Circumbinary Accretion
From Supermassive Binary BHs to Circumbinary Planets

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Harvard ITC, 4/6/2017
Galaxy merger $\Rightarrow$ SMBH binary in gas disk/torus

Mayer et al 2007
First discussion of the effect of gas accretion on binary BHs:

Begelman, Blandford & Rees 1980 Nature

In addition to these stellar dynamical effects, infall of gas onto the binary can also lead to some orbital evolution. Gas may be flung out of the system, acquiring energy (and angular momentum) at the expense of the binary; alternatively, gas may accrete onto the larger hole, causing orbital contraction as the product $Mr$ is adiabatically invariant. In either case, the evolution time scale is

$$t_{\text{gas}} \sim 10^8 M_8 (\dot{M} / 1 M_\odot \text{ yr}^{-1})^{-1} \text{ yr}$$

(5)
Disks around proto-stellar Binaries

**HD 142527**
- Outer disk: >100 AU
- Gap (cavity): 10-100 AU
- Inner binary: ~20 AU

**GG Tau**
- Binary: ~60 AU

University of Hawaii, Institute for Astronomy

A. Isella/ALMA
Pulsed Accretion Observed in T Tauri Binaries

DQ Tau:
P=15.8 days
a=0.13AU
e=0.57
M1~M2~0.6Sun

Tofflemire et al. 2016
Planets Around Binaries

~12 systems found by transit method
Circumbinary Disk

Spiral Density Waves

Gap/Cavity

Accretion Stream

Circumstellar Disk ("Mini Disk")
Simulations of Circumbinary Accretion

Simulations of Circumbinary Accretion

Artymowicz & Lubow (1996) – SPH

Günther & Kley (2002) – Hybrid grid

also:

de Val-borro et al. (2011) – cartesian grid
Hanawa et al. (2010) – Nested cartesian
Simulations of Circumbinary Accretion

Farris et al. (2014) – moving rings grid

Duffell & MacFadyen (2012) – DISCO code
What we do:

Munoz, Miranda & DL, in prep
Miranda & DL, in prep

Goals:

-- Accretion onto circular/eccentric binaries: circumbinary->circumstellar disks
-- Short-term & long-term accretion variabilities
-- Disk structure and dynamics (eccentricity, precession)
-- Angular momentum transfer between binary and disk
-- Key feature: Disk reaches quasi-steady state
\[ \langle \dot{M}(r, t) \rangle \simeq \text{const} \]
Numerical Tools

-- Solve viscous hydrodynamic equations in 2D
-- alpha viscosity, (locally) isothermal sound speed

-- **Numerical codes:**

**PLUTO:** finite-volume, polar grid (Mignone et al. 07)
   domain: \( a_b(1+e_b) < r < 70a_b \)

**AREPO:** finite-volume, moving mesh (Springel 2010)
   resolve accretion onto individual body to 0.02a_b
AREPO  (Springel, 2010)

Quasi-Lagrangian, moving-mesh code

Main features

- Shock-capturing, finite-volume method
- Unstructured moving grid
- Equations solved in the moving-frame
- Quasi-Lagrangian, adaptive resolution

(see also Pakmor et al. 2015)
Summary of Key Results

Binary mass ratio $q \sim 1 (\gtrsim 0.2)$

Disk $H/r \sim 0.1$, $\alpha = 0.05 - 0.1$
Short-term (~$P_b$) Accretion Variabilities

For $e_b \lesssim 0.05$: $\dot{M}(= \dot{M}_1 + \dot{M}_2)$ varies at $\sim 5P_b$ (Kepler period at $r_{in} \sim 3a_b$)

$e_b = 0$

Known from MacFadyen & Milosavljevic 08, Shi et al.12, D’Orazio et al.13, Farris et al.14

