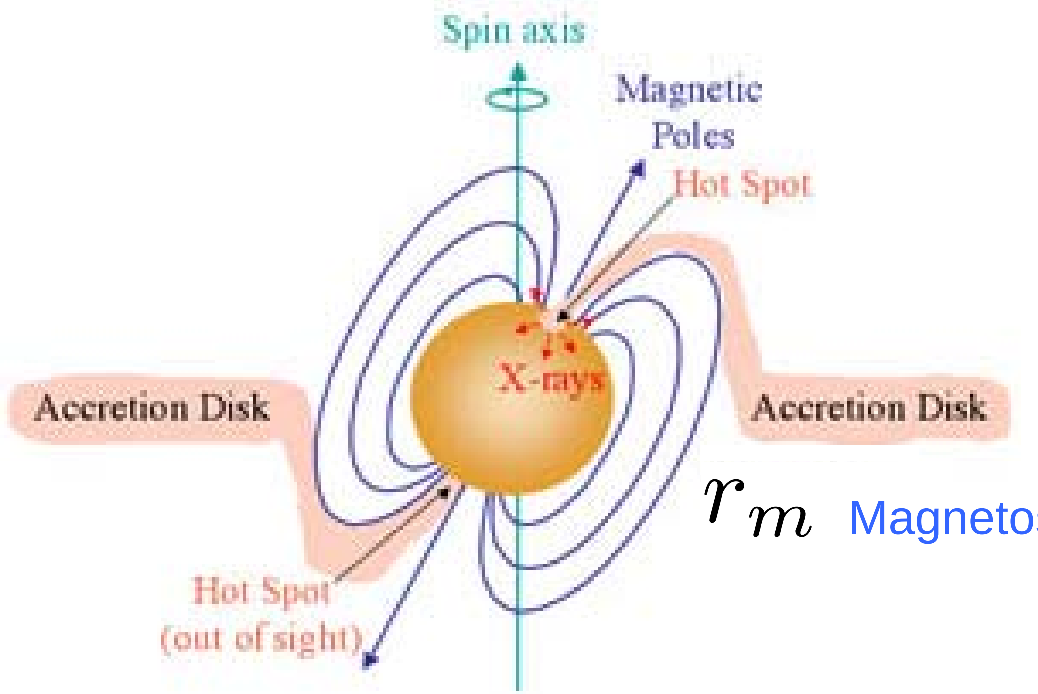
Magnetic Star - Disk Interaction

Dong Lai
Cornell University

Tsinghua IAS, 5/18/2014

Magnetic Star - Disk Interaction: Basic Picture



r_m Magnetosphere radius

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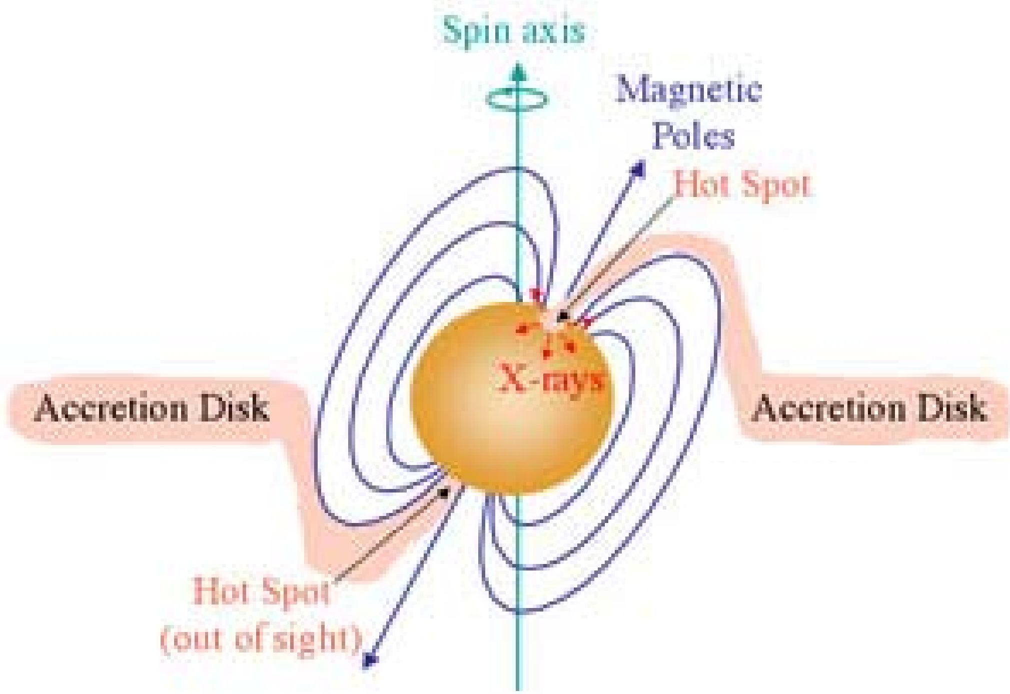
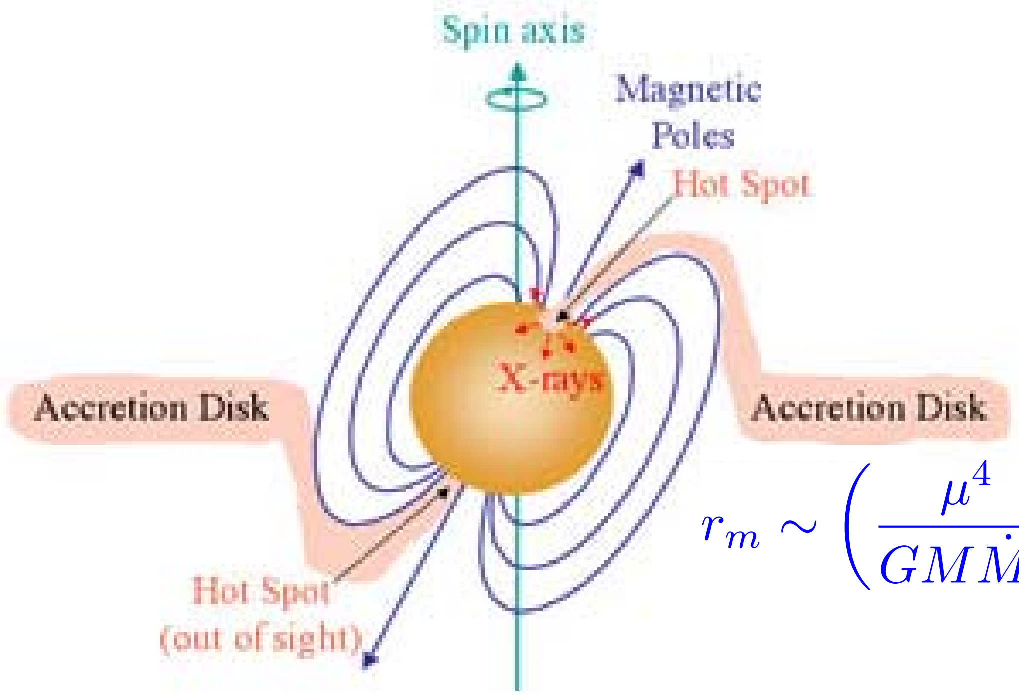


Magnetosphere boundary radius:

For spherical accretion:

$$\frac{B^2}{8\pi} \sim \frac{1}{2}\rho V^2 \quad \text{with} \quad B \sim \frac{\mu}{r^3}, \quad V \sim \sqrt{\frac{GM}{r}}, \quad \rho = \frac{\dot{M}}{4\pi r^2 V} \quad \Rightarrow \quad r_m \sim \left(\frac{\mu^4}{GM\dot{M}^2}\right)^{1/7}$$

Magnetic Star - Disk Interaction: Basic Picture



$$r_m \sim \left(\frac{\mu^4}{GM\dot{M}^2}\right)^{1/7}$$

$$\frac{B(r)^2}{8\pi} \sim \frac{1}{2}\rho V_r V_\phi$$

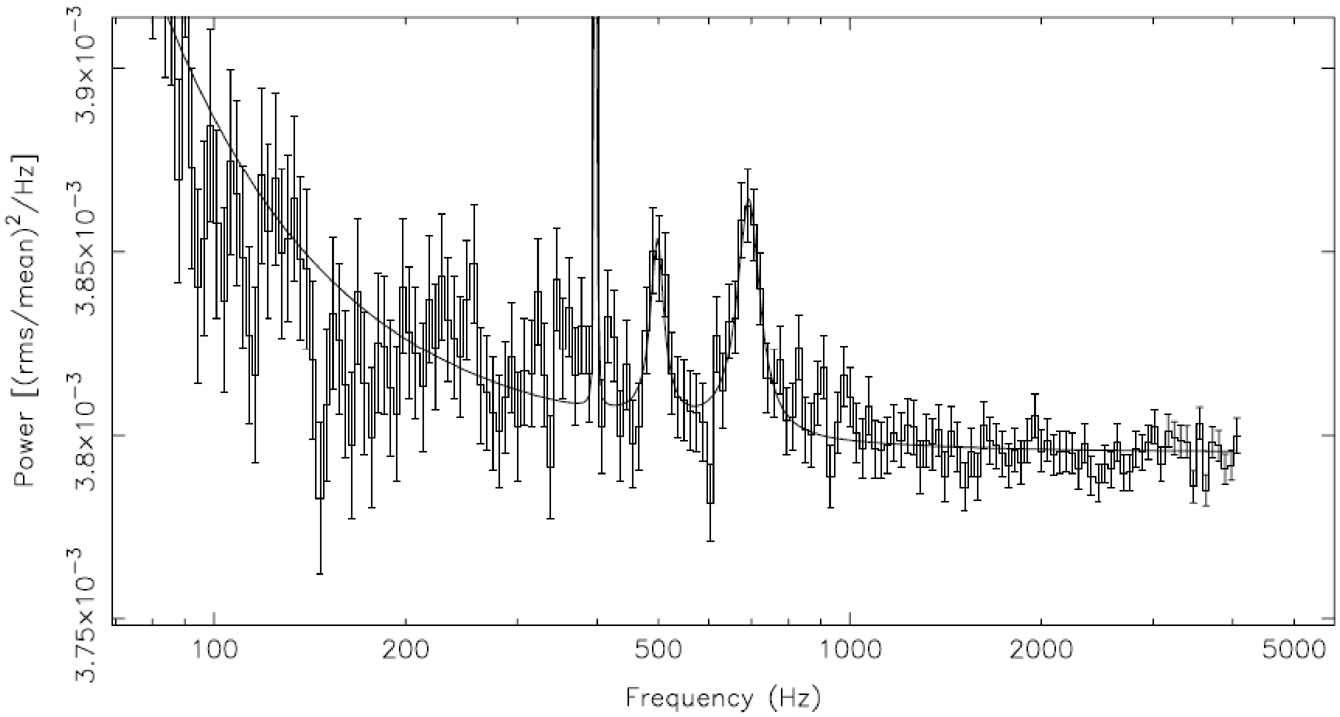
Accreting x-ray pulsars: $B_\star \sim 10^{12}\mathrm{G}, \quad r_m \sim 10^2 R_\star$

