes in which spacetime approaches a singularity
• Observing Jet/Accretion Flow/Black Hole (JAB) Systems is a methodology that links intuitive e-/e+ emission models of phenomenological processes such as turbulent heating and conversion of magnetic to particle energy with discrete near-horizon AGN observations
  • M87
    • GRMHD simulations can be used to replicate near-horizon polarized features with R-Beta Model and observational signatures of AGN jets including limb brightening with Constant $\beta_e$, Magnetic Bias and Current Density Models
  • Sgr A*
    • 230 GHz synthetic intensity maps on the scale of tens of gravitational radii appear with:
      • Emitting region most compact for low $\beta_{e0}$ and high $(f, \beta_c)$; more asymmetry for low $\beta_{e0}$, $n$ and high $(f, \beta_c)$; preferred models may be uniquely determined by upcoming EHT results...