Galaxies frequently collide and merge
Circumbinary disk
Periodic accretion
EM variability & GWs for pulsar timing arrays

Gravitational waves (LISA)

Precursor burst

GW dissipation

Mass-loss - shocks

Recoil - shocks

Accretion afterglow

-10^6 yr

-10 yr

-1 day

+1 hr

+1 wk

+1 mo

+10 yr
What should we expect to see

- Doppler effect (talks on Monday)
  - velocity offset in AGN broad lines
  - time variable broad lines
- Periodic accretion
- Gap/minidisks, gas pile up
  - missing blue/UV component
  - optical/infrared bump
  - features in X-ray iron lines
- Gravitational waves (pulsar timing, LISA)
  - Gas affects binary migration → GW spectrum
  - eccentricity → GW spectrum
Why is this an open problem?

- Gas + radiation
- Disk-satellite interaction
- Vast timescales
- Vast spatial scales (3D)
- Boundary conditions
- Initial conditions?
- Viscosity – MHD turbulence
- General Relativity
- Heating-cooling
- Plasma physics: electrons + ions
• What does the steady-state configuration look like?
  – assume unequal mass binary
  – initial condition for simulations
• How fast does the binary merge?
Good old models (steady state)

Shakura-Sunyaev 1973

Goldreich-Tremaine 1980

Gas + radiation
Viscosity - turbulence
Heating-cooling
Disk-satellite interaction

Good old models (steady state)
Steady state model without satellite

- Angular momentum flux = viscous torque

\[ \dot{M} \partial_r (r^2 \Omega) = \partial_r T_v \]

\[ T_v = -2\pi r^3 (\partial_r \Omega) \nu \Sigma \]

- Viscous heating = radiative cooling

\[ D_v = \frac{(\partial_r \Omega)T_v}{4\pi r} = \frac{9}{8} \Omega^2 \nu \Sigma \]

\[ F = \sigma T_s^4 = \frac{4 \sigma T_c^4}{3} \frac{\tau}{\tau} \]

optical depth \[ \tau = \kappa \Sigma/2 \]

Three unknowns: \( \Sigma(r), T_c(r), \nu(r) \)

- Viscosity: a prescription (Shakura-Sunyaev 1973)

\[ \nu = \alpha c_s H \beta^b \]

\[ \beta = p_{\text{gas}}/p \]

- Scaleheight \( \leftrightarrow \) vertical gravity = gas + rad. pressure

\[ H = \frac{c_s}{\Omega} \]

\[ c_s = \sqrt{p/\rho} \]

\[ p_{\text{gas}} = \rho k T_c/(\mu m_p) \]

\[ p_{\text{rad}} = \frac{1}{3} a T_c^4 \]
Steady state model with satellite

- Angular momentum flux \( = \) viscous + tidal torque
  \[
  \dot{M} \partial_r (r^2 \Omega) = \partial_r T_v - \partial_r T_d
  \]
  \[
  T_v = -2\pi r^3 (\partial_r \Omega) v \Sigma
  \]
  \[
  \partial_r T_d = 2\pi r \Lambda \Sigma
  \]

- Viscous heating = radiative cooling
  \[
  D_v + D_d = \frac{9}{8} \Omega^2 v \Sigma + \frac{1}{2} (\Omega_s - \Omega) \Lambda \Sigma
  \]
  \[
  F = \sigma T_s^4 = \frac{4}{3} \frac{\sigma T_c^4}{\tau}
  \]

Three unknowns: \( \Sigma(r), T_c(r), v(r) \)