Accreting ms pulsars: $B_\star \sim 10^{8}\mathrm{G}, \quad r_m \sim (\mathrm{a\ few}) R_\star$

Accreting WDs (Intermediate polars): $B_\star \sim 10^{7}\mathrm{G}, \quad r_m \sim 10 R_\star$

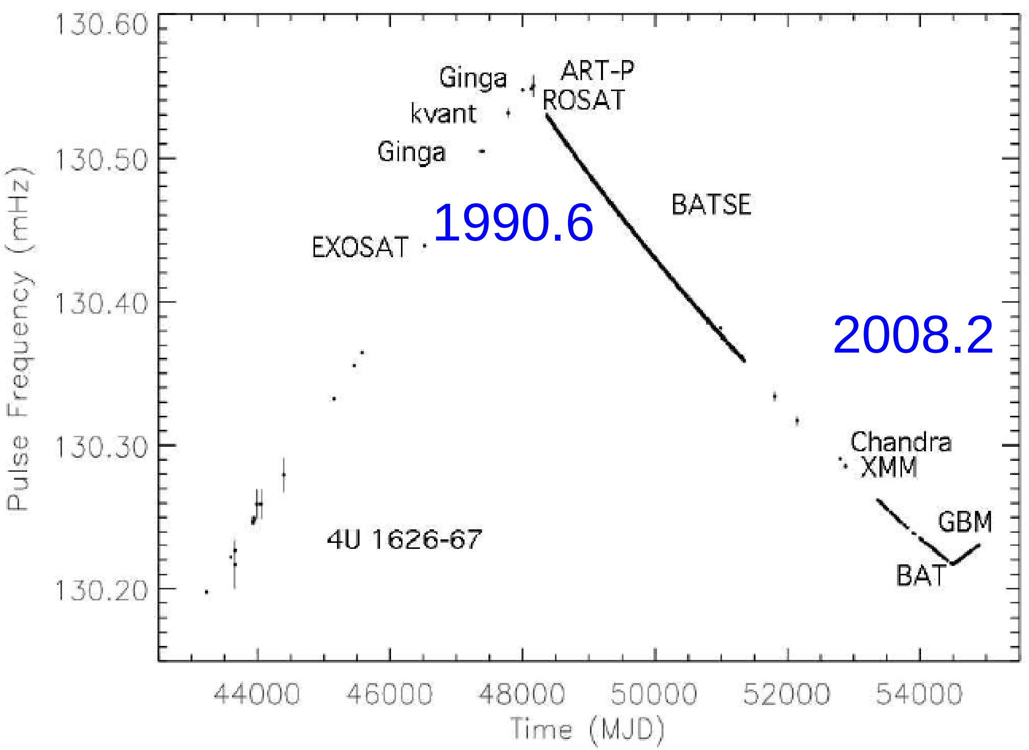
Protostars (Classical T Tauri stars): $B_\star \sim 10^{3}\mathrm{G}, \quad r_m \sim (\mathrm{a\ few}) R_\star$

Application:
QPOs in Accreting Millisecond Pulsars



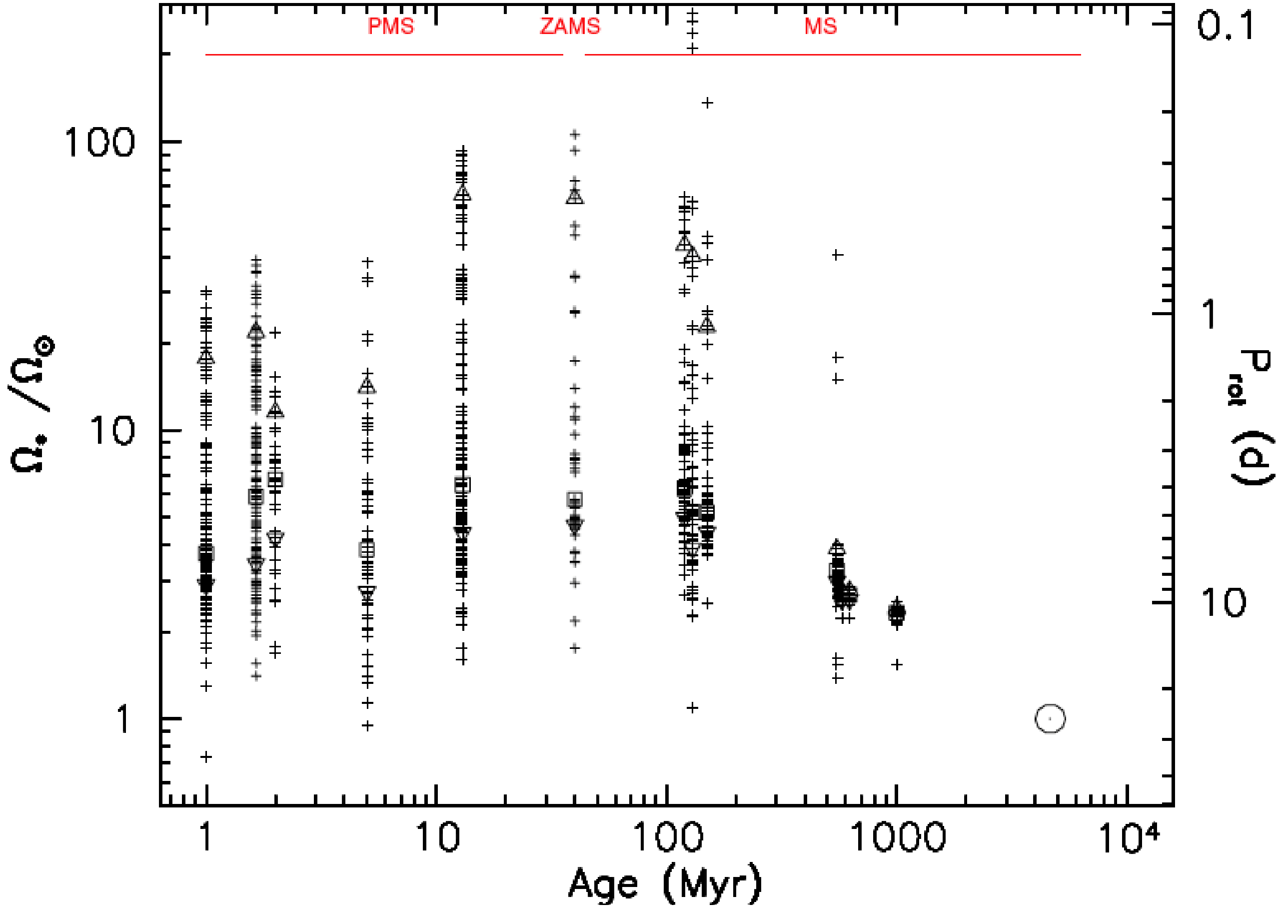
Van der Klis 2005

Application:
Spinup/Spindown of Accreting X-ray pulsars



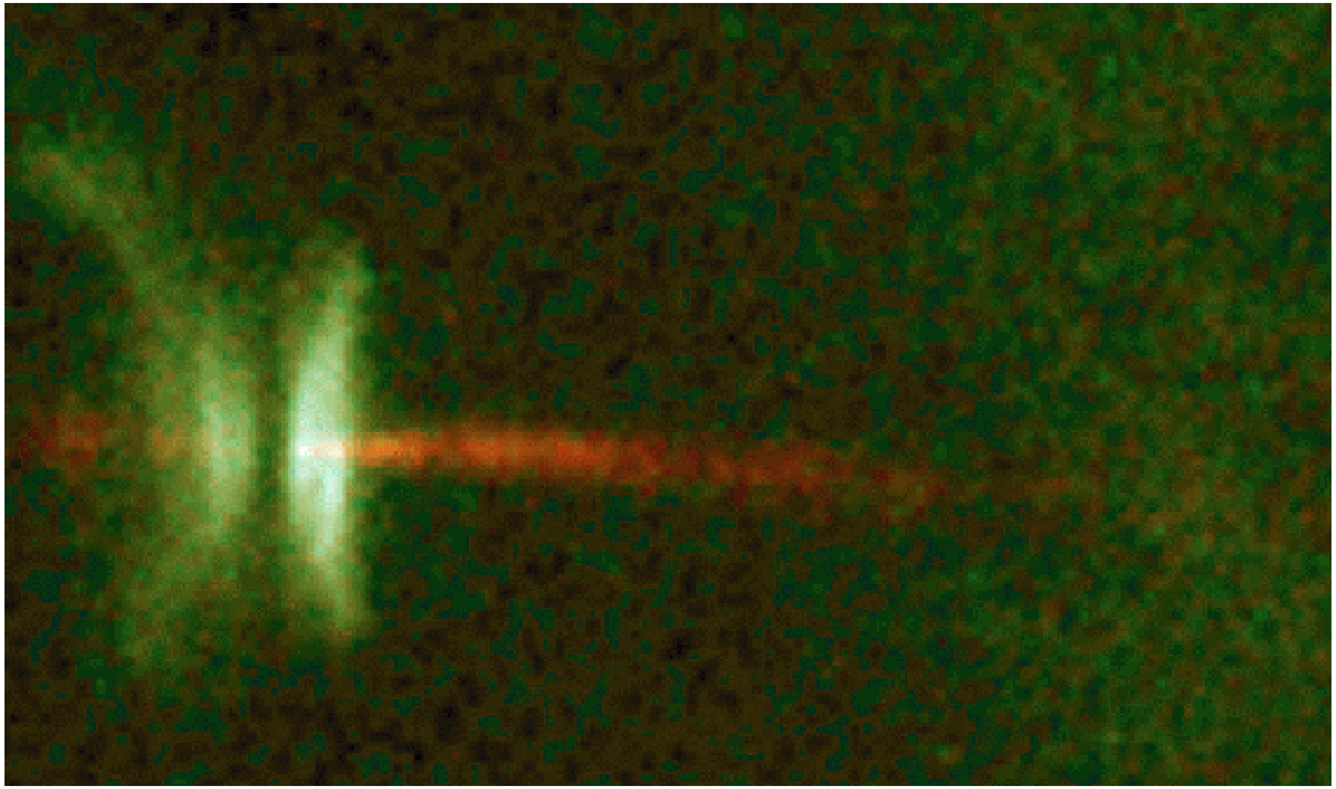
Camero-Arranz et al. 2010,2012

Application:
Rotation of Protostars: why 10% of breakup?



