Circumbinary Accretion
From Supermassive Binary BHs to Circumbinary Planets

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TDLI, Shanghai, 12/21/2018
Galaxy merger $\Rightarrow$ SMBH binary in gas disk/torus

Mayer et al 2007
A key question: Does the binary lose or gain angular momentum?
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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

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

(5)

Begelman, Blandford & Rees 1980 Nature
Disks around proto-stellar Binaries

HD 142527

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

GG Tau

A. Isella/ALMA

Binary: ~60 AU

University of Hawaii, Institute for Astronomy
Planets Around Binaries

~12 systems found by transit method
Simulations of Circumbinary Accretion


A Challenging Problem...
Circumbinary Disk

Gap/Cavity

Accretion Stream

Circumstellar Disk ("Mini Disk")

Spiral Density Waves

R.Miranda
Simulations of Circumbinary Accretion


A Challenging Problem...

Many simulations excised the inner “cavity”

Some cover the whole domain: Circumbinary disk → stream → circumsingle disks:

Using finite-volume moving mesh codes:

DISCO (Farris, Duffell, MacFadyen, Haiman 2014,15; Tang, MacFadyen, Haiman 2017)
AREPO: resolve accretion onto individual body to $0.02a_b$
(Munoz & Lai 2016; Munoz, Miranda & Lai 2018):
What we do:

Munoz, Miranda & DL 2018, arXiv:1810...

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

Method:
-- Solve viscous hydrodynamic equations in 2D
-- alpha viscosity, (locally) isothermal sound speed
**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/Issues

- Short-term variabilities
- Long-term variabilities
- Angular momentum transfer and binary evolution

Binary mass ratio $q \sim 1$ ($\gtrsim 0.2$)
Disk $H/r \sim 0.1$, $\alpha = 0.05 - 0.1$
Short-term ($\sim P_b$) 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 $\simeq P_b$

$e_b = 0.5$

Munoz & DL 16
Long-Term Variability:

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

\[ \dot{M}_1 \sim \dot{M}_2 \]
Long-Term Variability: 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 $\sim 200 \, P_b$

Munoz & Lai 2016

Single AGN with binary BHs?
Apsidal precession of eccentric disk around the binary

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

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

Precession period 200-300 \( P_b \)
Angular Momentum Transfer to Binary and Long-term Orbital Evolution
\( \dot{M}(r, t), \dot{M}_1, \dot{M}_2 \) are highly variable

**Quasi-Steady State:** \[ \langle \dot{M}(r, t) \rangle = \langle \dot{M}_1 \rangle + \langle \dot{M}_2 \rangle = \dot{M}_0 \]
Direct computation of torque on the binary

Gravitational torque from all gas
+ Accretion torque (due momentum of accreting gas onto each star)

\[ \dot{J}_b = (\dot{L}_b)_{grav} + (\dot{L}_b)_{acc} + (\dot{S}_1)_{acc} + (\dot{S}_2)_{acc} \]
Figure 2. The five different contributions to angular momentum change and its combined effect \( \tilde{F} \). From top to bottom: \( M_b \), \( \hat{q}_b \), \( \hat{h}_{\text{grav}} \), \( \hat{h}_{\text{acc}} \), and \( \hat{S} \) (see Section 2.2.1), and their combined effect \( \tilde{F} \) (bottom panel). In steady state, \( \langle M_b \rangle \approx M_0 \) and \( \langle \hat{q}_b \rangle \approx 0.076 M_0 \tilde{a}_0 \). Each time series is approximately stationary, and only \( \sim 30 \) binary orbits are needed to capture their behavior. The time sampling interval in each panel is \( \approx 0.02 \tilde{P}_b \). The accretion eigenvalue in this case is \( \tilde{h}_0 \approx \langle M_b \rangle / \langle \hat{q}_b \rangle \approx 0.076 \tilde{a}_0 \).
Direct computation of torque on the binary

Gravitational torque from all gas
+ Accretion torque (due momentum of accreting gas onto each star)

\[ \dot{J}_b = (\dot{L}_b)_{\text{grav}} + (\dot{L}_b)_{\text{acc}} + (\dot{S}_1)_{\text{acc}} + (\dot{S}_2)_{\text{acc}} \]

\[ l_0 \equiv \frac{\langle \dot{J}_b \rangle}{\langle M_b \rangle} = 0.68a_b^2\Omega_b \quad \text{e}_b=0 \]

