Illuminating Black Hole Spacetimes with Accretion Disks

Scott C. Noble (RIT)  
J. Krolik (JHU), J. Hawley (UVa), C. Gammie (UIUC)  
M. Campanelli, J. Faber, C. Lousto, B. Mundim, H. Nakano, Y. Zlochower (RIT)  

Strong Gravity Seminar -- Perimeter Institute -- March 25, 2010
Outline

- Overview of black hole accretion disks
- Brief model/simulation description under the GRMHD paradigm
- Self-consistent models of emission from Sgr A*
- Geometrically thin accretion disks
- Temporal power spectra of coronal X-ray emission
- Future Directions:
  - Further model-space explorations
  - Binary black hole accretion
The Exciting World of Black Hole Accretion!
Probing the Spacetime of BHs

- Variability: e.g. QPOs, short time scale fluctuations
- Polarization
  (e.g. Schnittman & Krolik 2009)
- Spectral Fitting of Thermal Emission
  \[ L = AR_{\text{in}}^2 T_{\text{max}}^4 \quad R_{\text{in}}^2 = f(a, M) \]
  McClintock et al. 2006, Shafee et al. 2006
- Relativistic Iron Lines
- Directly Resolving the BH Silhouette
  e.g. Sgr A* with sub-mm/mm VLBI
Disk “Dichotomy”

**Thin Disks:**
- Shakura & Sunyaev (1972)
- Novikov & Thorne (1972)
- Dissipation Rate < Cooling Rate
- “Cold”, Optically Thick
- Thermal or Multi-temperature black body

**Thick Disks:**
- Narayan & Yi (1994-5) (ADAF)
- Blandford & Begelman (1999) (ADIOS)
- Quataert & Gruzinov (2000) (CDAF)
- Dissipation Rate > Cooling Rate
- “Hot”, optically thin, outflows
- 2 Temperature flow, advected heat

Narayan & Quataert (2005)
Magneto-rotational Instability (MRI)

- Velikhov (1959)
- Chandrasekhar (1960)
- Balbus & Hawley (1991)

• Growth on orbital time scale.
• MRI develops from weak initial field --- relevant for any (partially) ionized gas.
• Magnetic coupling over different radii is not well described by local viscosity.
• Can explain high accretion rates where hydrodynamic viscosity cannot.
• Fastest instability known that feeds off free energy of differential rotation.
Global Disk Simulations

- Ideal GRMHD EOM
- Kerr-Schild coordinates
- Modern high-res. shock-capturing methods
- Flux (energy) conserving

\[ N_r \times N_\theta \times N_\phi = 192 \times 192 \times 64 \]
\[ r \in [\leq r_{\text{hor}}, 120 M] \]
\[ \theta \in \pi [\delta, 1 - \delta] \]
\[ \phi \in [0, \pi/2] \]
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\[ r \in [r_{\text{hor}}, 120M] \]
\[ \theta \in \pi [\delta, 1 - \delta] \]
\[ \phi \in [0, \pi / 2] \]
Disk Morphology

Hawley, De Villiers, Krolik, Hirose 2003+

Wednesday, April 28, 2010
Canonical Magnetic Field Distribution

Hirose et al. (2004)
Sagittarius A* (Sgr A*)
The black hole at the center of the galaxy is officially On Notice. I don't know where this super massive black hole gets off holding the Milky Way together, nor do I care. It is blatantly challenging The Lord and will be dealt with in time. Does this singularity think God cannot hold our galaxy together on His own? Black hole, you may have swallowed a million suns, but now you're dealing with America! You're On Notice.

Why Study Sagittarius A* (Sgr A*)?

