Simulations of Disk Accretion onto Black Hole Binaries

Brian D. Farris [1,2] Zoltan Haiman [2] Paul Duffell [1] Andrew MacFadyen [1]

[1] Center for Cosmology and Particle Physics, New York University

[2] Department of Astrophysics, Columbia University

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Physical Picture

- All bulge galaxies have SMBH at center with $M \sim 10^5 - 10^9 M_\odot$
- Galaxy mergers $\rightarrow$ formation of massive BH binary in merged remnant.
- Separation decreases by:
  1. dynamical friction
  2. gravitational slingshot interactions
  3. gravitational radiation
- The Final Parsec Problem is Not a Problem!
- Circumbinary disk forms

Motivation

- GWs from SMBH binaries detectable by eLISA during inspiral.
- May be detectable by Pulsar Timing Arrays for massive ($\sim 10^8 - 10^9 M_\odot$) binaries at $z \approx 1$.
- Gaseous accretion flow around binary may be a source of detectable EM radiation
- Help with source localization
- Standard Sirens (distance from GWs, redshift from EM)
- Learn about SMBH merger rates.

General Picture

- Viscous stresses in the disk transport angular momentum outward and allow gas to migrate inward
- Tidal torques from the binary add angular momentum and drive gas outward
- Viscous stresses balance balance tidal torques at inner edge of disk ($r_{edge} \approx 2a$)
- Binary carves out a low-density cavity surrounded by a circumbinary disk.
- Quasi-equilibrium state can be maintained provided $t_{vis} \ll t_{gw}$ (pre-decoupling epoch)
- When $t_{gw} \lesssim t_{vis}$ (i.e. GW dominated regime), binary inspiral must be included in simulations.
- We focus on pre-decoupling epoch.

Questions

- How hollow is the cavity? Is the accretion rate suppressed by the presence of a binary?
- Does the binary leave an imprint in the accretion rate?
- How is the accreted mass divided between the primary and the secondary?
- How are continuum spectra modified by presence of a binary?

Previous Work

1D

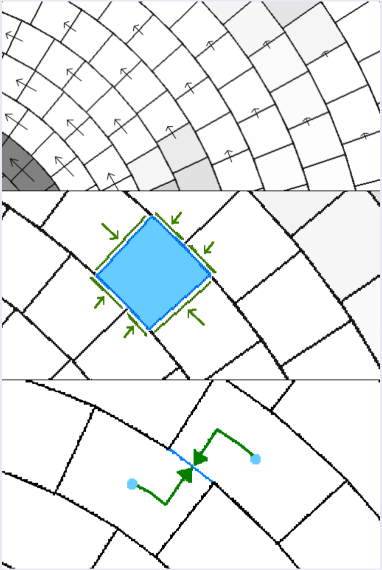
- Examples:
  - Goldreich & Tremaine 1980
  - Artymowicz & Lubow 1994
  - Milosavljević and Phinney 2005
  - Haiman et al. 2009
  - Tanaka & Menou 2010
  - Liu & Shapiro 2010
  - Kocsis et al. 2012
  - Tanaka 2013
- Use approximate angle-averaged tidal torque formulae.
- Useful for probing qualitative features of accretion.
- Fails to capture important, nonaxisymmetric features such as accretion streams.

2D

- Newtonian
  - MacFadyen & Milosavljević 1980
  - Cuadra et al. 2009
  - Roedig & Sesana, 2012
  - D'Orazio et al. 2012
  - Farris et al. 2013
- Useful for predecoupling, widely separated binaries.
- Can accomodate high res., many orbits.

3D

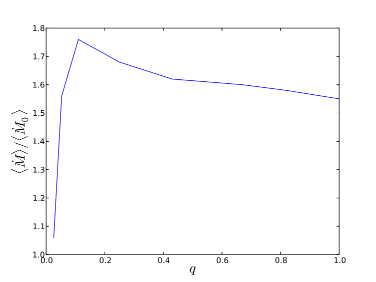
- Newtonian:
  - Shi et al. 2012
  - Roedig et al. 2012
- Relativistic:
  - Bode et al 2011
  - Farris et al. 2012
  - Noble et al. 2012
  - Giacomazzo et al. 2012
- Computationally expensive.
- Often require excised inner regions, thick disks, short simulations, etc.



