Stars, Disks and Massive Black Holes

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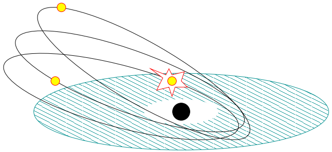
Gravitational vs hydrodynamical star-disk interactions



- Gravitational torques are typically much stronger than ram pressure torques:

$$\left.\frac{\Delta J_{\mathrm{ram}}}{\Delta J_{\mathrm{grav}}}\right|_{\mathrm{per\ period}} \sim \left(\frac{M_\bullet}{M_\star}\right)\left(\frac{R_\star}{R}\right)^2$$

- Compact disks (luminous active galactic nuclei / Quasars, $R \sim 2000 r_g$):

$$\left.\frac{\Delta J_{\mathrm{ram}}}{\Delta J_{\mathrm{grav}}}\right|_{\mathrm{per\ period}} \sim 0.02\left(\frac{M_\bullet}{10^6 M_\star}\right)^{-1}$$

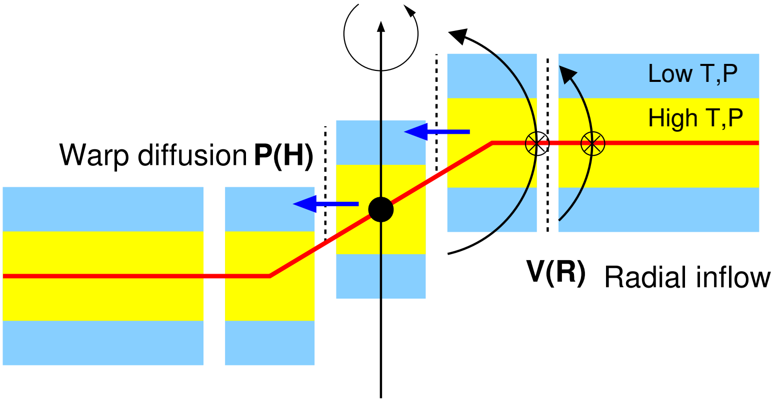
- Gravitational torques significant compared to internal viscous torques ($\alpha < 1$):

$$\left.\frac{\Delta J_{\mathrm{grav}}}{\Delta J_{\mathrm{visc}}}\right|_{\mathrm{per\ period}} \sim \left\{\begin{array}{c}\alpha \\ 1/\alpha\end{array}\right\}\sqrt{N_\star}\left(\frac{H}{R}\right)^{-2}\left(\frac{M_\bullet}{M_\star}\right)^{-1} \sim \begin{cases} 0.1-1 & \perp \text{ (unwarping)} \\ 1-10 & \parallel \text{ (inflow)} \end{cases}$$

Outline

- How do stellar torques affect the disk?
  - Warped accretion disks
  - Resonant relaxation
  - Proof of concept: The maser disk of NGC 4258
    - Disk warping
    - Covering factor
    - Accretion rate
    - MBH spin jitter
- What are the consequences for MBH evolution? (work in progress, open questions)
  - Statistical properties of resonant torques.
  - Stability of thin disks
  - Scaling with MBH

Accretion disk physics



α-disk model

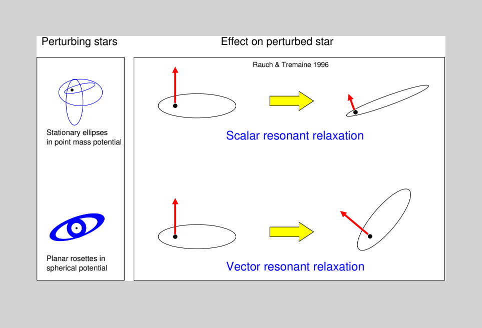
Stress tensor $\sigma_{ij} = \alpha P, \ (0 \lesssim \alpha \lesssim 1)$ (Shakura & Sunyaev 1973)

$t_{\mathrm{flow}} \propto 1/\alpha_1 \quad t_{\mathrm{warp}} \propto 1/\alpha_2$ (Pringle 1992)

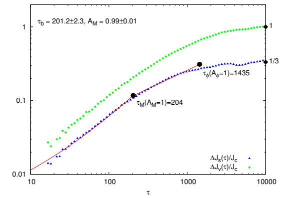
$\alpha_2 \simeq 1/2\alpha_1$ (Ogilvie 1999)

Disks unwarp faster than they flow in

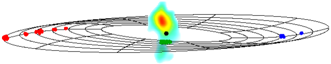
The randomization of stellar systems: Resonant Relaxation