Specific tidal torque density

specific tidal torque density:

\[
\Lambda \approx \begin{cases} 
-\frac{1}{2} f q^2 r^2 \Omega^2 r^4 / \Delta^4 & \text{if } r < r_s - r_H, \\
+\frac{1}{2} f q^2 r^2 \Omega^2 r_s^4 / \Delta^4 & \text{if } r > r_s + r_H,
\end{cases}
\]

\[
\Delta \equiv \max(|r - r_s|, H) \quad r_H \equiv (q/3)^{1/3} r_s
\]
Steady-state circumbinary disk
Disk scaleheight vs radius

\[ H \text{ [M\text{\textperiodcentered}] } \]

\[ q = 0.1, 10^{-2}, 10^{-3}, 10^{-4} \]

\[ r_s = 100M_\bullet \]

\[ r \text{ [M\text{\textperiodcentered}] } \]

\[ 10, 10^2, 10^3, 10^4 \]
Viscous and tidal heating vs. radius
disk spectrum

optical brightening!
Local brightening of disk due to secondary

Orbital period [days]

Mass ratio

Orbital radius [$r_\text{g}$]

$10^7 M_\odot$
Phase diagram

orbital period [days]

mass ratio

orbital radius [$r_g$]
Residence time

\[ q = 0.001 \]

- Type-1.5
- GW driven

\[ q = 0.01 \]

- Type-2

Mass:
- \( 10^5 M_\odot \)
- \( 10^7 M_\odot \)
- \( 10^9 M_\odot \)

Time:\n- \( t_{res} \) [yr]

\( P \) [day]
Requirements for an (optical) survey for finding periodic variable sources

**Require:**
- $\geq 100$ sources $@ t_{\text{var}} \leq 1 \text{ yr}$
- $\geq 5$ sources $@ t_{\text{var}} \leq 20 \text{ wk}$

**Assume:**
- $f_{\text{Edd}} = 0.3$
- $f_{\text{var}} = 0.1$
- $t_Q = 10^7 \text{ yr}$
- Hopkins et al. QSOLF $@ z=2$

**Conclude:**
- wide survey best to probe GW-decay
- disk physics at $i \sim 26.5$

Haiman, Kocsis, Menou (2009)
X-ray iron line features

Changing gap width

McKernan, Ford, Kocsis & Haiman (2013)
X-ray iron line features

Pile-up outside the gap

McKernan, Ford, Kocsis & Haiman (2013)
Gravitational Waves – Pulsar Timing Arrays

Gas OFF

Gas ON (Type-II)

Contribution of individual sources
Unresolved background
Total signal

Spectrum averaged over 1000 Monte Carlo realizations

Kocsis & Sesana (2011)
Conclusions

- Steady state circumbinary disk model
  - Gas pile up, overflow into gap
  - merger in gas (no gap decoupling $M < 10^7 \text{ M}_{\odot}$)
  - migration slower than previously thought

- Observational signatures
  - missing UV component
  - red/IR excess
  - periodic variability ($P \sim$ weeks to years)
  - peculiar iron line
  - pulsar timing array GW background
Simulations

SMBH binaries approaching merger

- **HD**: MacFadyen & Milosavljevic (2008); Hayasaki (2007); Cuadra et al. (2009); Roedig et al. (2012); D’Orazio, Haiman, MacFadyen (2012)
  - Central cavity, periodic accretion
- **HD+inspiral**: Baruteau, Ramirez-Ruiz, Masset (2012)
  - No central cavity
- **GR+D**: van Meter et al. (2010)
  - Launch outflow with high $\Gamma$
- **GR+EM**: Palenzuela et al. (2009, 10), Mösta et al. (2010)
  - Periodic variability in Pointing flux, dual jets
- **MHD**: Shi et al. (2011)
- **PN+MHD**: Noble et al. (2012)
- **GR+HD**: Bogdanovic et al. (2011), Bode et al. (2012)
- **GR+MHD**: Farris, Liu, & Shapiro (2011), Giacomazzo et al. (2012)
- **GR+MHD+“artificial gas cooling”**: Farris et al. (2012, 2013)

**Still to do:**
- Radiation pressure and plasma physics
- Initial and boundary conditions
- Run for many viscous times
Circumbinary accretion rates

\[ dM/dt \times 10^{-4} (GM_0)^{1/2} / \Sigma_0 \]

\[ t \times 2\pi (GM/a^3)^{-1/2} \]

\[ \text{Power} \times 10^3 \]

\[ \omega \times [1/2\pi (GM/a^3)^{1/2}] \]

\[ 0.01 \]