DISCO - Duffell & MacFadyen 2012, 2013

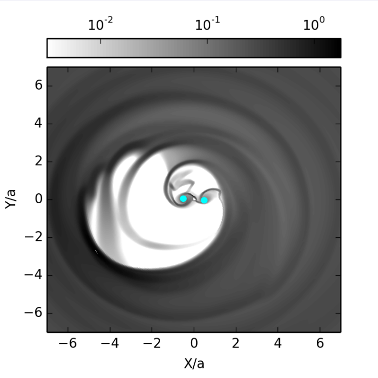
- Solves (Magneto)Hydrodynamics equations
- Uses conservative, shock-capturing finite-volume methods
- Effectively “Lagrangian”, as cells are able to move with fluid
- Minimizes advection errors, allows for longer timesteps

- For all mass ratios, accretion rate is enhanced relative to that of single BH.
- Consistent with some previous studies (e.g. Shi et al. 2012)
- Consensus emerging that accretion is **not** significantly reduced by presence of binary.
- Simulations needed to verify that this holds at smaller h/r.
- $\langle \dot{M} \rangle / \langle \dot{M}_0 \rangle$ approaches 1 for small q, as expected.

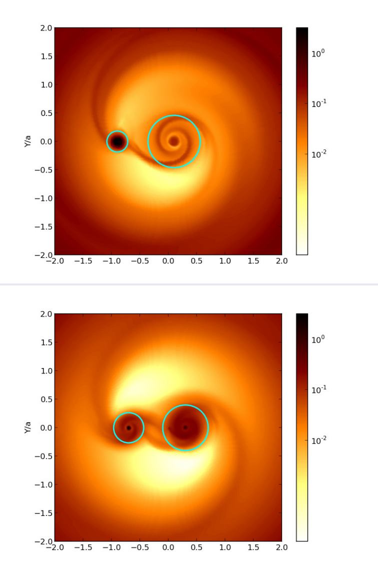


Growth of disk eccentricity

- Eccentric inner cavity for large mass ratio binaries seen in many calculations, e.g.
  - MacFadyen and Milosavljević 2008
  - D'Orazio et al. 2012
  - Shi et al. 2012
  - Noble et al. 2012
  - Farris et al. 2012
- A fraction of gas in each stream does not accrete onto BH, but rather is flung outward.
- This fraction impacts cavity wall on the opposite side from which it entered.
- If one stream is slightly larger it will push the opposity wall more, weakening the opposite stream.
- ⇒ the imbalance grows.



Artymowicz & Lubow 1994 (cyan circles)



Minidisk timescale

Accretion timescale

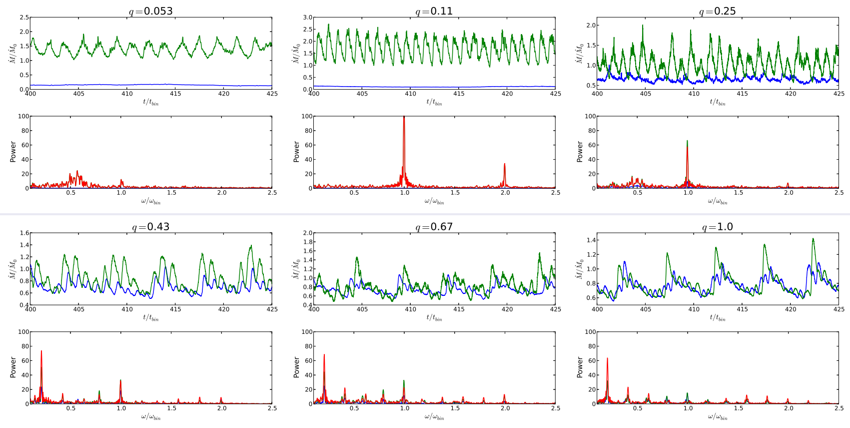
$$t_{vis,md} = \frac{2}{3}\frac{r_i^2}{\nu_i}$$

$$= 42\left(\frac{\alpha}{0.1}\right)^{-1}\left(\frac{h/r}{0.1}\right)^{-2}\left(\frac{r_{md}}{0.25a}\right)^{3/2}\left(\frac{q}{0.1}\right)^{-1/2} t_{bin}$$