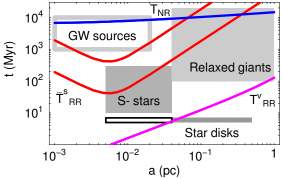
***N*-body simulations** (Eilon, Kupi & Alexander 2009)



NGC4258 maser disk (Herrnstein et al 1996)



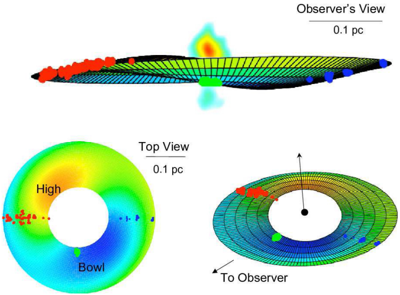
Maser disk warp (Bregman & Alexander 2009, 2012)



GC dynamics (Hopman & Alexander 2006)

The warped maser disk in NGC 4258

(Herrnstein et al 1996)



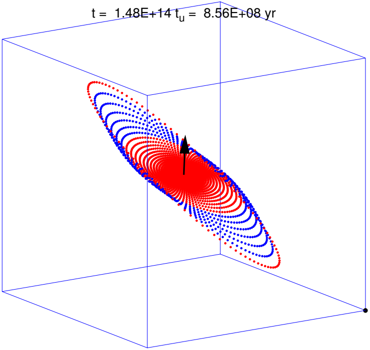
Radio measurements of x, v, $\dot{v}$

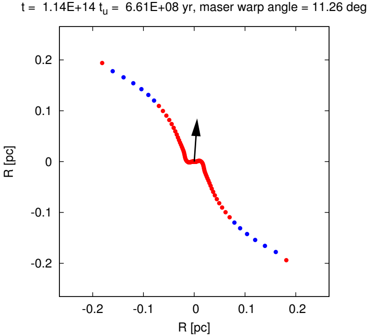
▼

$$M_\bullet = 3.7\times10^7\, M_\odot, \qquad D = 7.2 \text{ Mpc}, \qquad R_{\rm in} = 0.14,\ R_{\rm out} = 0.28 \text{ pc}, \qquad \omega \sim 8^\circ$$

$$\left(\Delta J_{\rm ram}/\Delta J_{\rm RR} \sim 10^{-7},\ \ \Delta J_{\rm grav}/\Delta J_{{\rm visc},\perp} \sim 0.25,\ \ \Delta J_{\rm grav}/\Delta J_{{\rm visc},\parallel} \sim 4\right)$$

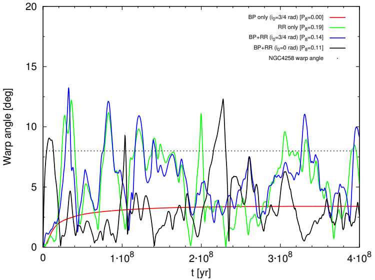
RR Disk warping

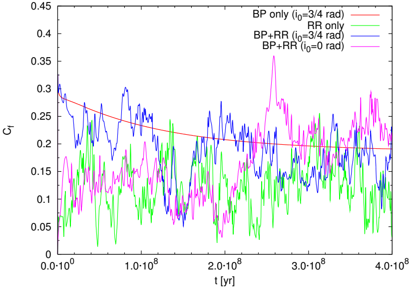




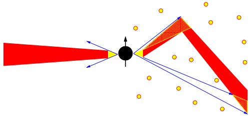
(Bregman & Alexander 2012)

RR-induced warping of NGC 4258: the covering factor



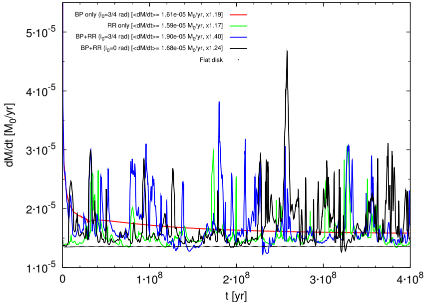


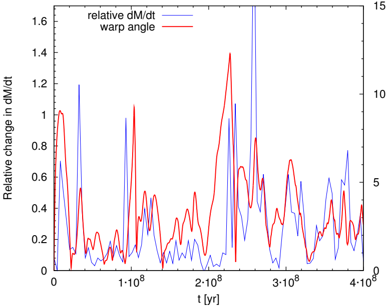
(Bregman & Alexander 2012)



- External heating and ionization thought crucial for explaining disk properties.
- RR-warping exposes disk to the ionizing central source.