- Biggest black hole on the sky!
- #5 out of 25 of David Gross' "Future of Physics" questions (tests of GR)
- Test masses orbiting it! (post-Newtonian parameters)
- Luminous plasma orbiting it! (disk theory tests, further gravity tests)
The Central Gravitational Source

$D \sim 8.4\text{kpc}$

$M_{BH} \sim 4.5 \times 10^6 M_{\odot}$

$r_s = 1 \times 10^{12}\text{cm} = 3.6 \times 10^{-7}\text{pc} = 0.07\text{AU} = 10\mu\text{as} = 33\text{sec}$
The Enigmatic Accretor

\[ \dot{M}_{RM} (r \approx r_s) \approx 10^{-3} \dot{M}_{X-rays} \]

\[ L_{SgrA^*} = 10^3 L_\odot = 10^{-9} L_{edd} \quad L_{SgrA^*} = 10^{-2} \left( \frac{\eta}{0.1} \right) c^2 \dot{M}_{RM} \]
Much Theoretical Interest!!

Moscibrodzka et al 2010, arxiv 1002.1261

Much Theoretical Interest!!

<table>
<thead>
<tr>
<th>Reference</th>
<th>dynamical model</th>
<th>radiative model</th>
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<td>scaling</td>
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<td>th</td>
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<td>th</td>
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<td>Noble et al. (2007)</td>
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</table>

Table 1. Summary of selected models of Sgr A*. Abbreviations: RT-ray tracing, MC-Monte Carlo, GR-general relativistic, RIAF-radiatively inefficient accretion flow, ADAF-advection dominate accretion flow, plasma-particles distribution, th-thermal, non-th-non-thermal, range-model radial range.
**Fiducial Model**

- $a = 0.94M$
- $\nu_{\text{obs}} = 3 \times 10^{11}$ Hz (1 mm)
- $i = 30^\circ$
- $M = 5 \times 10^{-9} M_\odot \text{yr}^{-1}$

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**SCN, Leung, Gammie, Book (2007)**

- Axi-symmetric GRMHD Simulations (256x256) w/ HARM
- $a = 0, 0.5, 0.75, 0.88, 0.93, 0.97$
- $R_{\text{out}} = 40M$, $P_{\text{max}}$ at $r=10-15M$
- Relativistic self-absorbed synchrotron and brems. rad. transfer
Black Hole Silhouette

- $a = 0.94$
- VLBI Base line = 8000km
- $\lambda = 1\text{mm}$

\begin{align*}
i &= 5^\circ \\
i &= 30^\circ \\
i &= 90^\circ
\end{align*}

"Infinite" Resolution

Earth-based VLBI Resolution
\[ a = 0.94M \]

- Relativistic beaming/boosting sensitive to inclination angle;
- Amplifies relative spectral importance of high-T inner region;
- Our model favored smaller inclinations or more “face-on” disks;

- Largest orbital velocities, temperatures and B-field increase with BH spin;
- Predict \( a < 0.88 \)
• Variability greatest at optically thin frequencies
• Weaker variability at 1mm consistent with flare events
• Time variation < spin variation
  • Hope for bracketing black hole spin
Towards Horizon-scale Observations:


- Observe at freq. where disk becomes transparent;
- ARO/SMT, CARMA, JCMT
- Baseline = 4700km
- FWHM \approx 4r_s
- Towards the “Event Horizon Telescope”

Shen et al (2005)

Radio VLBA

<table>
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<tr>
<th>Wavelength (cm)</th>
<th>FWHM Size (mas)</th>
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<tr>
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<tr>
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<td>10</td>
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<td>1</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Source-dominated

Scattering-dominated
\[ F_\nu(230\,\text{GHz}) = 3.4\,\text{Jy} \]

\[ T_i/T_e = 1, 3, 10 \quad i = 5^\circ, 45^\circ, 85^\circ \]

- Relativistic Monte Carlo, necessary for inverse-Compton emission (X-ray)
- Old ray-tracing method for images;
- Constrain time-averaged spectra to:
  - NIR, X-ray quiescent upper limits
  - sub-mm spectral slope
- Constrain time-averaged apparent sizes to mm-VLBI limits [Doeleman et al (2008)];


```
**Best-bet** Model:

\[ a = 0.94 \]

\[ \frac{T_i}{T_e} = 3 \]

\[ i = 85^\circ \]

- Size constraints favor large spin & inclination
- \( \frac{T_i}{T_e} = 1 \) ruled out by spectra

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Moscibrodzka, Gammie, Dolence, Shiokawa, Leung (2009)
```
Thin Disks
Thermal Spectral Fitting for BH Spin

\[ L = A R_{\text{in}}^2 T_{\text{max}}^4 \]

\[ R_{\text{in}} = R_{\text{in}} (M, a) \sim R_{\text{ISCO}} \]

\[ T_{\text{max}} \]