$t_{vis,md} > t_{bin} \Rightarrow$ minidisks are persistent.

caveats

- We have assumed $h/r \sim 0.1$ everywhere, including minidisks. If they are actually much hotter the accretion timescale is shortened.
- We have assumed $\alpha = 0.1$ everywhere. MHD simulations have indicated it may be larger near inner disk edge, and possibly inside minidisks as well.
- Binary eccentricity may reduce sizes of minidisks, leading to shorter accretion timescale.

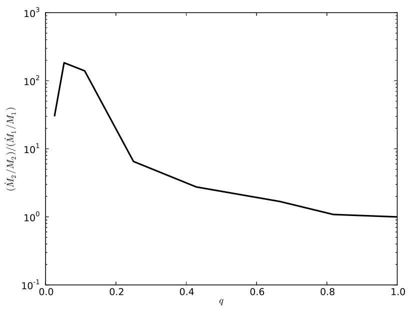


$q = 0.053$
$q = 0.11$
$q = 0.25$
$q = 0.43$
$q = 0.67$
$q = 1.0$
$\dot{M}/\dot{M}_0$
t/t_{bin}
Power
ω/ω_{bin}

$$\frac{dq}{dt} = \frac{d}{dt}\left(\frac{M_2}{M_1}\right) = \frac{M_2}{M_1}\left(\frac{\dot{M}_2}{M_2} - \frac{\dot{M}_1}{M_1}\right)$$

$$\dot{M}_2/M_2 > \dot{M}_1/M_1 \Rightarrow q \text{ increasing}$$

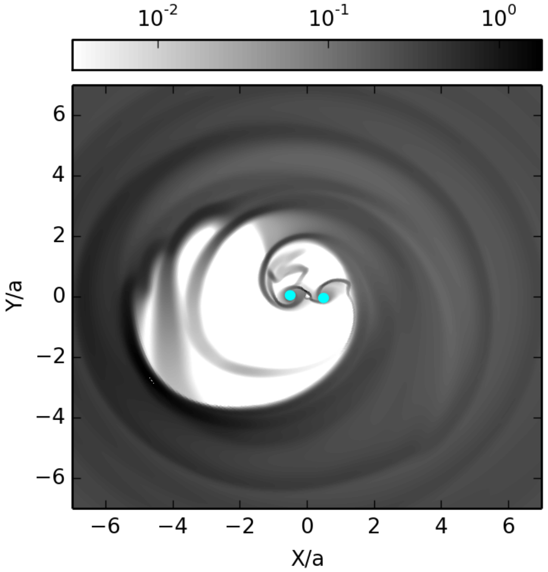
- Ratio > 1 for all cases. Binary driven toward equal mass.
- Consistent with previous studies (Hayasaki et al. 2007, Cuadra et al. 2009, Roedig et al. 2011,2012, Hayasaki et al. 2012)
- Possible that ratio < 1 for q less than some q_0, leading to bimodal mass-ratio distribution.