Munoz & DL 16
Short-term ($\sim P_b$) Accretion Variabilities

For $e_b \gtrsim 0.05$: $\dot{M} = \dot{M}_1 + \dot{M}_2$ varies at $\sim P_b$

$e_b = 0.5$

Munoz & DL 16
Short-term ($\sim P_b$) Accretion Variabilities

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For $e_b \gtrsim 0.05$: $\dot{M} = \dot{M}_1 + \dot{M}_2$ varies at $\sim P_b$
Compared to Observations: Pulsed Accretion onto DQ Tau \((P_b=15.8 \text{ d}, e_b=0.56)\)

U-band photometry of DQ Tau for >10 orbital periods

- **red**: simulation (D. Munoz)
- **blue**: observations

→ Can resolve the effective size of stars

Ben Tofflemire, Mathieu et al (in prep)
Long-Term Evolution:

\[ e_b = 0 \]
\[ q_b = 1 \]

\[ \dot{M}_1 \sim \dot{M}_2 \]
Long-Term Evolution: Symmetry Breaking

\[ e_b = 0.5 \]
\[ q_b = 1 \]

Switch between
\[ \dot{M}_1 \gtrsim 20 \dot{M}_2 \]
and
\[ \dot{M}_2 \gtrsim 20 \dot{M}_1 \]
every \( \sim 200 \, P_b \)
Apsidal precession of eccentric disk around the binary

\[ \dot{\omega}_d \approx \frac{3\Omega_b}{4} \frac{q_b}{(1 + q_b)^2} \left( 1 + \frac{3}{2} e_b^2 \right) \left( \frac{a_b}{R} \right)^{7/2} \]

\[ \approx 0.006 \Omega_b \left( \frac{3a_b}{R} \right)^{7/2}, \]

Precession period 200-300 P_b
Long-Term Evolution: Symmetry Breaking

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Long-Term Evolution: Disk Eccentricity

Inner disk ($<10a_b$) is coherently eccentric

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Long-Term Evolution: Disk Eccentricity

Inner disk (<10 \(a_b\)) is coherently eccentric

For \(e_b \lesssim 0.2\) and \(\gtrsim 0.4\): coherent apsidal precession

Miranda, Munoz & DL 17
Long-Term Evolution: Disk Eccentricity

Inner disk ($<10 a_b$) is coherently eccentric

For $e_b \lesssim 0.2$ and $\gtrsim 0.4$: coherent apsidal precession
For $0.2 \lesssim e_b \lesssim 0.4$: apsidally locked to binary
Theory of Eccentric Disks: Driving and Dynamics

Tidal potential from inner binary on disk:

$$\Phi(r, \phi, t) = \sum_{m,N} \Phi_{m,N} \cos(m\phi - N\Omega_b t) = \sum_{m,N} \Phi_{m,N} \cos[m(\phi - \omega_p t)]$$

$$m = 2, 3, \cdots, N = 1, 2, \cdots \quad \text{(for } q_b = 1)$$

Pattern frequency: $$\omega_p = \frac{N\Omega_b}{m}$$

Eccentricity excitation by rotating potential

Epicyclic motion of test mass in disk

$$\frac{d^2 \Delta r}{dt^2} + \kappa^2 \Delta r = 0 \quad (\kappa \simeq \Omega)$$

In the presence of the potential $$\Phi_{m,N} \cos[m(\phi - \omega_p t)]$$:

$$\frac{d^2 \Delta r}{dt^2} + \kappa^2 [1 + \epsilon \cos m(\omega_p - \Omega)t] \Delta r = 0 \quad (\epsilon \propto \Phi_{m,N})$$

Parametric resonance occurs when

$$m(\omega_p - \Omega) = 2\kappa \simeq 2\Omega$$

$$\Omega = \frac{m\omega_p}{m + 2} = \frac{N\Omega_b}{m + 2}$$

cf. Lubow 91
Goodchild & Ogilvie 2006
Miranda, Munoz & DL 2017

“Eccentric Lindblad Resonance”
(parametric resonance)
Theory of Eccentric Disks: Driving and Dynamics (continued)

Parametric resonance occurs when

\[ m(\omega_p - \Omega) = 2\kappa \simeq 2\Omega \]

\[ \Omega = \frac{m\omega_p}{m + 2} = \frac{N\Omega_b}{m + 2} \]