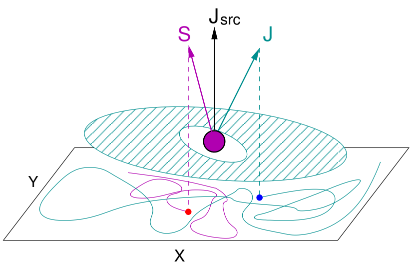
RR-induced warps and the mass accretion rate

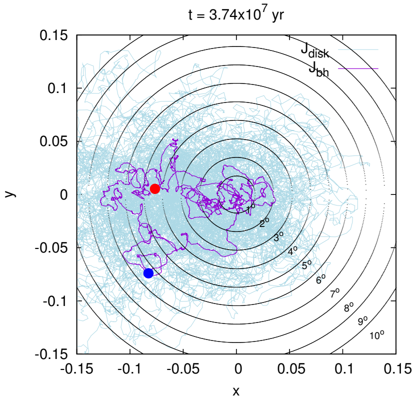




- RR-warping increases $\dot{M}$ by up to $\times 4$, $\left\langle \dot{M} \right\rangle$ by up to $\times 1.5$.
- Eddington-limited growth is exponential.
- RR can accelerate MBH mass and spin growth by $\times 100$ over disk's lifetime. Alternatively, enhanced mass flow can lead to gravitational instability, fragmentation and star formation.

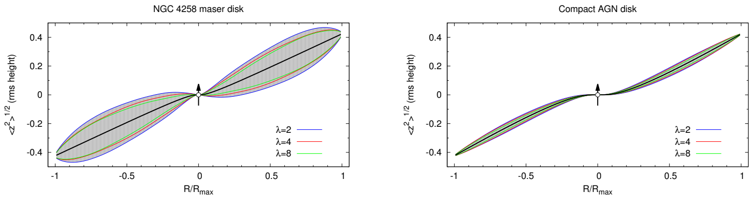
Disk and MBH spin jitter





- MBH-stars angular momentum coupling via the disk (The Bardeen-Petterson frame-dragging effect)
- Implications for radio jet opening angle and orientation?

RR warping of disks
Open questions: Stability and scaling relations



(Ben Bar-Or & T.A. 2013, work in progress)

- The goal: Full 3D statistical description of RR (spherical harmonics in 4D)
  Coherent and diffusive limits, amplitudes, correlation lengths and timescales
- When is a disk stable under RR torquing?
  $M_\bullet$, $M_\star$, $N_\star$, $M_{\rm disk}$, $T_{\rm disk}$, $\nu_{1,2}$, ...
- Warp angle rms: $\omega_{RR} \propto \sqrt{t_{\rm coh}/t_{\nu_2}} \propto M_\bullet^{-3/7}$
- RR warping stronger for growing MBHs in early universe.
- What came first, the MBH or the stars?

Summary

- Dense stellar clusters around an accreting MBH can strongly affect the disk by fast stochastic gravitational torques.
- Demonstration of concept: RR-induced warping can explain the observed warp of NGC 4258 maser disk.
- RR-induced warping increases covering factor, accelerates the accretion of mass and angular momentum, and changes the MBH spin direction.
- Work in progress:
  - Disk stability under RR.
  - Scaling properties with MBH mass, disk properties:
    RR stronger for lower-mass MBHs.
  - Implications for cosmic evolution of MBHs.

The disk evolution equation

Angular momentum density : $\boldsymbol{L}(R) = \Sigma(R)\sqrt{GM_\bullet R}\,\ell(R)$

$$\frac{\partial \boldsymbol{L}}{\partial t} = \underbrace{\frac{1}{R}\frac{\partial}{\partial R}\left[3R\frac{\partial}{\partial R}(\nu_1 L)\ell + \frac{1}{2}\nu_2 R L \frac{\partial \ell}{\partial R}\right]}_{\text{Diffusive accretion of ang. mom. into the MBH}}$$

$$+ \underbrace{\frac{1}{R}\frac{\partial}{\partial R}\left[\left(\nu_2 R^2 \left|\frac{\partial \ell}{\partial R}\right|^2 - \frac{3}{2}\nu_1\right)\boldsymbol{L}\right]}_{\text{Advective current of ang. mom. outward}}$$

$$+ \underbrace{\boldsymbol{T}_{\mathrm{BP}}(R) + \boldsymbol{T}_{\mathrm{RR}}(R) + \boldsymbol{T}_{\mathrm{src}}(R)}_{\text{External torques}}$$

Stochastic torques : $\boldsymbol{T}_{\mathrm{RR}}(R, t;\, M_\bullet, N)$