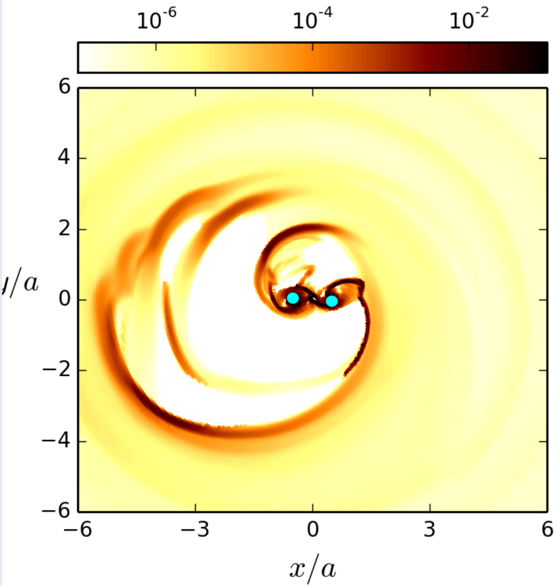
- Dynamics are sensitive to t_{vis} of minidisks
- Isothermal prescription locks h/r to match that of circumbinary disk
- Need to self-consistently balance viscous heating and shock heating with radiative cooling
- Optically thick disk $\Rightarrow q_{cool} = \frac{4\sigma}{3\tau} T^4$
- Assume electron scattering opacity
- Neglect radiation pressure $\Rightarrow P = (\Sigma/m_B)kT$
- Include viscous heating source term in energy evolution equation
- Test that scheme can reproduce Shakura-Sunyaev solution

show movie

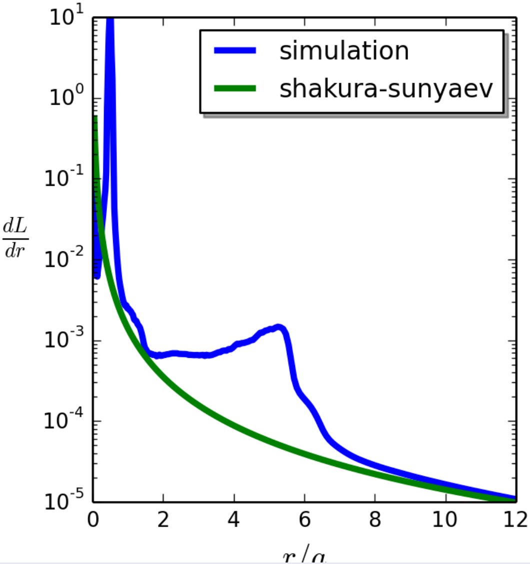
Density



Emission - 2D

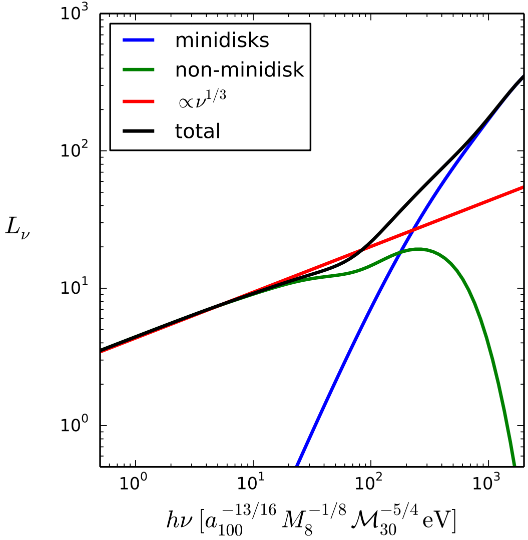


Emission 1D



simulation
shakura-sunyaev
$\frac{dL}{dr}$
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
2
4
6
8
10
12
r/a

spectrum



minidisks
non-minidisk
$\propto \nu^{1/3}$
total
L_ν
10^3
10^2
10^1
10^0
10^0
10^1
10^2
10^3
$h\nu\ [a_{100}^{-13/16}\, M_8^{-1/8}\, \mathcal{M}_{30}^{-5/4}\, \mathrm{eV}]$

