Magnetized Accretion onto Inspiraling Binary Black Holes: II. Disk Dynamics

Watch out for our paper next week on arXiv.org !!

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How do we find close \((a \lesssim 1000M)\) SMBBHs with EM waves?

- Need superb theoretical predictions to weed through high-cadence all-sky survey data (e.g., PanSTARRS, LSST) and differentiate them from solo AGN;

- Improbability of spatially resolving a “close” pair of SMBHs forces us to look in other ways:
  - Spectral shape and evolution;
  - Temporal variability;
  - Polarization;
  - Extended structure: e.g., double jets, unique outflows;
    - Need sophisticated analysis tools (e.g., radiative transfer);

- We will first consider binaries of \(q = M_2/M_1 \approx 1\)
  - Not as likely as \(q = 1/10\);
  - May be best case for seeing both simultaneously (e.g. emission onto primary may dominate that due to smaller secondary);
  - Fundamental starting point from which to explore parameter space;
  - Easier to calculate;
## Prior Work:

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<th>Gravity Model</th>
<th>Matter Model</th>
<th>Code</th>
<th>Algorithm</th>
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<tr>
<td>Farris++</td>
<td>GR</td>
<td>Hydro Cloud (cold) Hydro Disk</td>
<td>UI’s Cactus</td>
<td>Eulerian, HRSC</td>
<td>YES</td>
<td>$t_{disk} &gt; t_{shrink}$</td>
</tr>
<tr>
<td>Bode++</td>
<td>GR</td>
<td>Hydro Cloud (hot) Hydro Disk</td>
<td>ET/Cactus</td>
<td>Eulerian, HRSC</td>
<td>YES</td>
<td>$t_{disk} &gt; t_{shrink}$</td>
</tr>
<tr>
<td>Palenzuela++</td>
<td>GR</td>
<td>EM &amp; Force-free plasma</td>
<td>HAD &amp; Whisky (w/ Mosta)</td>
<td>Eulerian, FD</td>
<td>YES</td>
<td>(no disk)</td>
</tr>
<tr>
<td>Ours</td>
<td>2.5PN</td>
<td>(cool) MHD Disk</td>
<td>HARM3d</td>
<td>Eulerian, HRSC</td>
<td>NO (not yet)</td>
<td>$t_{disk} \leftrightarrow t_{shrink}$</td>
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<td>MacFadyen &amp; Milosavljevic</td>
<td>Newtonian, self-gravity</td>
<td>(cold) Hydro Disk</td>
<td>FLASH</td>
<td>Eulerian, HRSC</td>
<td>NO</td>
<td>$t_{disk} &lt; t_{shrink}$</td>
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<tr>
<td>Cuadra++</td>
<td>Newtonian</td>
<td>(cold) Hydro Disk</td>
<td>Gadget-2</td>
<td>SPH</td>
<td>NO</td>
<td>$t_{disk} &lt; t_{shrink}$</td>
</tr>
<tr>
<td>Shi++</td>
<td>Newtonian</td>
<td>(cool) MHD Disk</td>
<td>Zeus</td>
<td>Eulerian, FD</td>
<td>NO</td>
<td>$t_{disk} &lt; t_{shrink}$</td>
</tr>
</tbody>
</table>

**Acronyms:**  
- **UI** = Univ. of Illinois  
- **ET** = Einstein Toolkit  
- **HAD** = Hydro. ADaptive mesh refinement  
- **HRSC** = High-Resolution Shock-Capturing  
- **FD** = finite difference
Newtonian Simulations:

- Excellent for binary separations: $t_{\text{inflow}} \ll t_{\text{merger}}$
- Useful for understanding disk’s history and prior condition before late phase of inspiral;
- Codes are relatively cheap -- can evolve for $O(100)$ orbits
- Invalid for small separations, non-relativistic MHD physics

NR Simulations:

- Have ability to simulate dynamics without approximation;
- Produced a recent surge of results:
  - Hot gas accretion: Farris++2009, Bode++2009
  - Inviscid hydrodynamic circumbinary disks: Bode++2011, Farris++2011
  - EM and FF plasma Jets: Palenzuela++2009-2010, Mosta++2009
  - Most of luminosity is from the immediate vicinity of the BHs
- NR GRMHD is nascent;
- Evolutions usually limited to only $O(10)$ orbits: $t_{\text{inflow}} \gg t_{\text{merger}}$
  - Not long enough for disks to settle into quasi-steady state before merger happens;
  - Results may be strongly dependent on initial conditions;
Harm3d

- Harm3d written largely independent of chosen coordinate system (covariance)
  - GRMHD code
- ✓ Already used for many single BH disk runs
- ✓ Efficiency through static Fixed Mesh Refinement (FMR);
  - Added support for time-dependent metrics;

Grid:

- Resolves the MRI, spiral density waves
- Full azimuthal extent (resolve dominant m=1 mode)
- \( N_r \times N_{th} \times N_{ph} = [300, 160, 400] \)
- ✓ Spherical coordinates conserve ang. mom. well
- ✓ FMR eliminates excessive dissipation at AMR boundaries
- ✗ BHs not in domain, grid's extent: \( r = [0.75, 13]a_0 \)

Model Setup

- Cool to constant entropy s.t. \( H/r=0.1 \)
- ✓ Radiation predictions consistent with disk's thermodynamics;
  - Pressure maximum \( r_p = 5a_0 \)
  - Poloidal Magnet field following density contours
  - Disk extended over \( r = [3a_0, 10a_0] \)
  - Near “Equilibrium” Disk solution using time-averaged spacetime
The “Lump”

\[ \Sigma(r, \phi) \equiv \int d\theta \sqrt{-g\rho / \sqrt{g_{\phi\phi}}} \]

Newtonian MHD: Shi++2012
The “Lump”

McKinney++2012

Dolence++2012

Ours

Single BH Disks
Surface Density

\[ \Sigma(r, \phi) \equiv \int d\theta \sqrt{-g} \frac{\rho}{\sqrt{g_{\phi\phi}}} \]
Surface Density

\[ \Sigma(r, \phi) \equiv \int d\theta \sqrt{-g} \rho / \sqrt{g_{\phi \phi}} \]
Binary-disk separation when:

\[ t_{\text{gr}} = \frac{5}{64} \left( \frac{a}{M} \right)^4 \frac{(1+q)^2}{q} M \ll t_{\text{in}} = \alpha^{-1}(H/r)^{-2}(d \ln \Sigma/d \ln r)^{-1} \Omega^{-1} = \alpha^{-1}(H/r)^{-2}(d \ln \Sigma/d \ln r)^{-1}(r/r_g)^{3/2} M. \]

Commonly Imagined:

\[ a_{\text{dec}} \simeq 70M \left( d \ln \Sigma/d \ln r \right)^{-2/5} \left( \frac{\alpha}{0.01} \right)^{-2/5} \left( \frac{H/r}{0.15} \right)^{-4/5} \]

Ours:

\[ a_{\text{dec}} \simeq 10M \left( d \ln \Sigma/d \ln r / 6 \right)^{-2/5} \left( \frac{\alpha}{0.2} \right)^{-2/5} \left( \frac{H/r}{0.15} \right)^{-4/5} \]
\[ \frac{dL}{dr/a_0} = 4 \times 10^{-4} (\dot{M} / 0.01)(r/a_0)^{-2} \Sigma_0 a_0. \]

\[ L_{\text{disk}} \approx 2.4 \times 10^{40} (\dot{L} / 10^{-3}) M_6 \tau_0 \text{ erg/s}. \]

\[ T_{\text{eff}} \approx 4 \times 10^4 (\dot{L} / 10^{-3})^{1/4} M_6^{-1/4} \tau_0^{1/4} \text{ K}. \]

\[ \tau_0(r = 20M) \approx 2 \times 10^3 (\alpha / 0.1)^{-1} (\eta / \dot{m}) \]