Munoz, Miranda & Lai 2018
Angular Momentum Current (Transfer Rate) in CBD

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

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

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

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

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

\( q_b = 1.0 \)
\( e_b = 0.0 \)

3500 – 3700 \( P_b \)

\( \langle \dot{J}_T \rangle / (M_0 \Omega_b a_b^2) \)

\( R/a_b \)

Munoz, Miranda & Lai 18
Recap: Although the accretion flow is highly dynamical, the system reaches quasi-steady state:

\[ \langle \dot{M}(r, t) \rangle = \langle \dot{M}_1 \rangle + \langle \dot{M}_2 \rangle = \dot{M}_0 \]

\[ \langle \dot{J}_b \rangle \simeq \langle \dot{J}_{\text{disk}}(r, t) \rangle = \text{const} \]

Net angular momentum per unit mass transferred to the binary:

\[ l_0 \equiv \frac{\langle \dot{J}_b \rangle}{\langle \dot{M}_b \rangle} = 0.68a_b^2 \Omega_b \]
Implication of $\dot{J}_B > 0$:

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

$$\dot{J}_B = \dot{M}_B l_0 \quad l_0 \simeq 0.7 l_B \quad \text{where } l_B = a_B^2 \Omega_B$$

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

Binaries can expand due to circumbinary accretion!

For $e_b=0$:

$$\langle \dot{a}_b \rangle \approx 2.68 a_b \dot{M}_0 / M_b, \quad \langle \dot{e}_b \rangle \approx 0$$

For $e_b=0.6$:

directly compute $\langle \dot{E}_B \rangle$ and $\langle \dot{J}_B \rangle$ from simulation

$$\Rightarrow \langle \dot{a}_b \rangle \approx 0.38 a_b \dot{M}_0 / M_b \quad \langle \dot{e}_b \rangle \approx -2.34 \dot{M}_0 / M_b$$

Munoz, Miranda & Lai 2018
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. \( \frac{M_1}{M_2} >> 1 \), large (locally) massive disk:
  \[
  \sum \pi a_b^2 \gtrsim M_2
  \]
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

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

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

Miranda & DL 2018
So far: Co-planar disks

What about misaligned disks?
Observations

Misaligned circumbinary disks

IRS 43
ALMA
\(a_b \sim 74\) au, three disks

Brinch et al. 2016

Other Misaligned circumbinary debris disks:

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
Consider Binary + Inclined (initially) Disk

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

Disk warp + Viscosity $\rightarrow$ Dissipation $\rightarrow$ Align $L_b$ and $L_d$

Foucart & DL 2014
Zanazzi & DL 2018
**Surprise:** Disk around eccentric binary may evolve toward polar alignment
**Surprise:** Disk around eccentric binary may evolve toward polar alignment

Martin & Lubow (2017): viscous hydro simulation using SPH

- Initial disk-binary inclination $I(0) = 60^\circ$
- Binary eccentricity $e_b = 0.5$. 

![Graphs showing time evolution of inclination and eccentricity](image-url)
Theoretical Analysis:
Inclination Evolution of Disks Around Eccentric Binaries

With J.J. Zanazzi
(Cornell Ph.D.18 \rightarrow CITA)
Test particle (in circular orbit) around an eccentric binary

Test particle has two “masters” (by symmetry)

If $\hat{l}$ initially close to $\hat{b}$: $\hat{l}$ precesses around $\hat{b}$
If $\hat{l}$ initially close to $\hat{e}_b$: $\hat{l}$ precesses around $\hat{e}_b$

$$\Lambda = (1 - e_b^2)(\hat{l} \cdot \hat{b})^2 - 5(\hat{l} \cdot e_b)^2$$

$\Lambda > 0$

$\Lambda < 0$
Warped viscous disk around eccentric binary

Evolve towards either align (anti-align) or polar align with the binary

$e_b = 0.3$

$180^\circ - I_{\text{crit}}$

$I_{\text{crit}}$

$\Lambda = 0$

Zanazzi & DL 2018
99 Herculis: host to a circumbinary polar-ring debris disc

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\[ e_b = 0.77, \quad P_b = 56 \text{ yrs} \]
SUMMARY

◆ Understanding circumbinary accretion is
  Important: connect to SMBH binaries, protoplanetary 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 and can expand

◆ Misaligned disks
  -- Observed around young stars
  -- Quasi-rigid precession with small warp
  -- Dissipation leads to either alignment of polar alignment with binary
Thanks.