D’Orazio, Haiman, MacFadyen (2012)
Steady state model without satellite

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  \[ F = \sigma T_s^4 = \frac{4}{3} \frac{\sigma T_c^4}{\tau} \quad \text{optical depth} \quad \tau = \kappa \Sigma / 2 \]

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\[ p_{\text{gas}} = \rho k T_c / (\mu m_p) \]
\[ p_{\text{rad}} = \frac{1}{3} a T_c^4 \]
Conclusions

- Self-consistent steady-state model of strongly perturbed accretion disks with a secondary
  - analytical solution
- Accumulation of gas ➔ gap overflow
- New type of migration: Type-1.5
  - Slower than Type-2
- Premerger glow
  - 10–500 x optical brightening,
  - Truncated spectrum at NUV frequencies
  - Periodic variability on orbital timescale ➔ statistical measurement of migration and GWs
- Mergers are embedded in gas
  - Electromagnetic signal coincident with merger
  - PTA signal is not suppressed
Evolution of binary+disk

- Binary excites spiral density waves in the disk
- Waves carry away angular momentum
  ➡️ migration (Goldreich & Tremaine 1980)

• **Type 1 (weakly perturbed disk)**
  - small secondary
  - linear theory for unperturbed disk

• **Type 2 (gap forms in the disk)**
  - large secondary
  - viscous gas inflow rate = migration rate
Indirect detection of GWs with AGN statistics

- Look for periodically variable AGN in large scale surveys (e.g. PanSTARRS, LSST)
- Measure number of binaries as a function of orbital period
  - Residence time at each radius depends on
    - GW inspiral
    - Disk driven migration
A labyrinth of disk effects

SMBH mass increase
- Eddington limited accretion of mass (so that radiation pressure doesn’t blow the gas away)
- changes M → time dependent
- phase shift ~ 0.01 rad / yr

Secondary mass increase
- Bondi-Hoyle accretion of mass
- changes m → time dependent
- supply limited
- quenched by radiation pressure, etc.
- phase shift ~ 1-10 rad/yr

Radial Wind
- Bondi-Hoyle accretion of momentum → radial force
- Changes $\Omega$ for a given radius
- phase shift extremely small

Azimuthal Wind
- headwind: gas orbital velocity is slower
- Bondi-Hoyle accretion of momentum → azimuthal force
- changes $L'$
- phase shift ~ 0.01 – 1 rad / yr

Axisymmetric Gravity
- Changes $E$, $E'$, $\Omega$,
  - decompose disk into concentric rings
  - each ring attracts the CO
  - phase shift very small

Migration
- CO generates a spiral density wave
- spiral wave torques the binary
- Changes $L'$
- Gap opens at large separations, then refills
  - phase shift may be very large: 1–1000 rad/yr
  - sensitive to accretion disk model
  - dominates over GWs for wide binaries

Kocsis et al., astroph/0701629
Local brightening of disk due to secondary

Orbital period [days]

Orbital radius [r_g]

Mass ratio

10^5 M_☉

$r_s [M_☉]$

10^7 M_☉

$r_s [M_☉]$
Circumbinary Cavity

1. **Annular gap opens for massive secondary**
2. **Secondary migrates inward on viscous timescale**
3. **When** $M_2 \sim M_{\text{disk}}$, **secondary stalls, inner disk drains, dam forms**
4. **Secondary pushed in by dam until** $a \sim 100 R_{\text{sch}}$

Bad news for emission: central disk “missing”? 
Motivation

- Planet formation
  - How did hot Jupiters get to their observed proximity to the stars?
- Mergers of supermassive or intermediate mass BHs
  - Can gas solve the final parsec problem?
    - Controversial claims: ‘Yes’ Escala et al. (2005), ‘No’ Lodato et al. (2011)
    - Does this remove the GW background for pulsar timing array observations?
- Electromagnetic effects to catch sub-parsec supermassive binaries?
  - Premerger optical glow, truncated spectra
  - Periodic variability (PanSTARRS, LSST)
  - Iron line features (XMM Newton, Astro-H, IXO)