The most important tidal components are

- \( m = 2, \ N = 1 \): Resonance at \( \Omega = \frac{\Omega_b}{4} \), \( \Phi_{21} \propto e_b \)
- \( m = 2, \ N = 2 \): Resonance at \( \Omega = \frac{\Omega_b}{2} \), \( \Phi_{21} \propto \left( 1 - \frac{5}{2} e_b^2 \right) \) and \( \rightarrow 0 \) for large \( e_b \)

Combine eccentricity driving by at resonances with pressure and viscosity

\[
2r\Omega \frac{\partial E}{\partial t} = -\frac{iE}{r} \frac{\partial}{\partial r} \left( r^2 \frac{\partial \Phi_2}{\partial r} \right) + \frac{iE}{\Sigma} \frac{\partial P}{\partial r} \\
+ \frac{i}{r^2\Sigma} \frac{\partial}{\partial r} \left[ (1 - i\alpha_b) Pr^3 \frac{\partial E}{\partial r} \right] \\
+ \sum_i 2aB\gamma_i r\Omega E \delta(r - r_{res,i})
\]

For \( e_b \lesssim 0.2 \): \( e \) driven by \( \Omega = \frac{\Omega_b}{2} \) resonance; disk precesses

For \( e_b \gtrsim 0.4 \): \( e \) driven by \( \Omega = \frac{\Omega_b}{4} \) resonance; disk precesses

For \( 0.2 \lesssim e_b \lesssim 0.4 \): \( e \) driving suppressed by viscosity \( \rightarrow e \exp(i\omega) \) freezes
Angular Momentum Transfer to Binary
\[ \dot{M}_{\text{out}} = \dot{M}_0 = \text{const} \]
\( \dot{M}(r, t) \) is highly variable (in \( r \) and \( t \))

\[
\dot{M}(r, t) = - \int r \Sigma u_r \, d\phi
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\[
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\]
Angular Momentum Transfer Rate

\[ \dot{J}(r, t) = \dot{J}_{\text{adv}} - \dot{J}_{\text{visc}} - T_{\text{grav}}^{>r} \]

\[ \dot{J}_{\text{adv}} = - \oint r^2 \Sigma u_r u_\phi d\phi \]

\[ \dot{J}_{\text{visc}} = - \oint r^3 \nu \Sigma \left[ \frac{\partial}{\partial r} \left( \frac{u_\phi}{r} \right) + \frac{1}{r^2} \frac{\partial u_r}{\partial \phi} \right] d\phi \]

\[ T_{\text{grav}}^{>r} = \int_{r}^{r_{\text{out}}} \frac{dT_{\text{grav}}}{dr} dr, \quad \frac{dT_{\text{grav}}}{dr} = - \oint r \Sigma \frac{\partial \Phi}{\partial \phi} d\phi \]
Angular Momentum Transfer Rate

\[ \dot{J}(r, t) = \dot{J}_{\text{adv}} - \dot{J}_{\text{visc}} - T^{>r}_{\text{grav}} \]
Angular Momentum Transfer Rate

\[ \dot{J}(r, t) = \dot{J}_{\text{adv}} - \dot{J}_{\text{visc}} - T^{>r}_{\text{grav}} \]
Approaching Quasi-Steady State:

Each point is obtained by averaging $\sim 250 \, P_b$
Angular Momentum Transfer Rate

Recap: Although the accretion flow is highly dynamical, the system reaches quasi-steady state (when averaged over ~200-300 P_b, the precession period):

\[ \langle \dot{M} \rangle \simeq \dot{M}_{\text{out}} = \dot{M}_0(\text{const}) \]
\[ \langle \dot{J} \rangle \simeq \text{const} \]

Net angular momentum per unit mass transferred to the binary:

\[ l_0 \equiv \frac{\langle \dot{J} \rangle}{\langle \dot{M} \rangle} \]

(a global eigenvalue of accretion flow)

e.g. Popham & Narayan 1995
Angular Momentum Transfer Rate: \( \langle \dot{J} \rangle = \langle \dot{M} \rangle l_0 \)