Gallet & Bouvier 2013

Application:
Outflows/jets from protostars:



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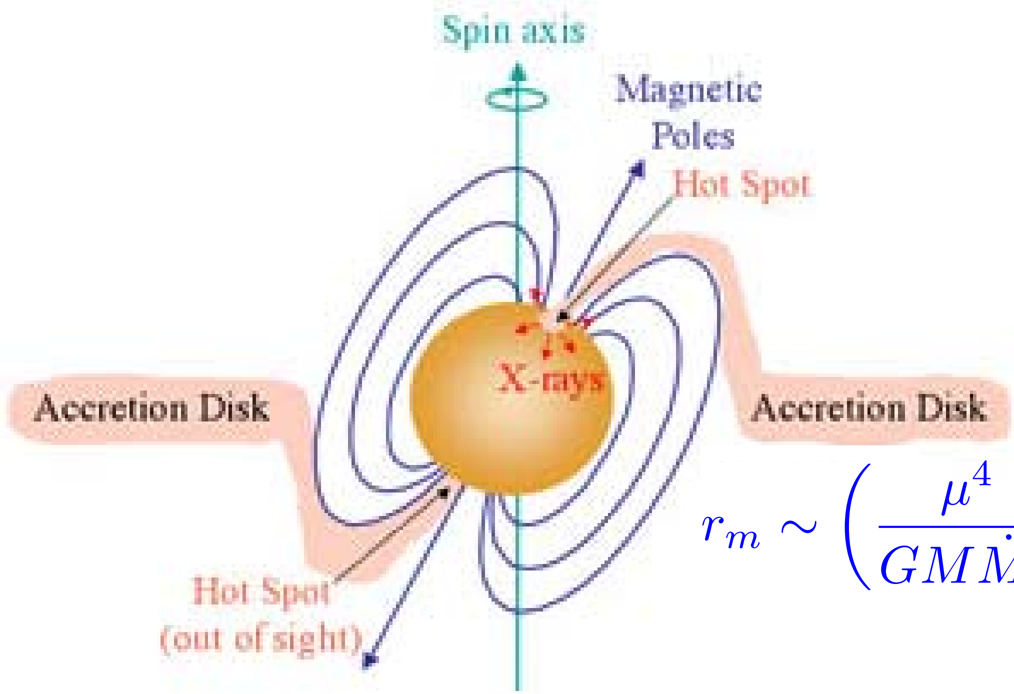

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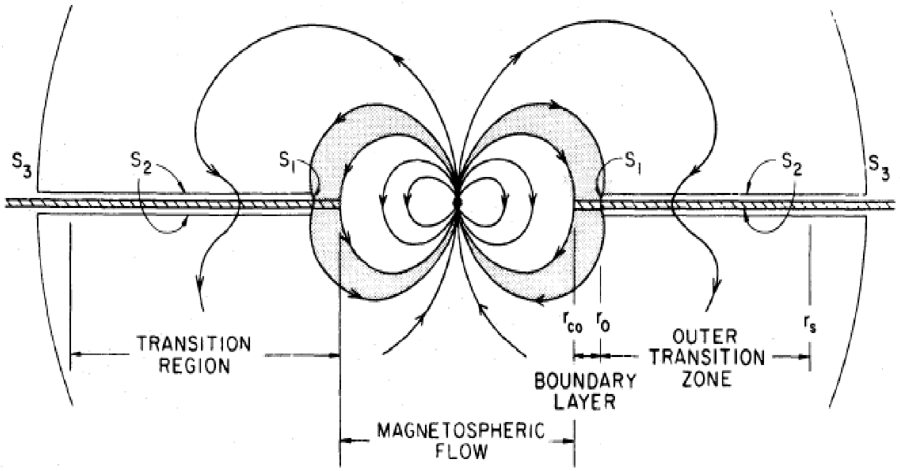
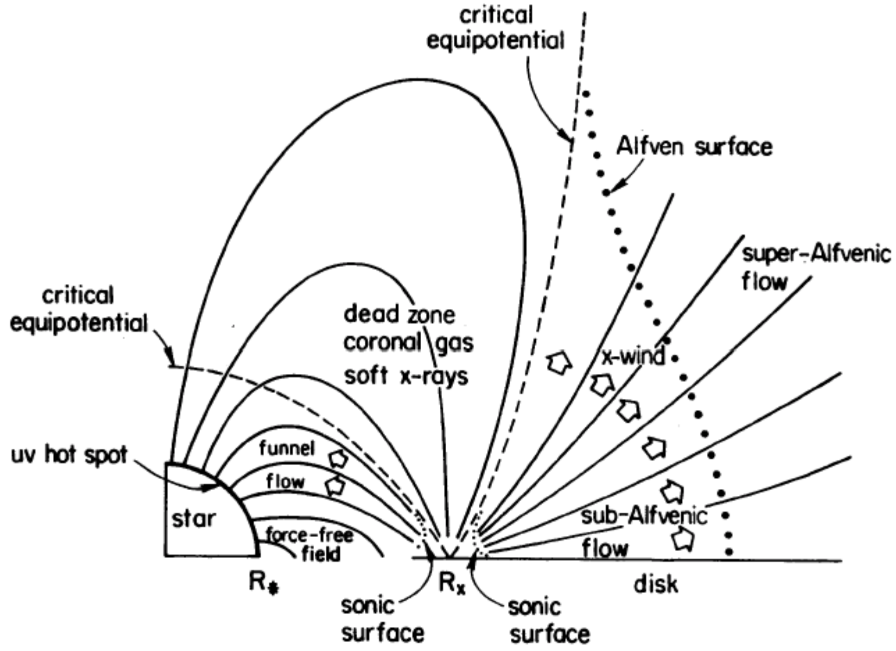
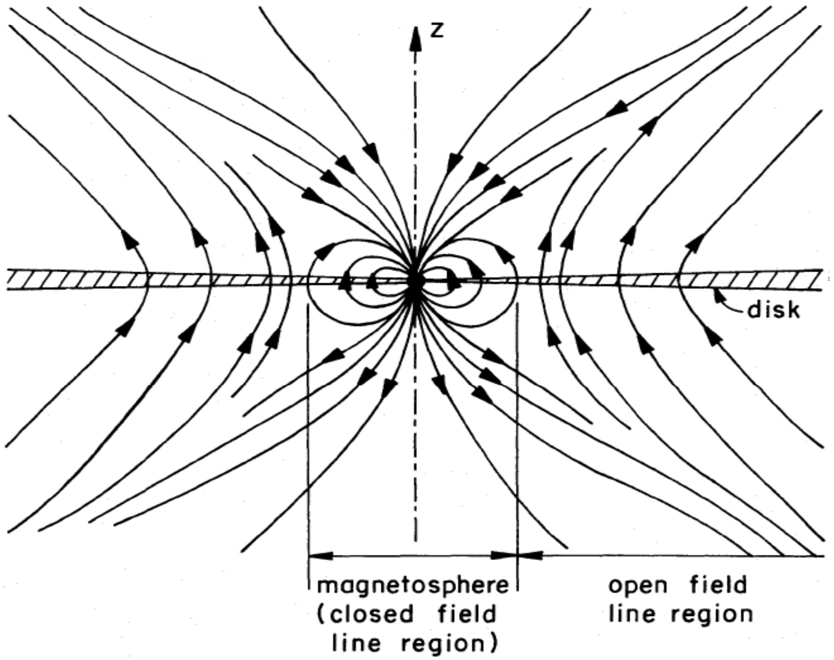