Summary

- First simulations of circumbinary disk accretion using moving-mesh, finite-volume code.
- $\dot{M}$ onto binary not reduced. Gas efficiently enters cavity along streams.
- For each mass-ratio, persistent mini-disks are formed. Accretion timescale of mini-disks exceed binary orbital timescale.
- Mini-disk sizes in rough agreement with analytic predictions (Artymowicz & Lubow 1994).
- Significant periodicity in $\dot{M}$ for $q \gtrsim 0.1$.
- Binary torques can excite eccentricity in inner disk and create overdense lump. Orbital frequency of lump can dominate $\dot{M}$ periodograms.
- For each mass-ratio considered, accretion rate onto secondary is large enough to cause q to increase.
- Emission can be enhanced in cavity region relative to single BH case
- Continuum spectra steepen in X-rays due to hot emission from minidisks and streams

Extra Slides

Setup

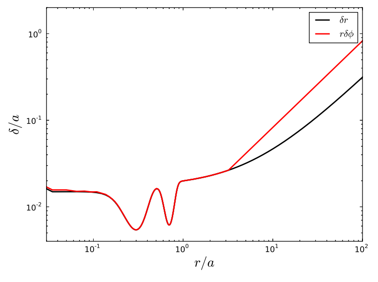
- Keep aspect ratio of cells ≈ 1, concentrate resolution near BHs.
- α-law viscosity $\nu = \alpha c_s h$, with $\alpha = 0.1$.
- include cavity in computational domain, treat accretion by adding sink term to continuity equation:

$$\left(\frac{d\Sigma}{dt}\right)_{sink,i} = -\frac{\Sigma}{t_{vis,i}}$$

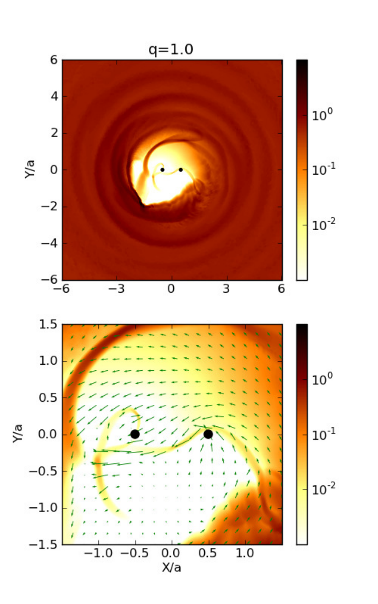
- Run simulation for longer than a viscous time at the cavity edge, so that quasi-equilibrium state is reached.

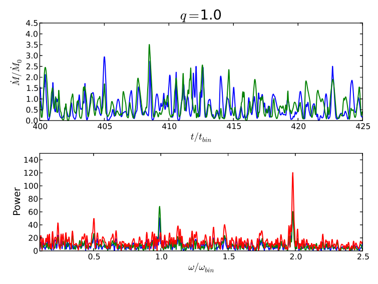
$$t_{sim} \gtrsim t_{vis}(r_{edge}) \sim 300 \left(\frac{r_{edge}}{2a}\right)^{3/2} t_{bin}$$

- Vary mass ratio in range $0.026 \leq q \leq 1.0$.



shorten t_{acc} in sink prescription by factor of 100

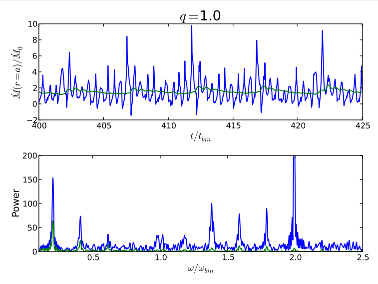




Conclusion

- The minidisk accretion timescale is extremely important in determining the periodicity of $\dot{M}$.
- Total time-averaged accretion rate mostly unchanged.

- Compare actual accretion rate with rest mass flux through surface at $r = a$.
- Flux through $r = a$ much more variable.
- Time averaged $\dot{M}$ is unchanged (expected for quasi-steady state).
- Exaggerates $\Omega = 2\Omega_{bin}$ component.



