Circumbinary Accretion
From Supermassive Binary BHs to Circumbinary Planets

Dong Lai
Cornell University

Berkeley/Miller Institute

T.D. Lee Institute

UC Berkeley Astro Colloquium, 3/5/2020
Galaxy merger ➔ SMBH binary in gas disk/torus

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

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 $M_r$ is adiabatically invariant. In either case, the evolution time scale is

$$t_{\text{gas}} \sim 10^8 M_8 (\dot{M}/1 M_\odot \text{ yr}^{-1})^{-1} \text{ yr} \quad (5)$$

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

A. Isella/ALMA

GG Tau

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
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 0.02$a_b$

(Munoz & Lai 2016; Munoz, Miranda & Lai 2019; Munoz, Lai et al 2020)

**ATHENA++** (Moody, Shi & Stone 2019)
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

Finite-volume moving mesh code

Farris et al. (2014) – moving rings grid

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

Munoz, Miranda & DL 2019
Munoz, DL et al 2020

Goals:
-- Accretion onto circular/eccentric binaries: circumbinary->circumstellar disks resolve accretion onto individual body to 0.02a_b
-- 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

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

Binary mass ratio $q \sim 1$
Disk $H/r \sim 0.1$, $\alpha = 0.05 - 0.1$ (down to 0.01)
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 $r_{in} \sim 3a_b$)

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

$e_b = 0$

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 $\sim P_b$

$e_b = 0.5$
Short-term (~$P_b$) Accretion Variabilities

For $e_b \lesssim 0.05$: $\dot{M} = \dot{M}_1 + \dot{M}_2$ varies at $\sim 5P_b$

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

Tofflemire, Mathieu et al. 2017
Long-Term Variability:

\[ e_b = 0 \]

\[ q_b = 1 \]

\[ \dot{M}_1 \simeq \dot{M}_2 \]
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 \( \sim 200 \ P_b \)

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

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

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

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

**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)

\[ \dot{J}_b = (\dot{L}_b)_{\text{grav}} + (\dot{L}_b)_{\text{acc}} + (\dot{S}_1)_{\text{acc}} + (\dot{S}_2)_{\text{acc}} \]
Figure 2. The five different contributions to angular momentum change and its combined effect $\dot{J}$, from top to bottom $\Delta M_0$, $\dot{q}$, $\dot{h}_{\text{grav}}$, $\dot{h}_{\text{acc}}$, and $\dot{h}_0$ (see Section 2.2.1), and their combined effect $\dot{J}_b$ (bottom panel). In steady state, $\langle M_0 \rangle \approx M_b$ and $\langle J_b \rangle \approx 0.636M_b\Omega_b^2$. 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 $\sim 0.03P_b$. The accretion eigenvalue in this case is $h_0 \equiv (\dot{M}_b)/(\dot{J}_b) \approx 0.07\Omega_b^2 a_b^2$. 
Direct computation of torque on the binary

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

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

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

Angular momentum transfer to the binary per unit accreted mass

Munoz, Miranda & Lai 2019
Angular Momentum Current (Transfer Rate) in CBD

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

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

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

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

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

\[ q_b = 1.0 \quad 3500 - 3700 P_b \]
\[ e_b = 0.0 \]

\[ \langle \dot{J}_r \rangle_T / (M_0 \Omega_0 a_b^2) \]

\[ \frac{\dot{J}_{\text{d, adv}}}{2\pi R} \equiv \langle F_{J, \text{adv}} \rangle_\phi \]
\[ \frac{\dot{J}_{\text{d, visc}}}{2\pi R} \equiv \langle F_{J, \text{visc}} \rangle_\phi \]
\[ \dot{J}_{\text{d, grav}} \equiv 2\pi R \langle F_{J, \text{grav}} \rangle_\phi \]

Munoz, Miranda & Lai 19
Recap: Although the accretion flow is highly dynamical, the system reaches quasi-steady state:

\[
\langle \dot{M}(r, t) \rangle = \langle \dot{M}_1 \rangle + \langle \dot{M}_2 \rangle = \dot{M}_0
\]
\[
\langle \dot{J}_b \rangle \simeq \langle \dot{J}_{\text{disk}}(r, t) \rangle = \text{const}
\]

Angular momentum transferred to the binary per unit accreted mass:

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

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

$$\dot{J}_B = \dot{M}_B l_0 \quad l_0 \simeq 0.68 l_B \quad \text{where } l_B = a_B^2 \Omega_B$$

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

Binaries can expand due to circumbinary accretion!

For $e_B=0$:

$$\frac{\dot{a}_B}{a_B} \simeq 2.68 \frac{\dot{M}_B}{M_B}$$
Implication of $\dot{J}_B > 0$:

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

$$\dot{J}_B = \dot{M}_B l_0 \quad l_0 \simeq 0.68 l_B \quad \text{where} \quad l_B = a_B^2 \Omega_B$$

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

Binaries can expand due to circumbinary accretion!