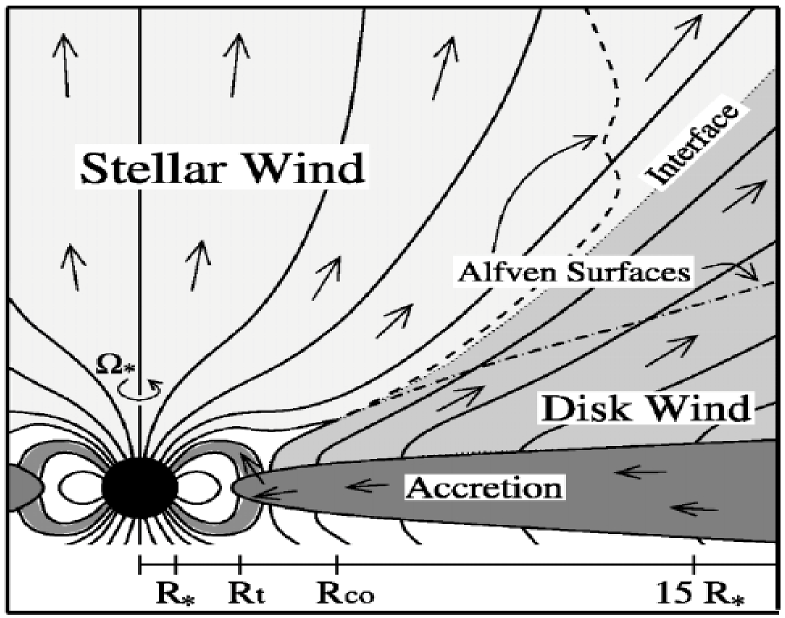
Ghosh & Lamb 1979



Shu et al. 1994



Lovelace et al. 1995

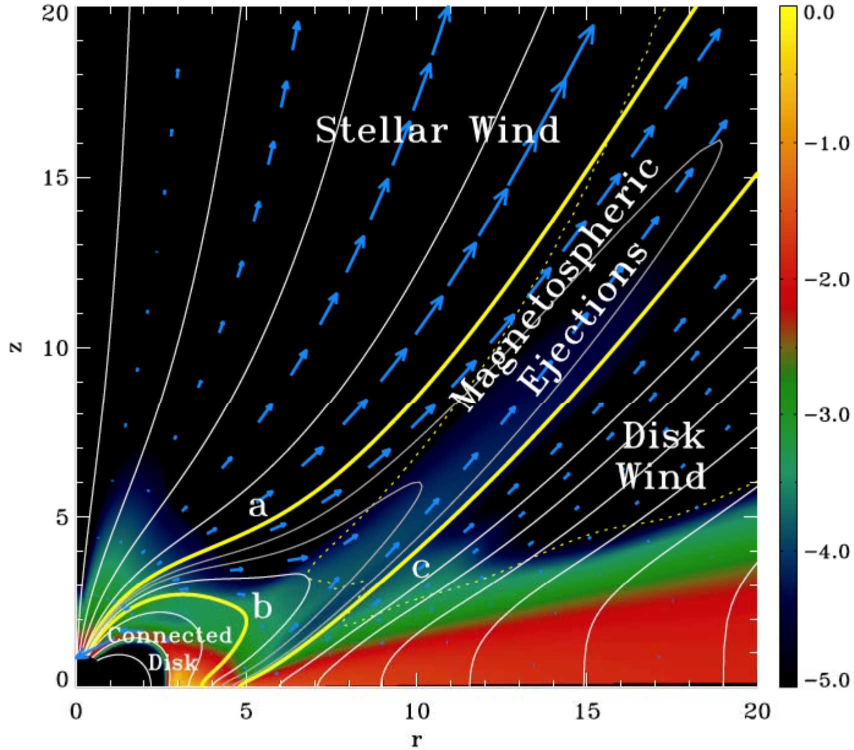


Matt & Pudritz 2005

Simulations…

Hayashi, Shibata & Matsumoto, Miller & Stone, Goodson, Winglee & Bohm, Fendt & Elastner, Matt et al, Romanova, Lovelace, Kulkarni, Long, Lii et al, Zanni & Ferreira, ……

Romanova et al. 12



Zanni & Ferreira ‘13

Outstanding Issues:
(uncertainties, possible applications…)

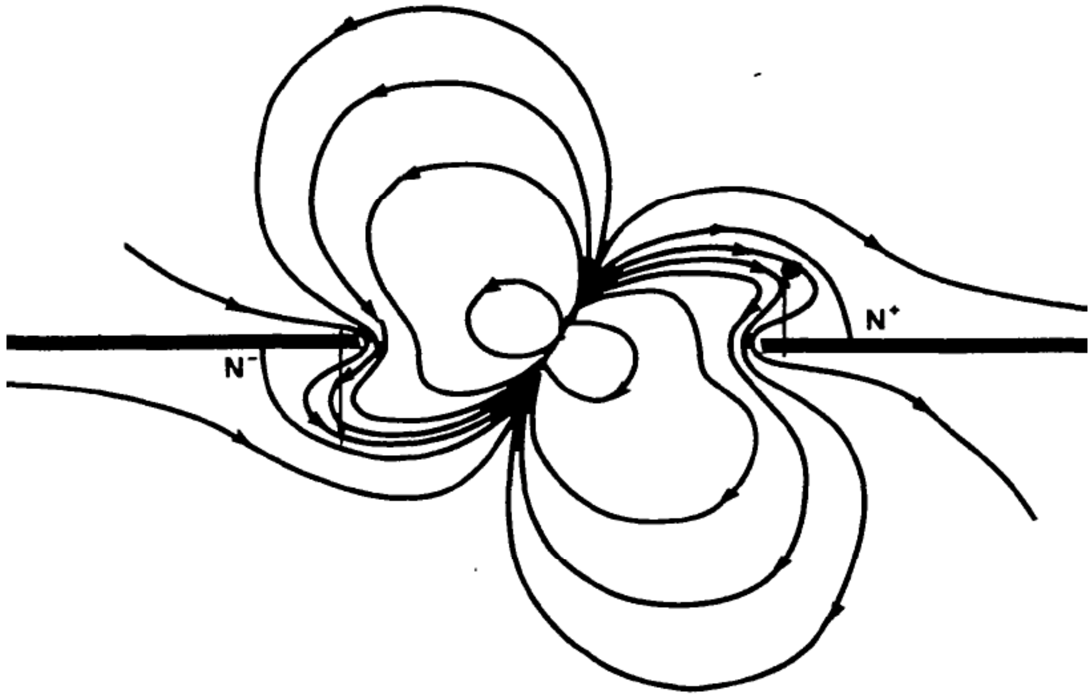
- Magnetosphere boundary vs disk inner radius
- Magnetic linkage between star and disk
  - quasi-cyclic behavior
- Magnetosphere outflows
- Torque on the star: Spinup/spindown
- Misaligned dipole: Effect on disks
- Spin-disk misalignment: Application to exoplanets

Dipole Field Invaded by a Conducting Disk

Disk is a good conductor:
Diffusion of B into disk:

$$t_{\rm diff} \sim \frac{H^2}{\eta} \sim \frac{1}{\alpha\Omega}$$

$$\eta \sim \nu = \alpha H c_s \qquad \text{(MRI)}$$



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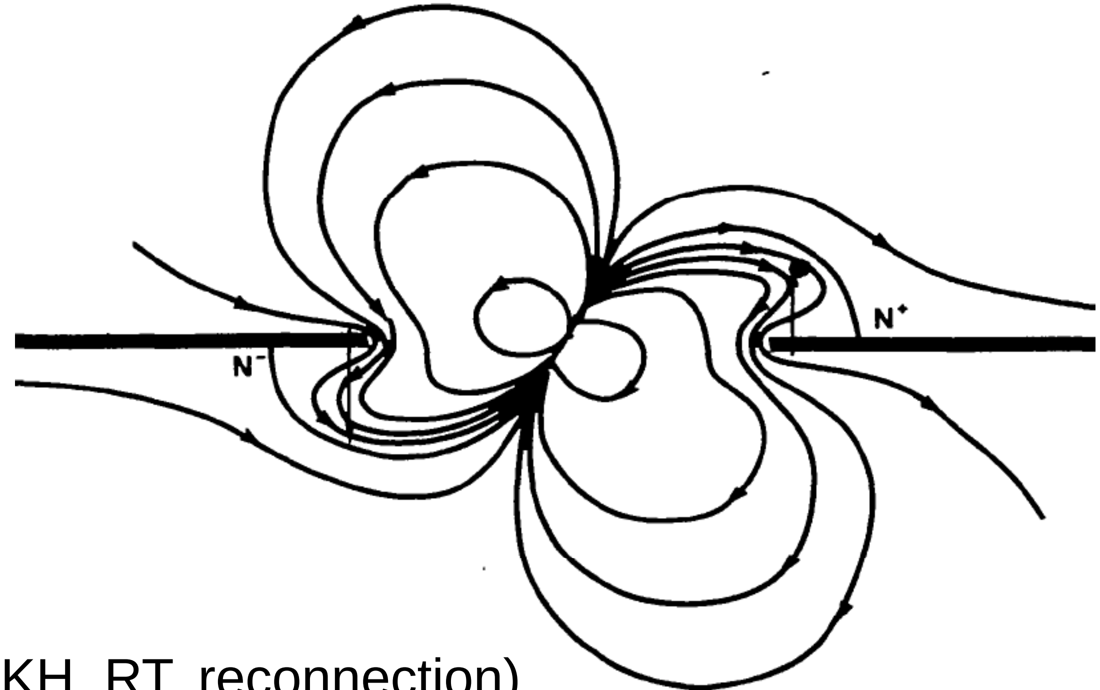


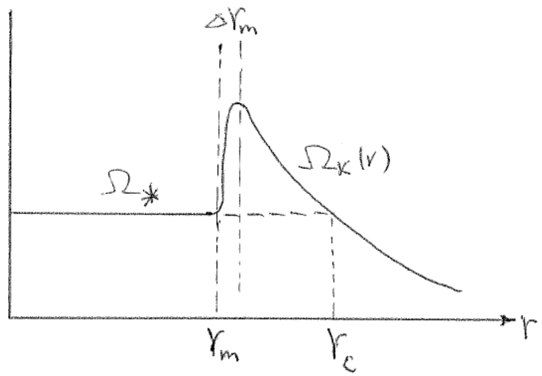
Instabilities at inner edge (KH, RT, reconnection)
➔ **Boundary layer**

Magnetosphere Boundary Layer

$r_m \rightarrow r_m + \Delta r_m$

Transition from Ω_K to $\Omega_\star$

$B_{\phi+} = -\zeta B_z$



Magnetic torque on BL (per unit area)

$$r\frac{B_z B_{\phi+}}{2\pi} = \Sigma\frac{\mathrm{d}(r^2\Omega)}{\mathrm{d}t} = \Sigma\, v_r \frac{\partial(r^2\Omega)}{\partial r}$$

$$\Rightarrow \; r_m \sim \left(\frac{\mu^4}{GM\dot{M}^2}\right)^{1/7}$$

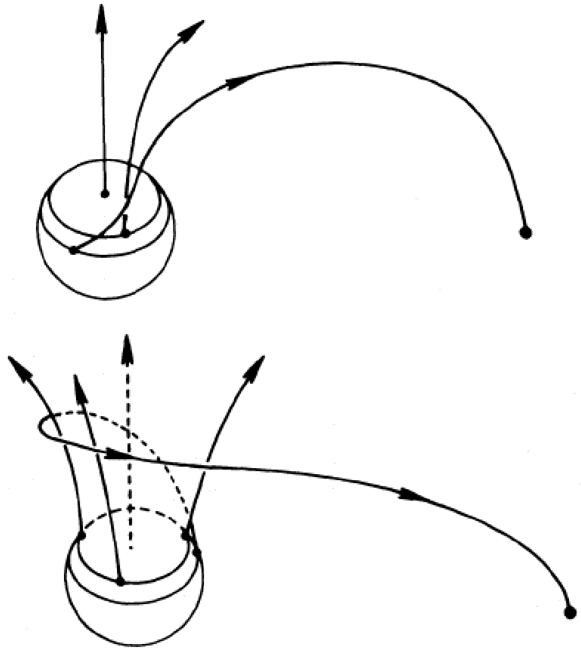
↑ depends on ζ, Δr_m.