**TABLE 1**

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Observation Date</th>
<th>Satellite</th>
<th>Detector</th>
<th>( a_* ) (D05)</th>
<th>( a_* ) (ST95)</th>
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<td>GRO J1655−40</td>
<td>1995 Aug 15</td>
<td>ASCA</td>
<td>GIS2</td>
<td>~0.85</td>
<td>~0.8</td>
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<tr>
<td></td>
<td>1997 Feb 25−28</td>
<td>ASCA</td>
<td>GIS2</td>
<td>~0.75(^a)</td>
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<tr>
<td></td>
<td></td>
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<td>GIS3</td>
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<tr>
<td>4U 1543−47</td>
<td>1997 Feb 26</td>
<td>RXTE</td>
<td>PCA</td>
<td>~0.75(^a)</td>
<td>~0.65</td>
</tr>
<tr>
<td>4U 1543−47</td>
<td>1997 (several)</td>
<td>RXTE</td>
<td>PCA</td>
<td>0.65−0.75(^a)</td>
<td>0.55−0.65</td>
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<tr>
<td>4U 1543−47</td>
<td>2002 (several)</td>
<td>RXTE</td>
<td>PCA</td>
<td>0.75−0.85(^a)</td>
<td>0.55−0.65</td>
</tr>
</tbody>
</table>

\(^a\) Values adopted in this Letter.

**Shafee et al. (2006)**

**McClintock et al. (2006)**

**Wednesday, April 28, 2010**
Steady-state Thin Disk Models

Novikov & Thorne (1973)
- Stationary gravity
- Perfect radiator
- Work done by stress locally dissipated & radiated
- Zero stress at ISCO as boundary condition
- Luminosity as total liberation of binding energy up until plunge into ISCO

\[ L = \eta \dot{M} c^2 \]
\[ \eta = 1 - \epsilon_{\text{ISCO}} \]

Shakura & Sunyaev (1973)
\[ T^r_\phi = -\alpha P \quad P = \rho c^2_s \]
\[ t^r_\phi = -\alpha c^2_s \]

No stress at sonic point:
\[ \rightarrow R_{\text{in}} = R_s \simeq R_{\text{ISCO}} \]

Muchotzeb & Paczynski (1982)
Abramowicz et al. (1988)

Gammie (1999)
- Magnetized inflow model matched to thin disk
- Efficiency tied to mag. flux BC

Agol & Krolik (2000)
- Magnetic torques at ISCO can affect radiative efficiency
SCN, Krolik & Hawley 2009

- 3D GRMHD thin disk evolution
- Local cooling function to constrain $H \sim r$
  - Cool when cell because hotter than target temperature
- Save as emissivity for post-processing
- Fully relativistic radiative transfer calculation
- Assume cooling and transfer is optically thin for now
- $a = 0.9M$

$$L = \eta \dot{M} c^2 \quad \eta_{NT} = 0.143$$

$\Delta \eta / \eta = 6\%$

$\Delta T_{\text{max}} / T_{\text{max}} = 30\%$

$\Delta R_{\text{in}} / R_{\text{in}} = 80\%$

$T \rightarrow 0 : \Delta \eta / \eta = 20\%$

Suggests previous spectral fits may overestimate spin.

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- Cooling function: Drive to constant entropy
- $a = 0M$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Shafee et al. 2008</th>
<th>SCN, Krolik, Hawley 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a/M$</td>
<td>0</td>
<td>0.9</td>
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<tr>
<td>Azimuthal Extent</td>
<td>$\pi/4$</td>
<td>$\pi/2$</td>
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<td># of B Loops</td>
<td>2</td>
<td>1</td>
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<tr>
<td>Size of B Perturbation</td>
<td>2% (50%)</td>
<td>0%</td>
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<tr>
<td>$H/R$</td>
<td>0.05 - 0.07</td>
<td>0.07 - 0.13</td>
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<td>WHAM</td>
<td>HARM3D</td>
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<tr>
<td>Resolution</td>
<td>512x120x32</td>
<td>192x192x64</td>
</tr>
</tbody>
</table>
ThinHR: \[ H/R = 0.06 \]
912x160x64

\[ \rho \]