- \( l_0 > 0 \) in most cases (i.e. binary receives angular momentum)
- “dip” in \( l_0 \) at intermediate \( e_b \) (corresponding to inner eccentric disk apsidally aligned with binary)
Convergence in the “dip” cases
Implication of $l_0 > 0$

For $q = 1$, $e_B = 0$ binary:

$$\dot{J}_B = \dot{M}_B l_0$$

$$\Rightarrow \frac{\dot{a}_B}{a_B} = 8 \left( \frac{l_0}{l_B} - \frac{3}{8} \right) \frac{\dot{M}_B}{M_B}$$

Binaries can expand due to circumbinary accretion!
Implication of $l_0 > 0$

For $q = 1$, $e_B = 0$ binary:

$$\dot{J}_B = \dot{M}_B l_0$$

$$\Rightarrow \frac{\dot{a}_B}{a_B} = 8 \left( \frac{l_0}{l_B} - \frac{3}{8} \right) \frac{\dot{M}_B}{M_B}$$

Binaries can expand due to circumbinary accretion!

Note: For $q \neq 1$ and $e_B > 0$ binaries:

$$\frac{\dot{J}_B}{J_B} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{2} \frac{\dot{M}_B}{M_B} + \frac{1}{2} \frac{\dot{a}_B}{a_B} - \left( \frac{e_B}{1 - e^2_B} \right) \dot{e}_B$$
Notions/Claims of binary decays due to cicumbinary disk

-- **Numerical simulations:**
  - Transient vs quasi-steady state?
  - Mass conservation? (e.g., the claim of mass pile-up)
Notions/Claims of binary decays due to cicumbinary disk

-- **Numerical simulations:**
  Transient vs quasi-steady state?
  Mass conservation? (e.g., the claim of mass pile-up)

-- **Is binary decay possible?** (e.g. Supermassive BH Binaries, final pc)
  Yes...
  e.g. $M_1/M_2 \gg 1$, large (locally) massive disk:
  $$\sum \pi a_b^2 \gtrsim M_2$$
Caveats/Issues??

Accretion onto binary is suppressed for $H/r \lesssim 0.1$

Ragusa, Lodato & Price 16

SPH simulations of spreading layer initially at $2.3-5\ a_b$
Caveats/Issues??

Disk with constant mass supply   (Preliminary run by R. Miranda)
Caveats/Issues??

Spreading layer (Preliminary run by R. Miranda)
Implications for Planet Formation Around Binaries

Many observed circumbinary planets are close to instability limit (consistent with uniform distribution in log $a$; Li, Holman & Tao 16)
Implications for Planet Formation Around Binaries

-- Planetesimal growth is likely suppressed

At $r \sim 3-4 \ a_b$, disk $e \sim 0.05-0.2$  
relative velocity of planetesimals $\sim eV_k \sim 5 \text{ km/s (at 0.2AU)} \gg v_{esc} \sim 10 \text{ m/s (10 km body)}$

-- Planet migration is strongly affected by disk structure
(e.g. mean-motion resonance with binary)
Planet Migration in Truncated Disk

Simulations by Ryan Miranda
So far: Co-planar disks

What about misaligned disks?
Misaligned Disks are “Naturally” Expected
Star Formation in Turbulent Molecular Clouds

-- Supersonic turbulence --> clumps --> stars
-- Clumps can accrete gas with different rotation axes at different times

Bate et al. 2003
Tsukamoto & Machida 2013
Observations

Circumstellar disks within wider binaries are generally misaligned

HK Tau:
ALMA CO 3-2 emission
($a_b \sim 400$ AU)

Jensen & Akeson 14
Observations

Circumbinary disks around binaries ??