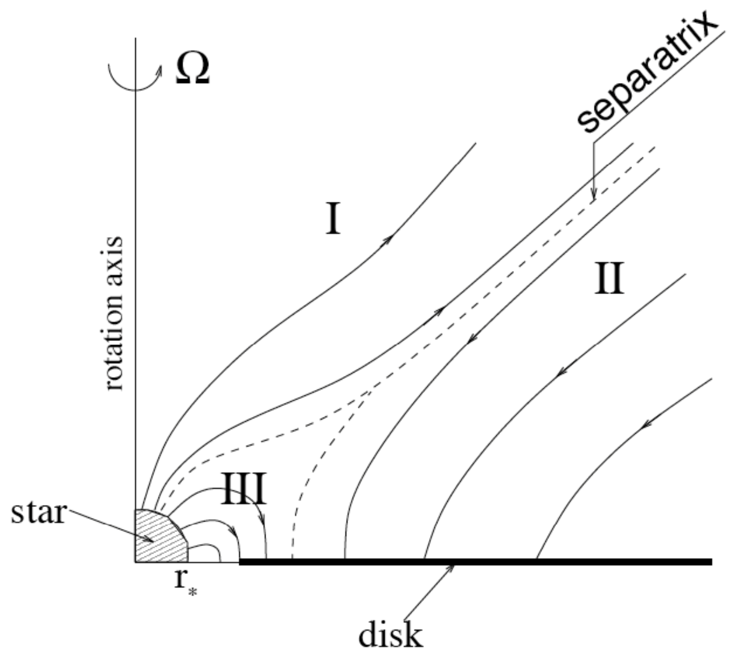
Star-Disk Linkage

(Width, Time-dependence…)

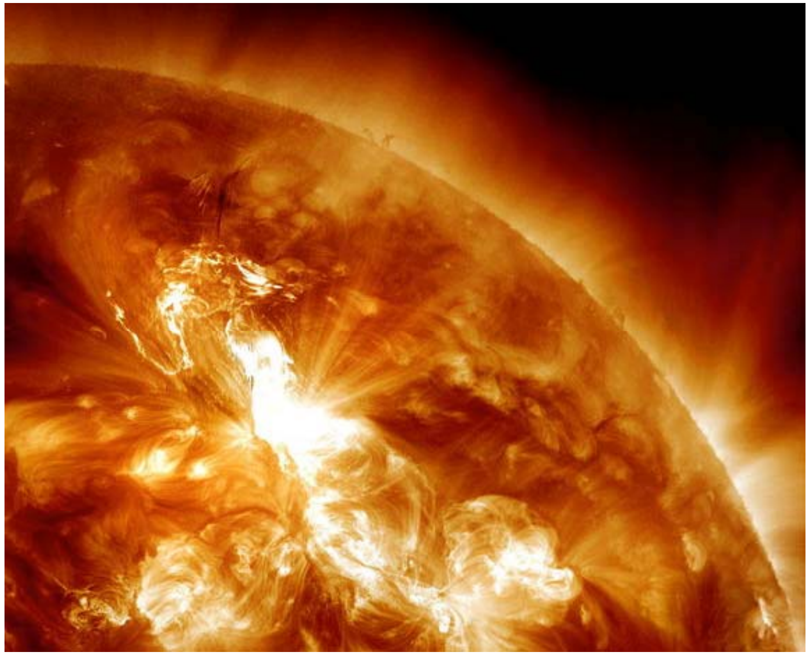
Linked fields are twisted by differential rotation…

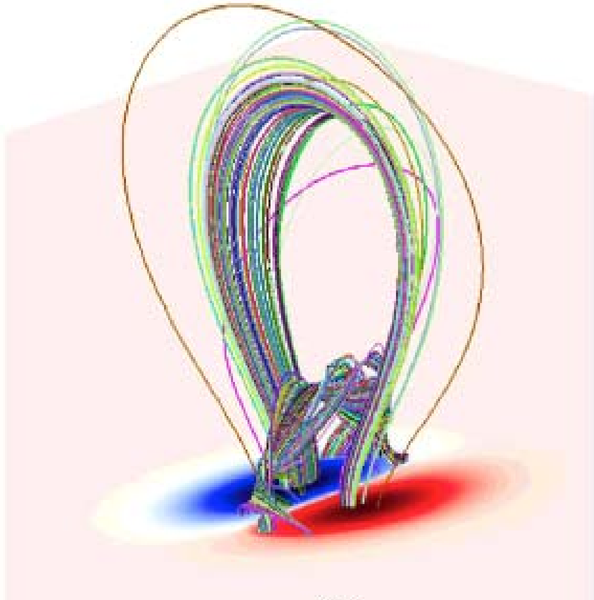
➔Field inflates, breaks the linkage



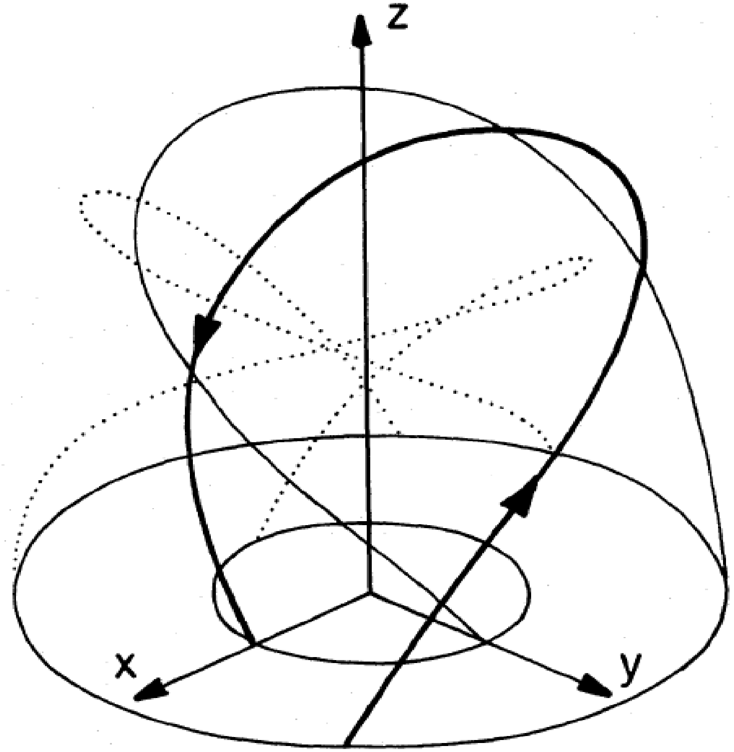


Aly; Lovelace et al.; Uzdensky,…





(b)



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(Width, Time-dependence…)

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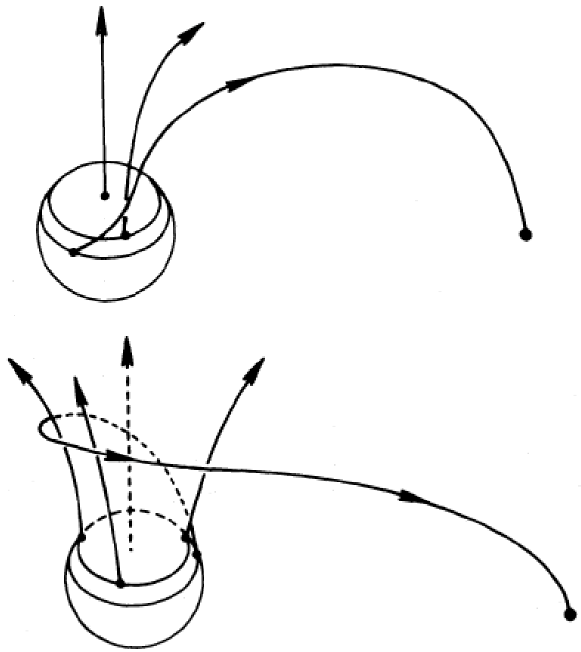
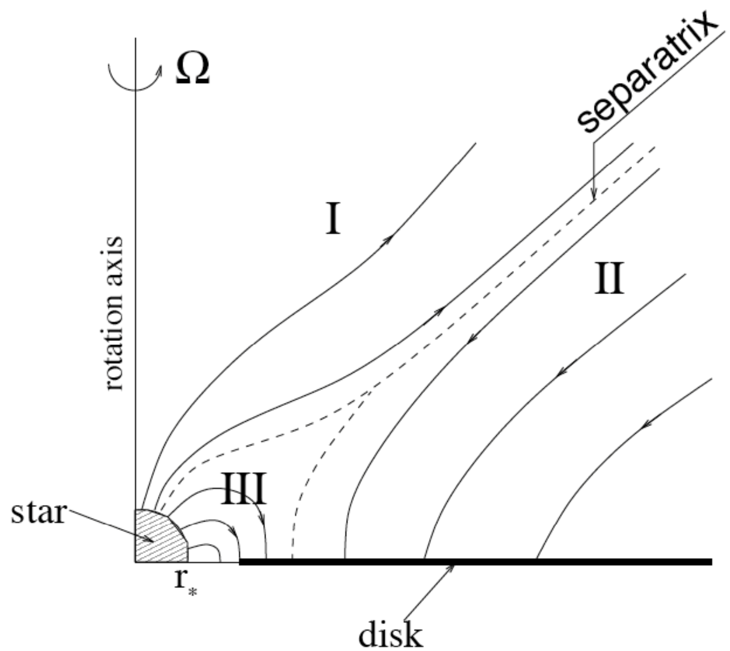


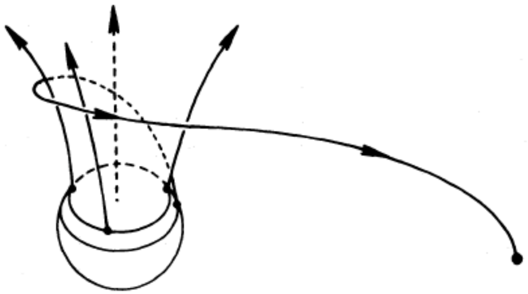


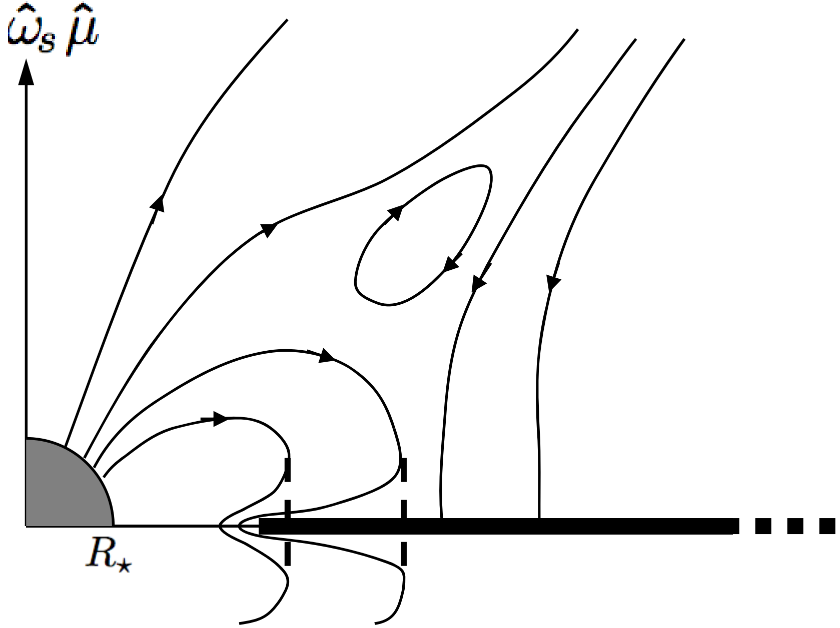
Maximum twist: $\left|\frac{B_{\phi+}}{B_z}\right|_{\max} \sim 1$