SCN, Krolik, Hawley 2010
ThinHR: \( H/R = 0.06 \)

\[ 912 \times 160 \times 64 \]

\( \rho \)

SCN, Krolik, Hawley 2010

\[ t/M = 0. \]
v1: (high resolution), Initial Disk:
- at target thickness
- with inner radius at 20M
- With Pmax at r=35M

v2: (low resolution), Initial Disk:
- at H/r ~ 0.15
- Inner radius at 15M
- Pmax at r=25M
Inflow Equilibrium

Defined to be when:
1) Accreted specific angular momentum \( (j_{\text{net}}) \) is steady;
2) Mass flux shows no trends in time over radius;

Remember these are turbulent MHD flows---they need not reach any kind of steady-state!
• No trend seen in Maxwell Stress
• Minor “sqrt” trend seen in spec. ang. mom.
  • Due to additional Reynolds stress for thicker disks

- De Villiers & Hawley code
- Vertical field with De Villiers & Hawley code
- Shafee et al 2008
Track MRI Resolution for all time!

Suggestions from local shearing box simulations:

- Sano et al. 2004
  \[ \frac{\lambda_{\text{MRI}}}{\Delta z} > 6 \]

- Davis, Stone, & Pessah 2009
  \[ \frac{H}{\Delta z} > 60 \]
"\[ t = 0 \]

\[ t = [12500 - 27350]M \]
• Resolution, spin, thickness study;
• Canonically use 4 loops of magnetic field;
• Various azimuthal extents and resolutions;
• Perform resolution in w/ grid sizes below ThinHR’s (reach same azimuthal grid size only);
• 10 to 44 cells per H/r ;

• Show trend toward NT with thickness;
  • Thinnest disks show ~2% deviations from NT even over spin
  • Larger deviations for the 1 Loop configuration

Open Questions:
• What are natural magnetic field topologies?
• What are the convergence criteria for global disk calculations?
• What luminosity profiles do these new models predict?
Variability
Coronal X-ray Variability

X-ray variability:
- is always dominated by corona;
- is dependent on spectral state;

\[ P \sim \nu^\alpha \]
\[-3 < \alpha < -1\]

AGN Markowitz et al 2003

X-ray Binaries Remillard & McClintock 2006

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**Variability Models**

\[ P \sim \nu^{\alpha} \]

Lyubarskii et al. 1997
- Total variability is a superposition of independent variability from larger radii modulating interior annuli on inflow (viscous) times scales

Churazov et al. 2001
- Outer radius of corona may be cause of (temporal) spectral slope

\[ \tau_a = \left[ \alpha \left( \frac{H}{r} \right)^2 \Omega_K \right]^{-1} \]

- Accretion rate modulation modeled as variability of \( \alpha \) (disk parameter)
- Predicts phase coherence at frequencies longer than inverse of inflow timescale

Armitage & Reynolds 2003
Machida & Matsumoto 2004
Schnittman et al. 2006
Reynolds & Miller 2009
- Used accretion rate or stress as dissipation proxies
- PLD breaks at local orbital frequency per annulus
- Composite PLD \( \rightarrow \alpha \simeq -2 \)

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SCN & Krolik 2009

- Use “thin disk” cooling rate in corona as emissivity
- Thomson Opacity model (e- scattering)
- Integrate to photosphere ($\tau = 1$)
- Include finite light speed effect
- Parameterized by accretion rate and inclination

$m = 0.003$

$i = 53^\circ$

$\dot{m} = 0.003$
$i = 29^\circ$

$m = 0.01$
- Dissipation approximately follows accretion rate
- Not all accretion rate modes are dissipated
- Variability at infinity follows local dissipation var.
• Mostly incoherent between adjacent radii and frequencies;
• Possible coherence at $\nu < 1/T_{\text{inflow}}(r)$
• Need longer runs to verify;