For $e_B = 0$:

$$\frac{\dot{a}_B}{a_B} \simeq 2.68 \frac{\dot{M}_B}{M_B}$$

For $e_B = 0.6$:

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

$$\frac{\dot{a}_B}{a_B} \simeq 0.38 \frac{\dot{M}_B}{M_B} \quad \hat{e}_B \simeq -2.34 \frac{\dot{M}_B}{M_B}$$
Unequal-mass binaries

\[ q = \frac{M_2}{M_1} < 1 \]

\[ e_b = 0 \]

Munoz, DL +2020
Unequal-mass binaries

\[ q = \frac{M_2}{M_1} < 1 \]

\[ e_b = 0 \]

Munoz, DL +2020

See also Bate+2000; Farris+2014

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Low-mass component accretes more
Unequal-mass binaries

\[ q = \frac{M_2}{M_1} < 1 \]

\[ e_b = 0 \]

-- Dominant variability frequency

Munoz, DL +2020
Unequal-mass binaries

\[ q = \frac{M_2}{M_1} < 1 \]

\[ e_b = 0 \]

-- Angular momentum transfer

\[ \frac{\dot{L}_b}{L_b} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{2} \frac{\dot{M}_b}{M_b} + \frac{1}{2} \frac{\dot{a}_b}{a_b} \]

Munoz, DL +2020
Previous claims of binary decay due to cicumbinary disk?

-- Numerical simulations:
  Mass conservation? (e.g., the claim of mass pile-up)
  Transient vs quasi-steady state?
Binary accretion from a finite disk/torus

\[ \dot{M}_t [\dot{M}_0] \]

\[ t / P_b \]

\[ \dot{M}_1 \]

\[ \dot{M}_2 \]

Munoz, DL + 2020
Binary accretion from a finite disk/torus

Angular momentum transfer per unit (accreted) mass

Orbital expansion rate
Is binary decay possible?

e.g. Supermassive BH Binaries, final pc problem
e.g. Formation of close (AU) stellar binaries?
Is binary decay possible?

e.g. Supermassive BH Binaries, final pc problem
e.g. Formation of close (AU) stellar binaries?

Yes...

e.g. \( \frac{M_1}{M_2} > 1 \), large (locally) massive disk:

\[
\Sigma \pi a_b^2 \gtrsim M_2
\]

e.g. Gas gets ejected in outflow...
Implications for Planet Formation Around Binaries

Many observed circumbinary planets are close to instability limit
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 \( \sim eV_k \sim 5 \, \text{km/s (at 0.2AU)} \) \( \gg \) \( v_{\text{esc}} \sim 10 \, \text{m/s (10 km body)} \)

-- 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?
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
Misaligned circumbinary disks

IRS 43
ALMA
$a_b \sim 74$ au, three disks

Brinch et al. 2016
Consider (circular) 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 => disk (ring) nodal precession

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

Differential precession + internal fluid stress ==> 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.
However, small warp exists.

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

\[
\frac{\partial \tilde{I}}{\partial \ln r} \sim \frac{\alpha}{c_s^2} T_{\text{ext}} \quad |T_{\text{ext}}| \sim r^2 \Omega \omega_{\text{ext}}, \quad \omega_{\text{ext}} = \Omega_{\text{prec}}
\]

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

Typical alignment time $\sim$ precession period

Foucart & DL 2014
Zanazzi & DL 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 \( e_b = 0.5 \).
Theoretical Understanding: Inclination Evolution of Disks Around Eccentric Binaries

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

(see also Farago & Laskar 2010; Li, Zhou + 2014)

Test particle has two “masters” (by symmetry)

If \( \hat{l} \) initially close to \( \hat{l}_b \): \( \hat{l} \) precesses around \( \hat{l}_b \)

If \( \hat{l} \) initially close to \( \hat{e}_b \): \( \hat{l} \) precesses around \( \hat{e}_b \)

\[
\Lambda = (1 - e_{b}^{2})(\hat{l} \cdot \hat{l}_b)^2 - 5(\hat{l} \cdot \hat{e}_b)^2
\]
\[ \Lambda = (1 - e_b^2)(\hat{l} \cdot \hat{l}_b)^2 - 5(\hat{l} \cdot \hat{e}_b)^2 \]

For \( \hat{l} \) to precess around \( \hat{e}_b \), require \( \sin I > \sin I_{\text{crit}} \)

\[ I_{\text{crit}} = \cos^{-1} \sqrt{\frac{5e_b^2}{1 + 4e_b^2}} \]

Zanazzi & DL 2018
Warped viscous disk around eccentric binary

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

Zanazzi & DL 2018
A circumbinary protoplanetary disk in a polar configuration

Grant M. Kennedy, Luca Matrà, Stefano Facchini, Julien Milli, Olja Panić, Daniel Price, David J. Wilner, Mark C. Wyatt and Ben M. Yelverton
The Degree of Alignment between Circumbinary Disks and Their Binary Hosts

Ian Czekala\textsuperscript{1,8}, Eugene Chiang\textsuperscript{1,2}, Sean M. Andrews\textsuperscript{3}, Eric L. N. Jensen\textsuperscript{4}, Guillermo Torres\textsuperscript{3}, David J. Wilner\textsuperscript{3}, Keivan G. Stassun\textsuperscript{5,6}, and Bruce Macintosh\textsuperscript{7}
Are there misaligned circumbinary planets?