Aly; Lovelace et al.; Uzdensky,…

Star-Disk Linkage: Quasi-cyclic behavior
(Width, Time-dependence…)

Stellar field penetrates the inner region of disk;
Field lines linking star and disk are twisted --> toroidal field --> field inflation
Reconnection of inflated fields restore linkage





Inevitable…

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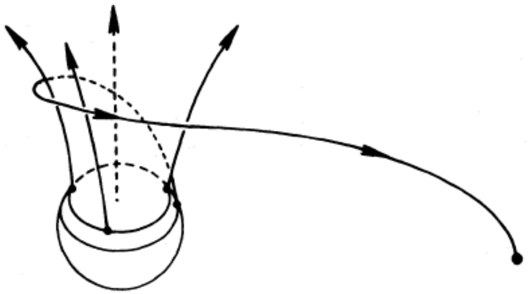
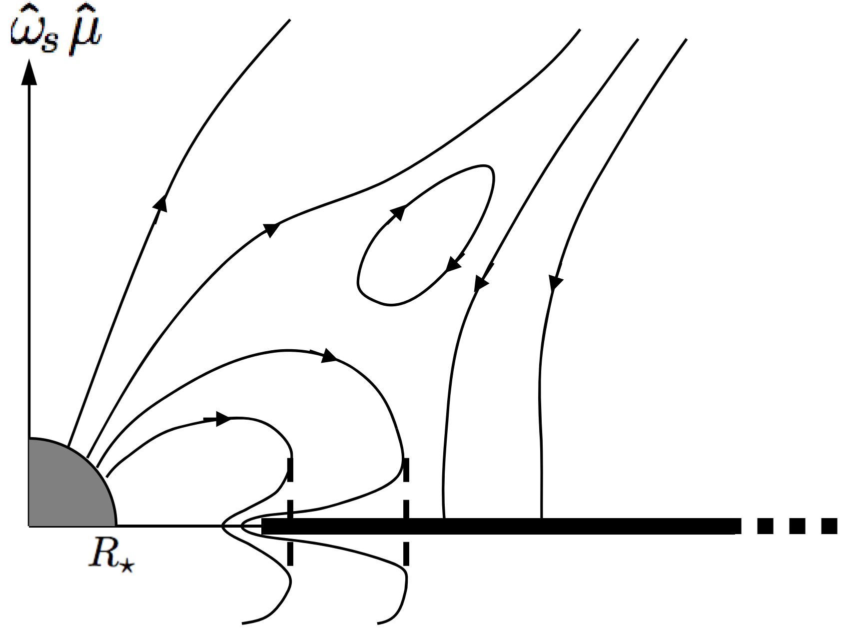
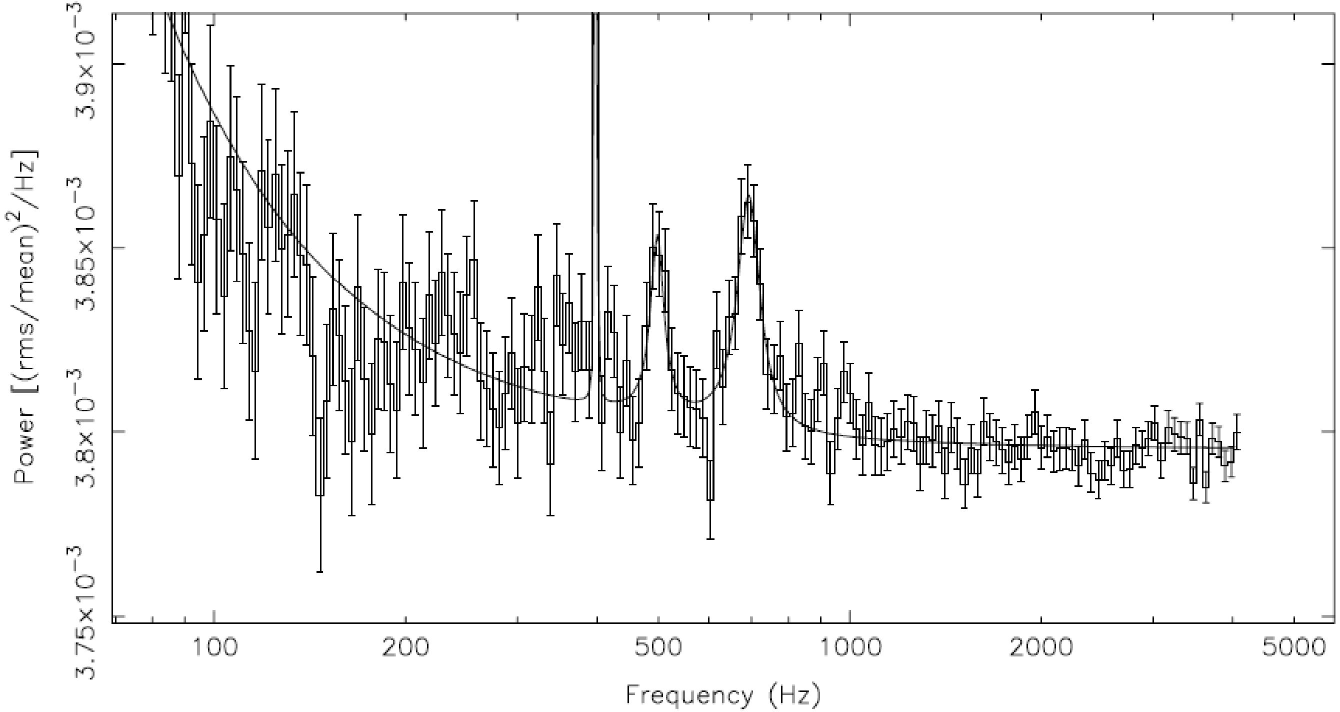




Application: Connection with QPOs in LMXBs (and other systems) ?

Quasi-Periodic Oscillations (QPOs)

Power density spectrum of x-ray flux variations of accreting millisecond pulsars



Van der Klis 2005

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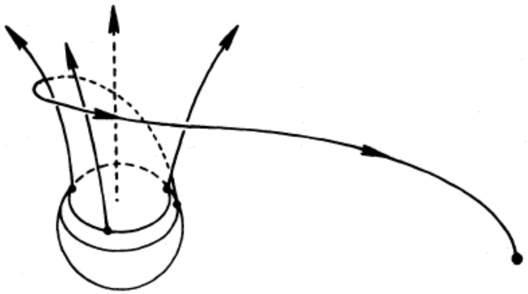
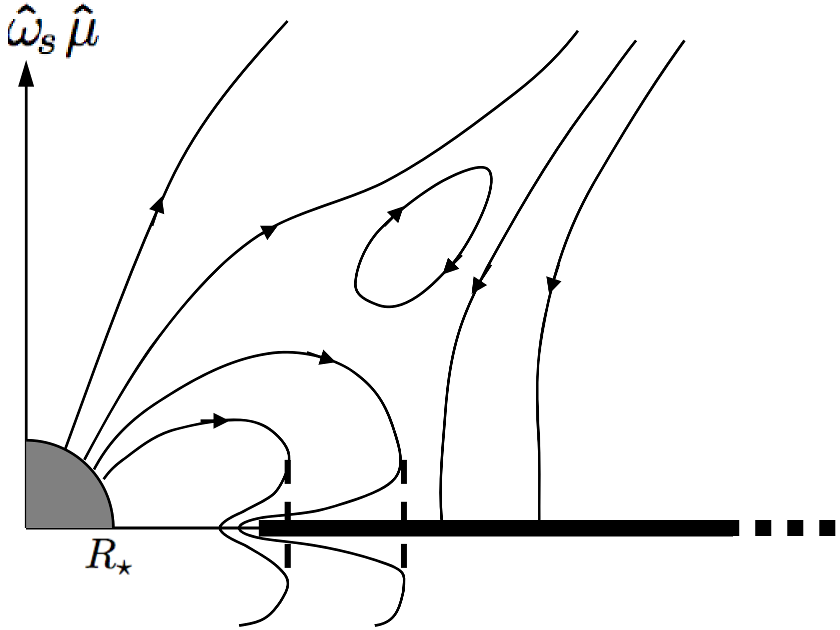
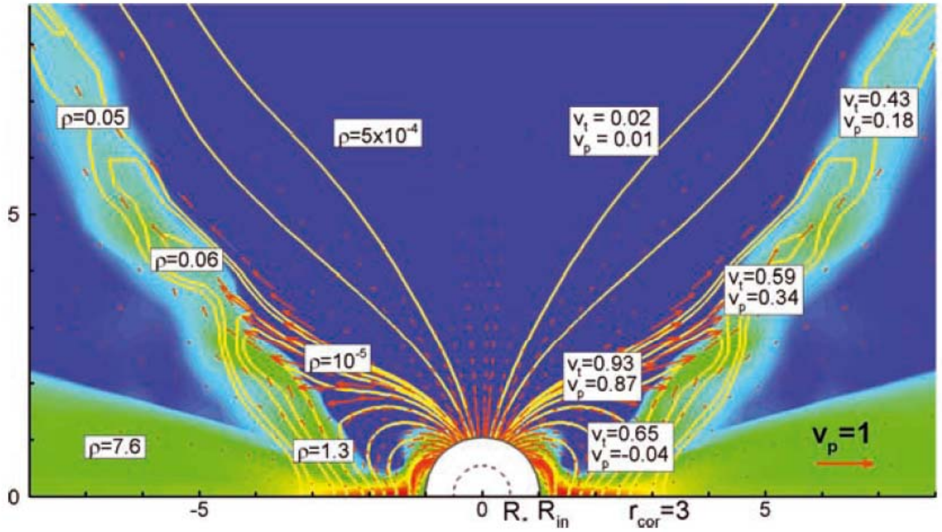