• Degenerate Result;
• No inclination angle effect;
• Consistent w/ observed power-law exponents
• See no QPOs, though we lie between LFQPO and HFQPO range
Degeneracy Explanation

\( \alpha_a > -2 \)

\( \alpha_c < -2 \)

\( \alpha_i \approx -2 \)

\( \alpha_b > -2 \)

\( \alpha_d < -2 \)

\( i \approx 0^\circ \)
Out-standing Issues in black hole accretion

Warped Disks  Fragile et al. 2007-2009

Initial Field Topology  Beckwith et al. 2008

- Poloidal
- Quadrupolar
- Toroidal

Jet  Jet  “No” Jet

McKinney & Blandford 2009

Gammie et al (unpub.)

Full 2π Evolutions
m=1 mode dominance

Image Unavailable

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Binary Black Hole Accretion
Circumbinary Black Hole Disks

Artymowicz & Lubow 1994
Armitage & Natarajan 2002,2005
MacFadyen & Milosavljevic 2008
Cuadra et al 2009
Schnittman & Kroll 2008

Hayasaki et al 2007

Figure 2 also shows how the secondary migrates in disks with initial accretion.

The long-wavelength wave appears to be associated with the tidal torques, while the inner disk is partially depleted by the gravitational torques, could then contribute to the surprisingly low levels of accretion inferred as-riche n environment.

The disk eccentricity precesses slowly in the prograde direction, which have radially infalling velocity components.

For test particles orbiting in the gravitational potential of a binary, the tidal effect is significant and can be modeled by introducing a perturbation in the potential.

The density profile is significantly shallower than expected in a nonaccreting, quiescent Galactic Nuclei from Black Hole Binaries.

The general theory of black hole accretion is based on the assumption that the accretion disk is a thin, optically thick, and geometrically thin disk, which is in hydrostatic equilibrium and is fed by radial inflow.

The disk is neither exactly an accretion nor a decretion disk, since the associated epicyclic motion is (mildly) supersonic.

The disk is radiatively stable, the dissipated energy will instead go into thermal energy.

The outer disk is unable to evolve on such a rapid timescale, begins to sweep up the gas in the inner disk, forming a narrow cavity.

As in the common envelope evolution of binary stars, the outer disk is exhausted, the dissipated energy will instead go into thermal energy.

This can be compared with the apsidal precession rate $\dot{\omega}_t$ which would be expected for a test particle orbiting in the gravitational potential of a binary.

The disk eccentricity precesses slowly in the prograde direction, which have radially infalling velocity components.

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O’Neill et al 2009  “Kicked” Thin Disk (near BH)

<table>
<thead>
<tr>
<th>ID</th>
<th>Type of Simulation</th>
<th>Resolution</th>
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<td>H5</td>
<td>Hydrodynamic</td>
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<td>M1</td>
<td>MHD</td>
<td>$768 \times 256 \times 32$</td>
<td>0.01</td>
</tr>
</tbody>
</table>

$L_{\text{brem}} = \int j_{\text{brem}} dV$

$j_{\text{brem}} \propto \rho^2 T^{1/2}$

- Newtonian Hydro/MHD
- Mass Loss
- Non-conservative Hydro
Summary & Conclusion:

- Moving towards fully self-consistent accretion models
- MRI-driven, uncooled accretion can match the full spectrum of Sgr A*
  - Vital for understanding its evolution and polarization
- Building the analytical tools to evaluate disks’ statistical steady-state
- Find that magnetic fields can dramatically change the “thin disk” picture within the ISCO
- MRI turbulence can explain the high frequency X-ray variability in AGN and low/hard state of galactic black holes
  - Emissivity is not trivially dependent on accretion rate

Future Work:

- 3D Sgr A* models
- Inclined disks;
- Further magnetic field topology studies;
- What are “natural” initial disk conditions?
- How does Unary Black Hole accretion physics carry over to Binary Black Holes?
version to Boyer-Lindquist coordinates was known, the test matter, we integrate the geodesic equation for given by the BSSN formulation (Shibata & Nakamura given a spin of particles were initially distributed uniformly throughout the cases with an isolated spinless black hole (solid black) relative speeds through collisions. We explored two initial velocity configurations for the typical binary black hole runs, the constant of motion

\[ E^2 - 2 \langle \mu \nu \rangle_{ij} \nu^i v^j = M^2, \]

where \( E \) is the energy, \( M \) is the mass, and \( \langle \mu \nu \rangle_{ij} \) is the energy-momentum tensor. In our simulations, we found that the Lorentz factors of collisions between particles

\[ \gamma = \frac{1}{\sqrt{1 - v^2/c^2}}, \]

where \( v \) is the speed of the particle and \( c \) is the speed of light. The data have been aligned with respect to these facts of the limitations of our simulation. For example, we have found quasi-stable orbits further out. In this case the binary motion are expected to alter significantly the energy and angular momentum of particles within the binary. More rapid orbits therefore are expected to maximized shortly before merger. This peak is highest when the excess of their initial orbital speeds. Given that the particle horizon and thus have acquired speeds considerably in the spinning case, the collisions throughout and near merge are in all cases considerably higher than in the isolated analogue. More rapid orbits therefore are expected to maximized shortly before merger because this is when the orbital speeds are reasonable fraction of particles is captured by the black hole.

\[ \gamma > \gamma_c \]

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Fig. 4.— (a) in “Stirring Test Particles” panel) and spinning (bottom panel) binaries. The merger time [M] for a variety of trajectories. The data have been aligned with respect to these facts of the limitations of our simulation. For example, we have found quasi-stable orbits further out. In this case the binary motion are expected to alter significantly the energy and angular momentum of particles within the binary. More rapid orbits therefore are expected to maximized shortly before merger. This peak is highest when the excess of their initial orbital speeds. Given that the particle horizon and thus have acquired speeds considerably in the spinning case, the collisions throughout and near merge are in all cases considerably higher than in the isolated analogue. More rapid orbits therefore are expected to maximized shortly before merger because this is when the orbital speeds are reasonable fraction of particles is captured by the black hole.

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\[ \gamma > \gamma_c \]
Palenzuela et al 2009

Mosta et al 2009

BBH Merger in Magnetic Field

GW

EM

\[ E_{EM}^{rad} \approx 10^{-15} \left( \frac{M}{10^8 M_\odot} \right)^2 \left( \frac{B}{10^4 G} \right)^2 \]

\[ L_{EM} \equiv \frac{E_{EM}^{rad}}{\tau} \approx 10^{-4} \left( \frac{B}{10^4 G} \right)^2 L_{Edd} \]

\[ \nu = 10^{-4} \left( 10^8 M_\odot / M \right) \text{Hz} \]
run G0. Since the orbital hang-ups of runs G1 and G2 result in the maximum bremsstrahlung luminosity measured at merger in a longer inspiral, the two BHs have more time to deplete the gas cloud described here, can have very low radiative efficiency. At the time of merger occur due to the error in locating the common, initially highly deformed, AH of the final BH. This is then less effective at channeling the gas into the BH, leading to a lower accretion rate visible in Fig. 9. Nevertheless, the gas in the vicinity of the binary and consequently lower accretion rates.

The discontinuities in the accretion rates observed in Fig. 8 can be explained by the more turbulent post-merger variability present in runs G2 and G3 (Fig. 8). The strength of the accretion curve as derived using the reflection symmetry about the plane of the binary of runs G2 and G3. In all cases, the gas is compressed into the front of the density wake which is then less effective at channeling the gas into the BH, leading to a lower accretion rate visible in Fig. 9. As mentioned before, the BHs are placed at a coordinate distance of 32 grid points while the 4 coarsest have radii of $10^{-2}$, while the 8 coarsest are $10^{1}$, $10^{2}$, and $10^{3}$. The spin modes for the BH are selected to be either aligned or anti-aligned with the orbital angular momentum. As mentioned before, the BHs are placed at a coordinate distance of 32 grid points while the 4 coarsest have radii of $10^{-2}$, while the 8 coarsest are $10^{1}$, $10^{2}$, and $10^{3}$. The spin modes for the BHs are selected to be aligned or anti-aligned with the orbital angular momentum. The spin value for a given system is then estimated from the minimum value that would yield the same total mass as that of the BBH systems discussed in this section. This is done by exploring all of the gas nuclei (AGN) nor for cooling by emission of radiation.
“Prototype”
Boosted Temperature