~12 transiting circumbinary planets

3 non-transiting planets (candidates) around eclipsing binaries (detected using eclipse timing variation) (Bill Welsh, 2018)
Take-Home Messages

◆ **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:**
  
  -- short-term variabilities: $\sim 5 \ P_b$ (for $e_b \sim 0$) vs $P_b$ (finite $e_b$, or $q<0.4$)
  -- Small-mass accretes more; symmetry breaking in accretion ($q=1$, $e_b>0$)
  -- Inner disk is eccentric: precess coherently...
  -- Binary can gain angular momentum and can expand

◆ **Misaligned disks**
  
  -- In PPDs, hydro effects efficient ➔ Quasi-rigid precession with small warp
  -- Dissipation leads to either alignment or polar alignment with binary
\( \dot{M}(r, t) \) is highly variable (in \( r \) and \( t \))

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

\( \langle \dot{M} \rangle / \dot{M}_0 \) (averaged over 250 \( P_B \) )
Consider the specific angular momentum \( l_b = \mathbf{r}_b \times \dot{\mathbf{r}}_b \) and specific energy \( \mathcal{E}_b = \frac{1}{2} \mathbf{r}_b^2 - \mathcal{G} M_b/r_b \) of the binary. The changes in \( l_b \) and \( \mathcal{E}_b \) due to an external force \( \mathbf{f}_{\text{ext}} \) (other than the mutual Keplerian force) are

\[
\frac{dl_b}{dt} = \mathbf{r}_b \times \mathbf{f}_{\text{ext}} \tag{32}
\]

and

\[
\frac{d\mathcal{E}_b}{dt} = -\frac{\mathcal{G} \dot{M}_b}{r_b} + \frac{\mathcal{G} \dot{M}_b}{r_b^3} \mathbf{r}_b \cdot \dot{\mathbf{r}}_b + \dot{\mathbf{r}}_b \cdot \frac{d\dot{\mathbf{r}}_b}{dt} \tag{33}
\]

\[
= -\frac{\mathcal{G} \dot{M}_b}{r_b} + \dot{\mathbf{r}}_b \cdot \mathbf{f}_{\text{ext}} ,
\]

where, \( \frac{d\dot{\mathbf{r}}_b}{dt} = -(\mathcal{G} \dot{M}_b/r_b^3) \mathbf{r}_b + \mathbf{f}_{\text{ext}} \) and \( \mathbf{f}_{\text{ext}} \) is a general (reduced) external force per unit mass affecting both members of the binary: \( \mathbf{f}_{\text{ext}} \equiv \mathbf{f}_{\text{ext},1} - \mathbf{f}_{\text{ext},2} \). In this case, \( \mathbf{f}_{\text{ext},i} = \mathbf{f}_{\text{grav},i} + \mathbf{f}_{\text{acc},i} \) (defined in Section 2.2.1 above). Since \( e_b^2 = 1 + 2l_b^2 \mathcal{E}_b/(\mathcal{G} M_b)^2 \)
Direct computation of torque on the binary

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

$$\langle T \rangle \approx 0.7 \dot{M}_0 a_B^2 \Omega_B$$
$$\approx \langle \dot{J} \rangle$$

(for $q=1$, $e_B=1$ binary)
**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
Circumstellar Disk within Binary

Disk is warped at outer region

⇒ Smaller warp

Typical alignment time >> precession period

⇒ Misalignment can persist
Observations

Circumbinary disks around binaries??

AK Sco
Czekala+15

Misaligned circumbinary debris disk systems:

KH 15D (Winn+04; Capelo+12)
99 Herculis (Kennedy+12)

DQ Tau
Czekala+15
99 Herculis: host to a circumbinary polar-ring debris disc

G. M. Kennedy, 1* M. C. Wyatt, 1 B. Sibthorpe, 2 G. Duchêne, 3, 4 P. Kalas, 3
B. C. Matthews, 5, 6 J. S. Greaves, 7 K. Y. L. Su 8 and M. P. Fitzgerald 9, 10

1Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA
2UK Astronomy Technology Center, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ
3Department of Astronomy, University of California, B-20 Hearst Field Annex, Berkeley, CA 94720-3411, USA

$e_b = 0.77$, $P_b = 56$ yrs
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 $0.02a_b$
Pulsed Accretion Observed in T Tauri Binaries

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

Tofflemire et al. 2016