AK Sco
Czekala+15

Misaligned circumbinary debris disk systems:

KH 15D (Winn+04; Capelo+12)

99 Herculis (Kennedy+12)
**HD 142527:** a well-known gapped disk system

- **Outer disk:** >100 AU
- **Gap (cavity):** 10-100 AU
- **Binary:** ~20 AU (2 Sun + M dwarf)

Inner (circumstellar) and outer (circumbinary) disks misaligned by 70 degrees (Marino et al. 15)

see Owen & DL 2017, arXiv:1703
Consider Binary + Inclined (initially) Disk

Questions:  What is the shape of the disk?
How does the mutual inclination evolve?
Dynamics of Warped Disks

Torque from binary on disk $\Rightarrow$ disk (ring) nodal precession

$$\Omega_p(r) \approx \frac{3\mu}{4M_t} \left(\frac{a}{r}\right)^2 \Omega(r)$$

Differential precession + internal fluid stress $\Rightarrow$ warped/twisted disk
For protoplanetary disks, warp/twist smoothed by bending waves, which propagate at $c_s/2$ (Lubow & Ogilvie 2000).

Since $r/c_s <<$ precession period $\Rightarrow$ disk is close to flat.
Dynamics of Warped Disks

However, small warp exists.

Warp + Viscosity $\rightarrow$ Dissipation $\rightarrow$ Align $L_b$ and $L_d$

$$\frac{d\mathbf{i}}{d\ln r} \sim \frac{\alpha}{c_s^2} T_{\text{ext}} \quad |T_{\text{ext}}| \sim r^2 \Omega \omega_{\text{ext}}, \quad \omega_{\text{ext}} = \Omega_{\text{prec}}$$

$$\left| \frac{d\mathbf{i}}{dt} \right|_{\text{visc}} \sim \left\langle \left( \frac{\alpha}{c_s^2} \right) \frac{T^2_{\text{ext}}}{r^2 \Omega} \right\rangle \sim \left\langle \frac{\alpha}{c_s^2} (r^2 \Omega) \omega_{\text{ext}}^2 \right\rangle$$

Typical alignment time $\sim$ precession period

Foucart & DL 2014
Zanazzi & DL 2017
Circumstellar Disk within Binary

Disk is warped at outer region
⇒ Smaller warp

Typical alignment time $>>$ precession period
⇒ Misalignment can persist
Observations

Circumstellar disks within wider binaries are generally misaligned.

HK Tau:
ALMA CO 3-2 emission
($a_b \sim 400$ AU)

Jensen & Akeson 14
Warped Disks Around or Within Binaries

Simulations (e.g. with AREPO) would be very interesting!
Are there misaligned circumbinary planets?

**Kepler mission:**

~12 transiting circumbinary planets

3 non-transiting planets (candidates) around eclipsing binaries (detected using eclipse timing variation) *(Bill Welsh, 2017)*
SUMMARY

◆ **Understanding circumbinary accretion is**
  
  **Important:** connect to SMBH binaries, proplanetary disks and planets
  
  **Challenging:** long-term secular effect in the presence of highly dynamical flows

◆ **Key Recent Results:**
  
  -- Quasi-steady state can be achieved
  -- short-term variabilities: $\sim 5 \ P_b$ (for $e_b \sim 0$) vs $P_b$ (high $e_b$)
  -- Symmetry breaking in accretion ($q=1$, $e_b>0$)
  -- Inner disk is eccentric: precess coherently vs apsidal locking
  -- Binary can gain angular momentum (dependence on $e_b$) and can expand

◆ **Misaligned disks**
  
  -- Observationally common
  -- Inner/outer warps give very different damping rates for inclination
Thanks.
Spreading Circumbinary Disk (Torus)

Figure 1. Mass accretion rate (left), angular momentum transfer rate (middle), and their ratio (right), smoothed over 10 orbits, at different radii for a spreading circumbinary disk. The initial bump of material starts at $20a_B$, and the disk has $H/r = 0.1$ and $\alpha = 0.1$. The binary is equal-mass and has $e_B = 0$. The dashed red lines show the analytic behavior for a disk around a single star of equivalent mass. In this run, the inner boundary has been placed at a very small separation from the binary.
Figure 2. Same as the previous figure, but for $e_B = 0.2$. 
Figure 3. Same as Figure 1, but with $H/r = 0.05$. 