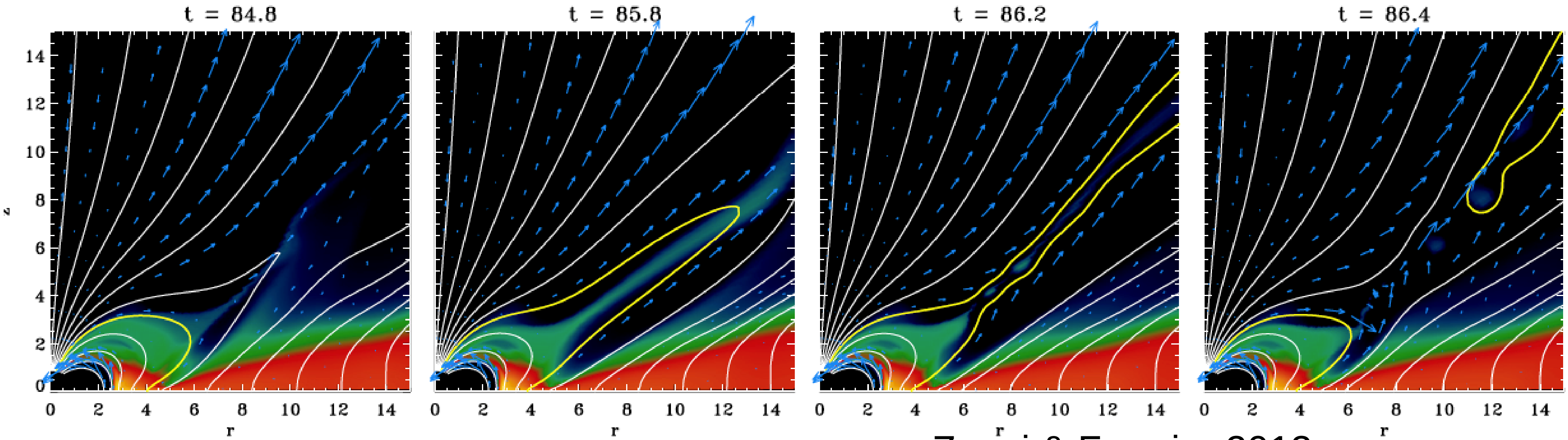


Application: Episodic outflow … Connection with observations?

Ejection from Magnetospheric Boundary



Romanova et al. 2009



Zanni & Ferreira 2013

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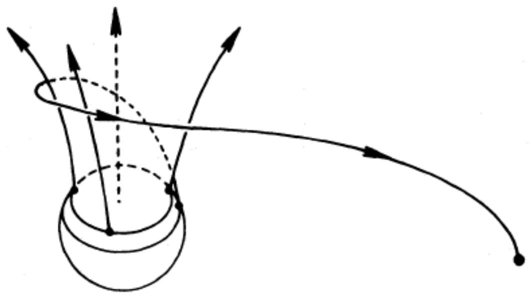
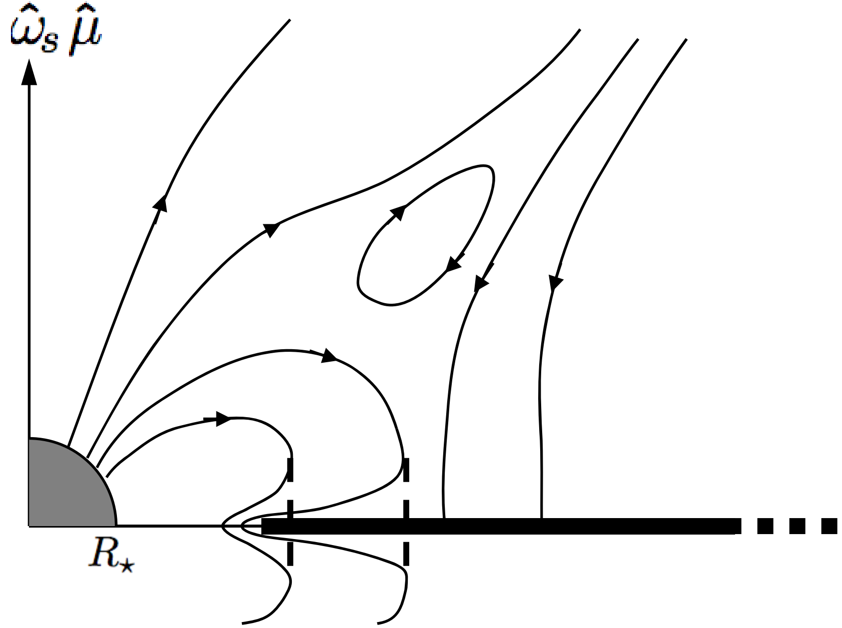
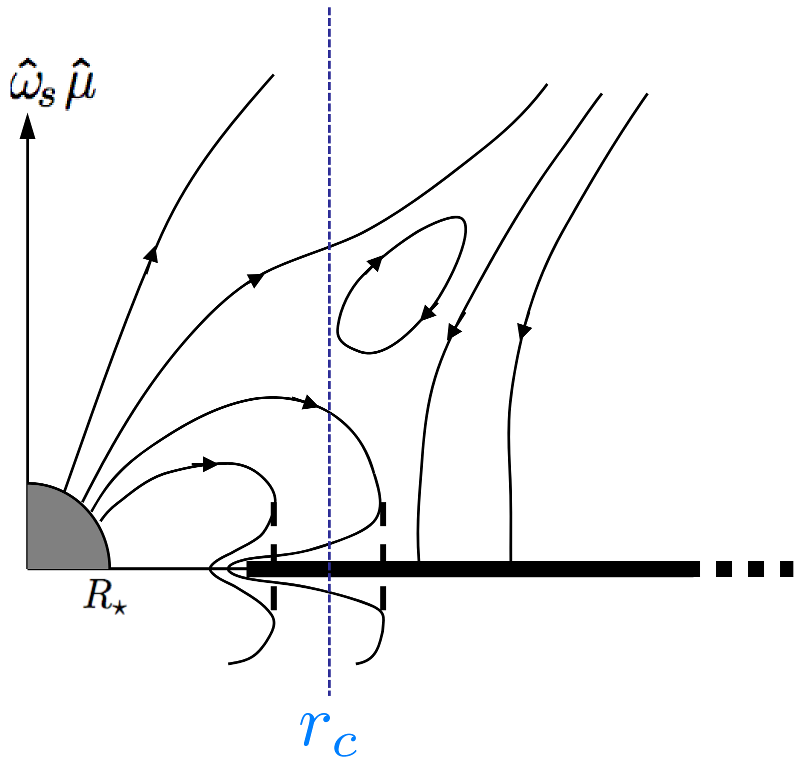




QUESTION: On average, what is the width of the linked region? Δr

Torque on Star



$$\frac{dJ_\star}{dt} \simeq \dot{M}_{\rm acc} r_m^2 \Omega(r_m) + T_m$$

$$T_m \simeq -\left(r^2 B_z B_{\phi+}\right)_{r_m} \Delta r = \zeta \left(r^2 B_z^2\right)_{r_m} \Delta r \quad \text{for } B_{\phi+} = -\zeta B_z$$

Note: $|\zeta| \sim 1$: $\zeta > 0$ when $r < r_c$ and $\zeta < 0$ when $r > r_c$

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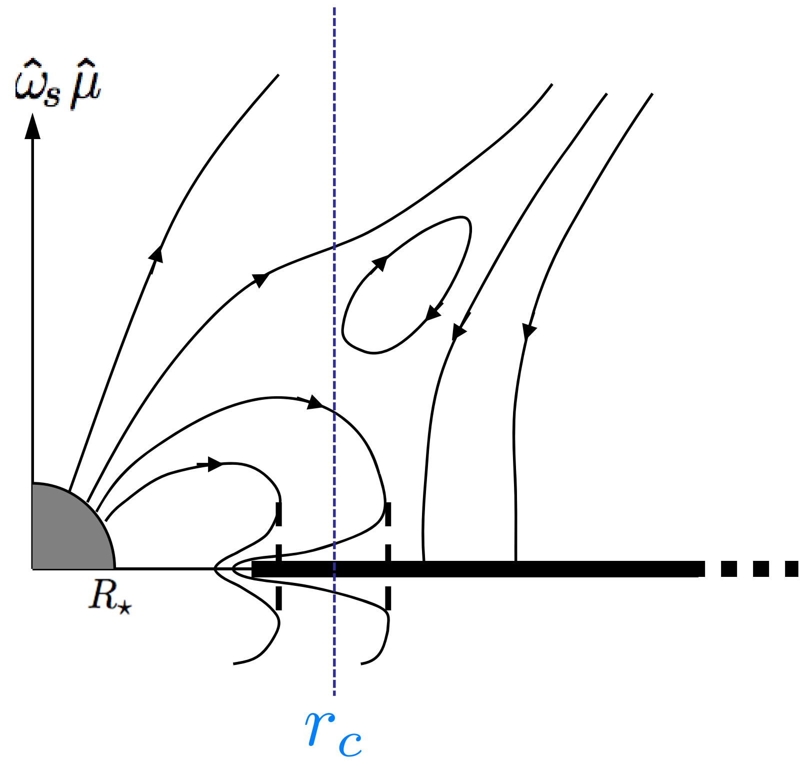