--- peak in UV assuming thermal emission

Excess from dissipation of bin. torque work
Variability

FFT close-up

$r_{\text{peak}} \approx 2.3a$

$r_{\text{lump}} \approx 2.5a$

$\Omega_K(r_{\text{lump}}) = 1.47\Omega_{\text{bin}}$

(r, ω) space

integrated over radius
Origin of Variability

\[ \omega_{\text{peak}} = 2 (\Omega_{\text{bin}} - \Omega_{\text{lump}}) \]

\[ 1 < \frac{\omega_{\text{peak}}}{(\Omega_{\text{bin}} - \Omega_{\text{lump}})} < 2 \]

\[ 0 < \frac{M_2}{M_1} < 1 \]

May be obfuscated by "low-pass filter" of disk's opacity and cooling rate:

\[ 0.24 \left( \frac{200}{\tau_0} \right) \geq f_{\text{supp}} \geq 0.12 \left( \frac{200}{\tau_0} \right) \]

\[ 0.32 \left( \frac{\alpha}{0.3} \right) \geq f_{\text{supp}} \geq 0.16 \left( \frac{\alpha}{0.3} \right) \]

Ray-tracing will help determine quality of signal
Summary:

(Though I don’t know what the next talks will include, I can safely say the following as this is fortuitously one of the first talks in this section)

- Evolve a circumbinary disk with grMHD for the first time;
- Observe binary/disk decoupling dynamically for the first time;
- Find first nontrivial periodic EM signal: binary/lump interaction;
  - It would not have been found without evolving for >70 orbits;
- Luminosity is characteristic of AGN with excess at edge of gap due to dissipated binary torque work, though small surface density within the gap leads to luminosity deficit there;
- Confident in our results as we agree well with prior Newtonian simulations;
Extra Slides
Binary Torque Density

\[ \frac{dT}{dr} = \int \sqrt{-g} T^{\mu \nu} \Gamma_{\mu \nu} d\theta d\phi \]
Binary Torque Density

\[ \frac{dT}{dr} = \int \sqrt{-g} T^{\mu \nu} \Gamma_{\mu \nu \phi} d\theta d\phi \]
Accretion Rate:

- Both decrease over time
- \( \dot{M}_{\text{Run1}} > 0.3 \dot{M}_{\text{Run2}} \)
- Decrease due largely to torques
- Decrease of Run1 also due to decoupling
Angular Momentum Transport

\[ \partial_r \partial_t J = \frac{dT}{dr} - \{ \mathcal{L} u_\phi \} - \partial_r \{ M^r_\phi \} - \partial_r \{ R^r_\phi \} - \partial_r \{ A^r_\phi \} \]

\( = \text{[Bin.]} - \text{[Rad.]} - \text{[\nabla Maxwell]} - \text{[\nabla Reynolds]} - \text{[\nabla Adveced]} \)
Binary Torque Density

\[ \frac{dT}{dr} = \int \sqrt{-g} T_{\mu \nu} \Gamma^{\mu \nu}_{\mu \phi} \, d\theta d\phi \]
Binary Torque Density

\[ \frac{dT}{dr} = \int \sqrt{-g} T^{\mu \nu} \Gamma_{\mu \nu} \phi \, d\theta d\phi \]

Shi++ 2012

\[ \times 0.68 \]

\[ \times 0.25 \]
Surveying effects of $r_{in}$

$\ln(e_{disk})$

$t(\Omega_{bin}^{-1})$

Shi++2012
MRI Resolution


\[ Q^i = \frac{2\pi |b^i|}{\Delta x^i \Omega(r) \sqrt{\rho h + 2p_m}} \]

\( Q^\theta > 10 \)

\( Q^\phi > 25 \)
Plasma Beta parameter = \( \frac{p_{gas}}{p_{mag}} \)