General Relativistic Mergers of SMBH in Astrophysical Environments:

A Fair and Balanced Review

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Single and Double Black Holes in Galaxies
University of Michigan
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But first, more on BH super-kicks

FIG. 7 (color online). The magnitude $|k|$ of the recoil velocity in km/s as a function of the polar angle $\phi$ between the spin $b$ of black hole $B$ and the orbital angular momentum in the configuration of case 4. The square points correspond to the simulations listed in Table XVI, while the green (dotted), red (dashed), and blue (solid) curves show the best fits of Eq. (48c) to these simulations using terms derived from expanding Eqs. (48a) and (48b) to first, second, and third order in $a$, respectively. The error bars correspond to $1\sigma$ errors of 15% in the kick magnitudes $|k|$ reported by Herrmann et al. [7] as the accuracy of their simulations.
The Grand Challenge of Modeling SMBH Mergers

- Galactic mergers scales: $10^2$ kpc scales
- BH binaries scales: few pc when binding and AU near coalescence
- How do BHs reach the gravitational wave inspiral regime?
- What is the role of the environment?

Tremendous computational modeling grand challenge!

$10^5$ pc $\leftrightarrow$ $10^{-5}$ pc
Late Inspiral and Merger of SMBHs

- The tools of numerical relativity are available, but
- Simulations are expensive: ~2 weeks for ~10 orbits
- Hydro cost ~ 70%
- “Realistic” initial conditions are very difficult construct.
SMBH mergers in environments with:

**Tests Particles**

**Maxwell Fields**
Neilsen, et al arXiv:1012.5661
Palenzuela, Bona, Lehner, Reula, CQG, 28, 134007 (2011)

**Hot Gas**
Farris, Liu, Shapiro, Phys Rev D, 81, 084008 (2010)

**Circumbinary Disks**
Bode, Bogdanovic, Haas, Healy, PL, Shoemaker arXiv:1101.4684
Farris, Liu, Shapiro, Phys Rev D, 84, 024024 (2011)
Modeling flows around merging BBH


- **Simulations:** Track geodesic motion of particles in the dynamical spacetime of merging BHs:
- **Goal:** Identify high speed outflows and "particle collisions," hinting where shocks would develop.
- **Setup:** 75,000 particles, in random "isotropic" and random "orbital" configurations.
Flare!

“orbital”

Single BH

Non-rotating BBH

Spinning BBH

“isotropic”

Flare!
SMBH Mergers Surrounded by EM Fields

(Palenzuela, Lehner Liebling 09a, 09b, 10; Mösta+ 09)

• Unlikely that this EM emission can be detected directly.
• The EM emission could be observable indirectly from its effects on the BH accretion rate.
Blandford & Znajek: E&M flux extracts the BH’s rotational energy

Jets are formed even for non-spinning BHs!

(a) $-11.0 \, M_\odot$ hrs  
(b) $-3.0 \, M_\odot$ hrs  
(c) $4.6 \, M_\odot$ hrs  
(d) $6.8 \, M_\odot$ hrs  

Single BH
What is the environment during the late inspiral and merger of BBHs?

• Not well known at scales < 0.01 pc
• Two physically motivated scenarios depending on the balance of heating and cooling:

  **Radiatively Inefficient Hot Gas:** If cooling is inefficient, the BBH is immersed in a pressure supported, geometrically thick torus or cloud. $kT \sim 10^{-1}$-100 eV (UV, optical)

  **Circumbinary Disk:** If cooling is relatively efficient, the gas settles into a rotationally supported geometrically accretion disk around the BBH. $kT \sim 0.1$–1 MeV (hard X-ray, $\gamma$-ray)

  **Chaotic Central Accretion:** sequence of randomly oriented disks.
SMBH Mergers Surrounded by Gas

Relativistic Mergers of Supermassive Black Holes and their Electromagnetic Signatures

Binary Black Hole Mergers in Gaseous Environments: "Binary Bondi" and "Binary Bondi-Hoyle-Lyttleton" Accretion
Farris, Liu, Shapiro, Phys Rev D, 81, 084008 (2010)
We focused first on the hot gas cloud

Binary is placed in a gas cloud which has constant density and temperature at infinity, governed by a gamma-law EOS

\[
\begin{align*}
V_\infty & = 0.0 - 0.2 \\
T & \approx 10^{11} K \\
\Gamma & = 4/3 - 5/3 \\
n & \approx 10^{11} \text{ cm}^{-3} \\
M_b & = 10^6 M_\odot
\end{align*}
\]

Farris, Liu & Shapiro

\[
\begin{align*}
T & \approx 10^{10} - 10^{12} K \\
\Gamma & = 5/3 \\
n & \approx 10^{10} \text{ cm}^{-3} \\
M_b & = 10^7 M_\odot
\end{align*}
\]

Bode, Bogdanovic, Haas, PL, Shoemaker

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Bremsstrahlung luminosity

\[ L_{\text{Brem}} \left( 10^{45} \text{ erg/s} \right) \]

\[ s_1 = s_2 = 0.6 \]

rise

sudden drop off

quasi-periodic variability

(Bode+ 09)

(Farris+ 09)
EM & GW emission

$s_1 = s_2 = +0.6$

$t(M)$

$s_1 = s_2 = +0.4$

$CHI$

$i = 0$
$i = 30^\circ$
$i = 45^\circ$
$i = 60^\circ$
$i = 90^\circ$

$CM1$

$CL1$

$-500$ $-450$ $-400$ $-350$ $-300$ $-250$ $-200$ $-150$ $-100$ $-50$

$t(M)$

$0.95$ $0.96$ $0.97$ $0.98$ $0.99$ $1.00$ $1.01$ $1.02$ $1.03$ $1.04$

$CH2$

GW
Dependence on Mass Ratios and Spins

\[ q = 1 \quad q = \frac{1}{2} \quad \text{Generic} \]
Merger of SBHs in a circumbinary disk

- Late inspiral and merger (BH separation 8M)
- Equal and unequal mass, spinning BHs
- Initially, orbital plane in the plane of the disk
- Pressure supported disk, h/r = 0.2, 0.4 inner edge at 16M
- Not modeled: AGN feedback, radiative cooling, magnetic fields, viscosity.

\[ \rho(R, \theta) = \rho_c \exp \left( - \frac{\cos^2 \theta}{2(h/r)^2 \sin^2 \theta} \right) \]

\[ p(R, \theta) = \frac{M R (h/r)^2 \sin^2 \theta}{(R - 4M)^2} \rho(R, \theta) \]

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Accretion Rate Reversal
$M_1 > M_2$

Bode, Bogdanovic, Haas, PL, Shoemaker
Las Películas

Hot Cloud

Circumbinary Disk
Conclusions

• Hot accretion flow:
  – Correlated EM+GW chirp-like oscillations.
  – Luminosity drop-off a robust signature.

• Circumbinary disk:
  – Binary promptly clears the gas from the central region.
  – Luminosity from the gap region in the BBH case is comparable to that of a single BH.
  – The BBH merger does not seem to perturb the disk.

![Graph showing luminosity vs. time for different mass ratios](image)
Open Questions

• In the absence of information regarding the environment surrounding the binary, our best option is to explore a range of scenarios and look for characteristic features (flares, variability).

• These are prototype simulations. Follow-up work is needed to explore more astrophysically plausible configurations (MHD, cooling, radiation)

• The marriage between GR and Hydro needs to be improved (e.g. AMR, implicit-explicit time-stepping)

• To expand the dynamical range of simulations, we need to consider hybrid Post-Newtonian + Gen Rel evolutions