Farris, Liu, Shapiro 2009

Binary Bondi-Hoyle-Lyttleton Accretion
Similarly, the peak luminosity for case RA2 (peak luminosity shortly before the merger of an equal mass binary) is given by:

\[ L_{ff}^{\text{max}} \approx 3 \times 10^{37} n_1^2 T_6^{-3} M_6^3 \text{ erg s}^{-1} , \]

\[ L_{\text{syn}}^{\text{max}} \approx 3 \times 10^{43} n_1^2 T_6^{-3} \beta_1^{-1} M_6^3 \text{ erg s}^{-1} . \]

For case RA2, the characteristic synchrotron frequency to be:

\[ \nu_{\text{syn}}^{\text{max}} = \frac{230 \text{ MeV}}{1 + z} \text{ (RA2)} \]

And the characteristic bremsstrahlung frequency is:

\[ \frac{h \nu_{ff}^{\text{max}}}{1 + z} = \frac{100}{1 + z} n_1^{1/2} T_6^{-3/4} \beta_1^{-1/2} \text{ eV (RA2)} \]

Thus, we see that in these regimes, it is a good approximation to neglect energy losses due to radiation.

Thus during the final stages of the merger, the validity of our assumption of adiabatic flow begins to break down for the gas parameters near the horizon, we are primarily concerned about the region of the gas with density less than a certain threshold. We estimate that the flux from this emission will be predominantly in the synchrotron regime.

Given the bremsstrahlung luminosity calculated above, we estimate that the flux from this emission will be characteristic observed frequency produced in this region. For the gas parameters chosen for this study (the gas is optically thin. We can verify this assumption by estimating the optical depth. For the gas parameters we choose for this study (the gas is optically thin. We can verify this assumption by estimating the optical depth.
Sub-kpc Resolved Dual Nuclei

0402+379:
(Xu et al. 1994, Maness et al. 2004, Rodriguez et al. 2006):
- Radio, Elliptical galaxy host
- \( z = 0.055, \; d = 5 \) pc \( M \sim 10^8 M_\odot \)

NGC 6240: (Komossa et al. 2003)
- Optical ID: (Fried & Schulz 1983)
- HST, Ultra-lum. IR galaxy host
- \( z = 0.024 \), \( d = 0.5 \) kpc

Chandra/Komossa et al. 2003
First Spatially Resolved Binary Quasar: SDSS J1254+0846

Green et al.  arxiv1001.1738

$z = 0.44 \quad d = 21 \text{kpc}$

$\Delta v = 215 \text{km/s}$
OJ287: Pre-minor-merger??

Lehto & Valtonen 1996:

\[ M_1 = 1.7 \times 10^{10} M_\odot \quad M_2 = 10^8 M_\odot \]

\[ T_{\text{orb}} = 12.07 \text{yr} \quad T_{\text{precess}} = 130 \text{yr} \quad T_{\text{merge}} \approx 10^4 \text{yr} \]

\[ i_{\text{disk}} = 4^\circ \]

\[ e = 0.68 \]

Valtonen et al Nature 2008:

- 20 days earlier than expected
- Consistent to 10% predicted by radiation decay

Valtonen et al 2010:

Fit with 2.5PN expansion \( \leftrightarrow a = 0.28 \pm 0.05 M \)
Recoiled SBH?  
SDSS J0927+2943

Komossa, Zhou, Lu (2008)

\[ z = 0.713 \quad r_{BL} \sim 0.1 \text{pc} \]

\[ v_b - v_r = 2650 \text{km/s} \]

Other Explanations:

Another Similar Candidate:
SDSS J105041.35+345631.3  (Shields et al. 2009)

\[ v_{BL} - v_{NL} = 3500 \text{km/s} \]
Megevand et al 2009  Kicked Thick Disk (near BH)

- GR Hydro (not self-gravitating)
- Mass Loss and Kicks
- Conservative Hydro