Viscosity Code Test

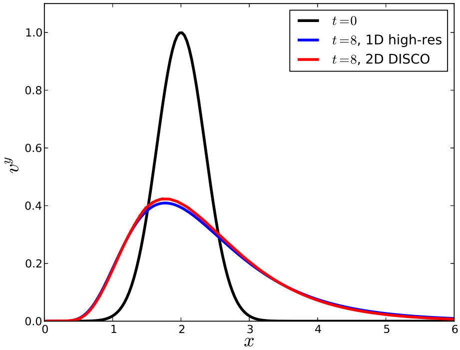
- "Cartesian" test performed on cylindrical grid
- Test balance of all viscous forces and hydrodynamic fluxes and source terms in all directions.

initial state

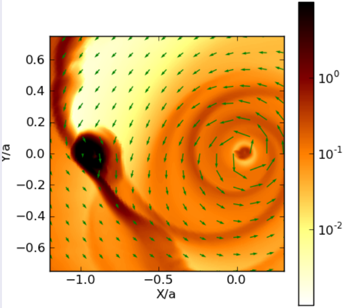
$$\begin{aligned} \rho &= 1.0 \\ P &= 0.1 \\ v^x &= 0 \\ v^y &= \exp\left(-\frac{(x-x_0)^2}{\sigma^2}\right) \end{aligned}$$

viscosity

$$\nu = \nu_0 \frac{\Gamma P}{\rho} x^2$$

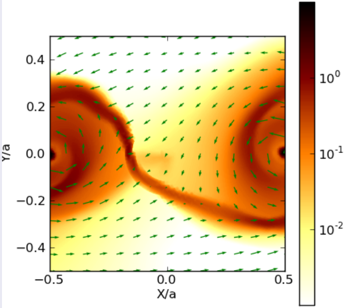


q=0.053

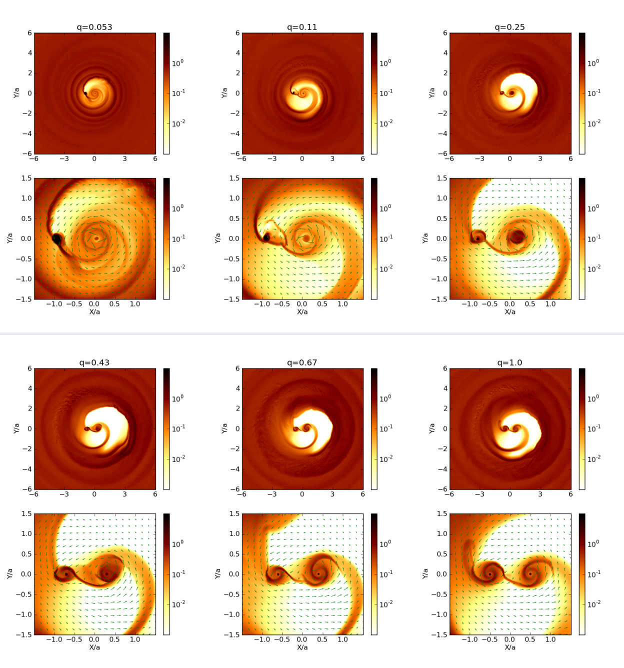


0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
Y/a
−1.0
−0.5
0.0
X/a
10^0
10^{-1}
10^{-2}

q=1.0



0.4
0.2
0.0
−0.2
−0.4
Y/a
−0.5
0.0
0.5
X/a
10^0
10^{-1}
10^{-2}


q=0.053
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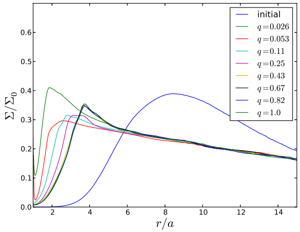
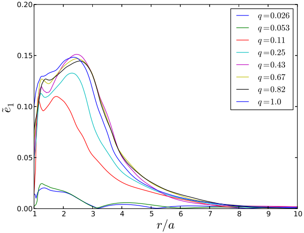
q=0.25
q=0.43
q=0.67
q=1.0
Y/a
X/a

Surface Density



Eccentricity



cavity size and max eccentricity vs q