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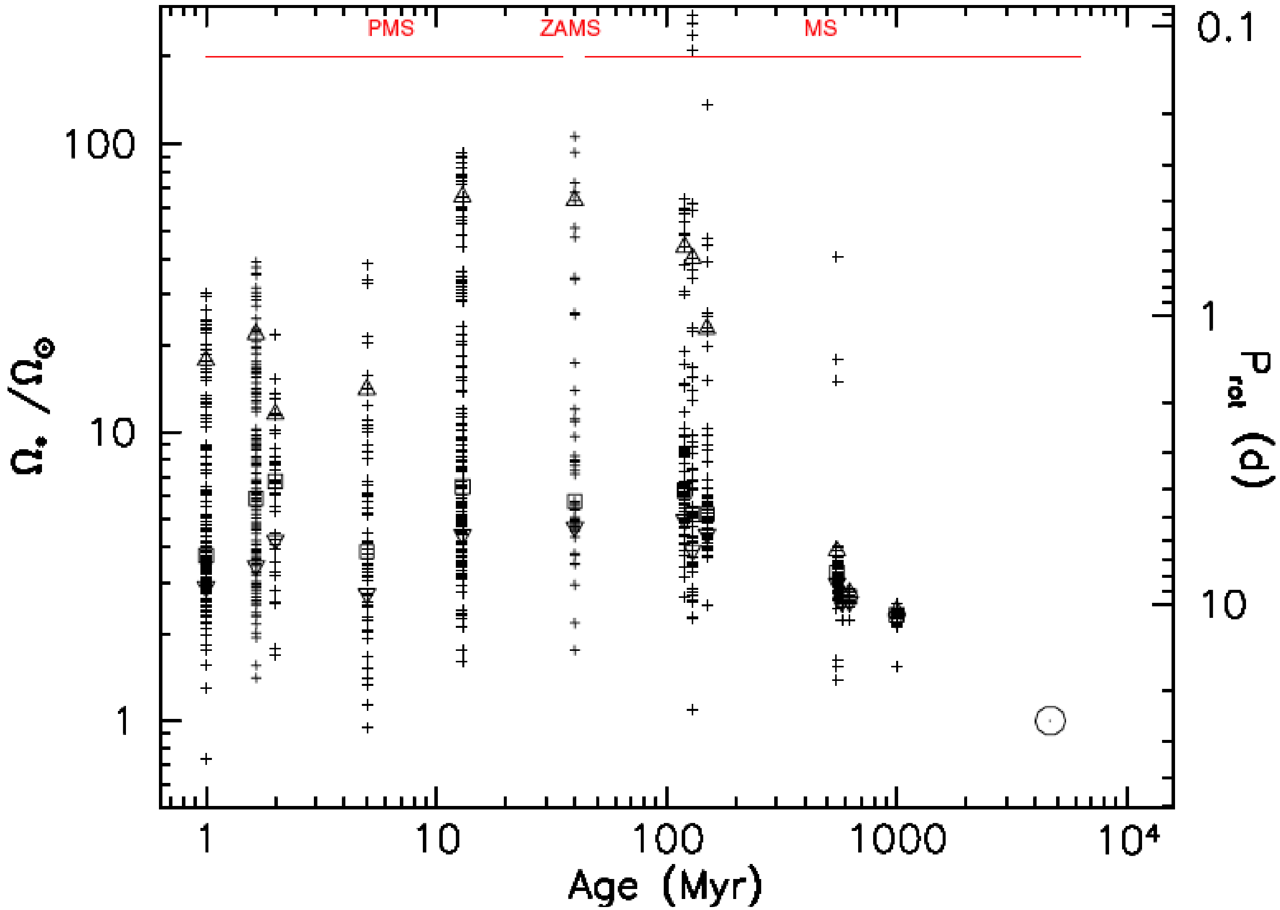
Issues:

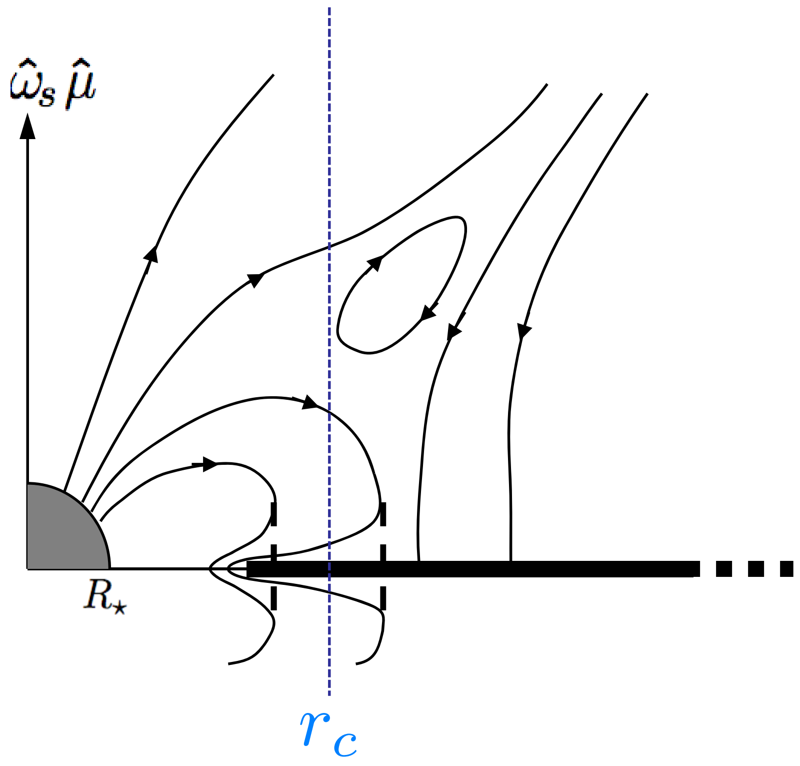
Equilibrium spin: Protostars, millisecond pulsars, long-period pulsars

Application:
Rotation of Protostars: why 10% of breakup?



Gallet & Bouvier 2013

Torque on Star



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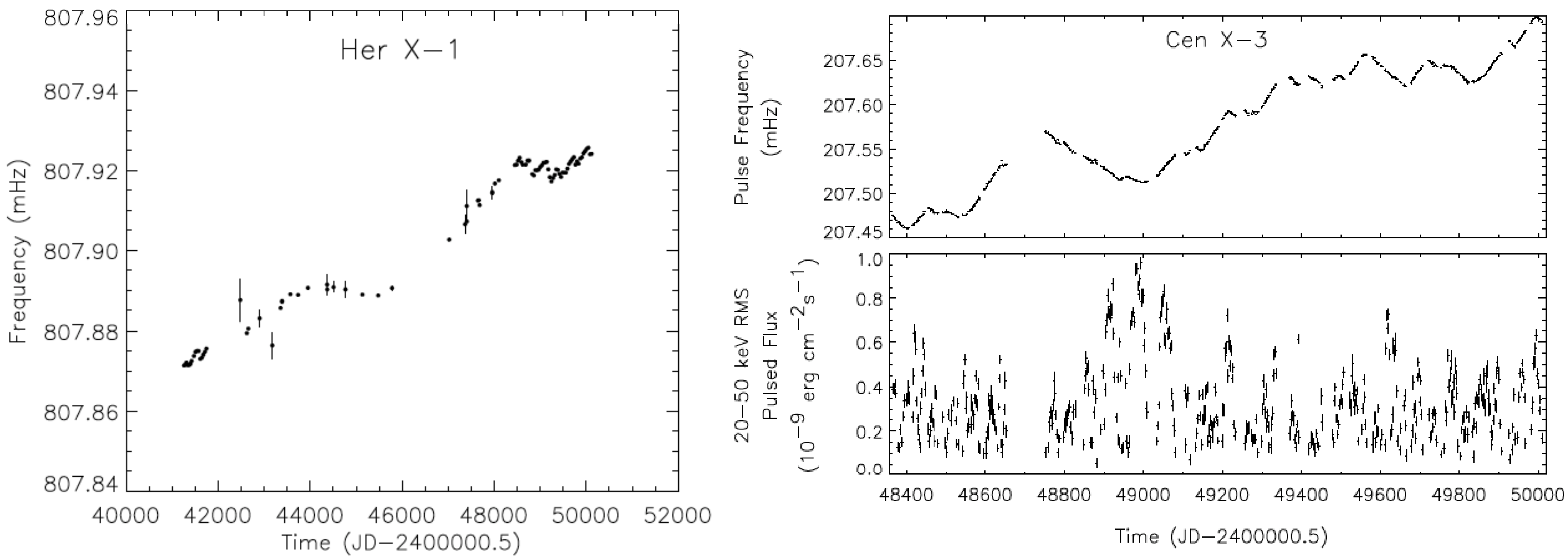
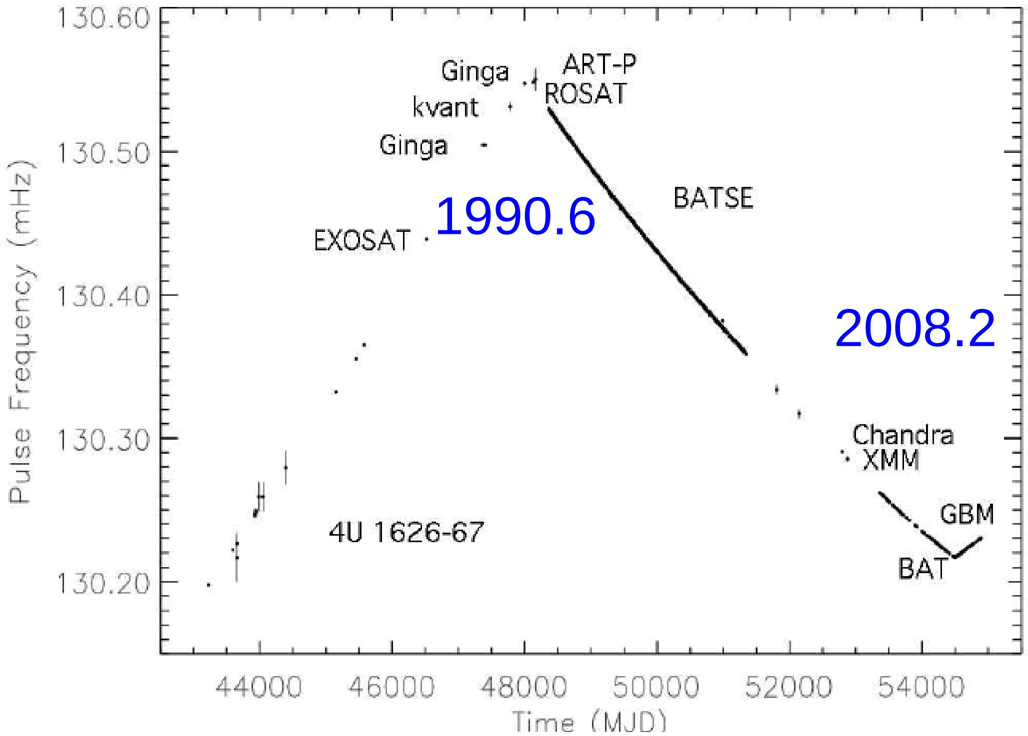
Issues:

Can we understand spinup/spindown of X-ray pulsars?

Spinup/Spindown of Accreting X-ray pulsars



Bildsten et al. 1997

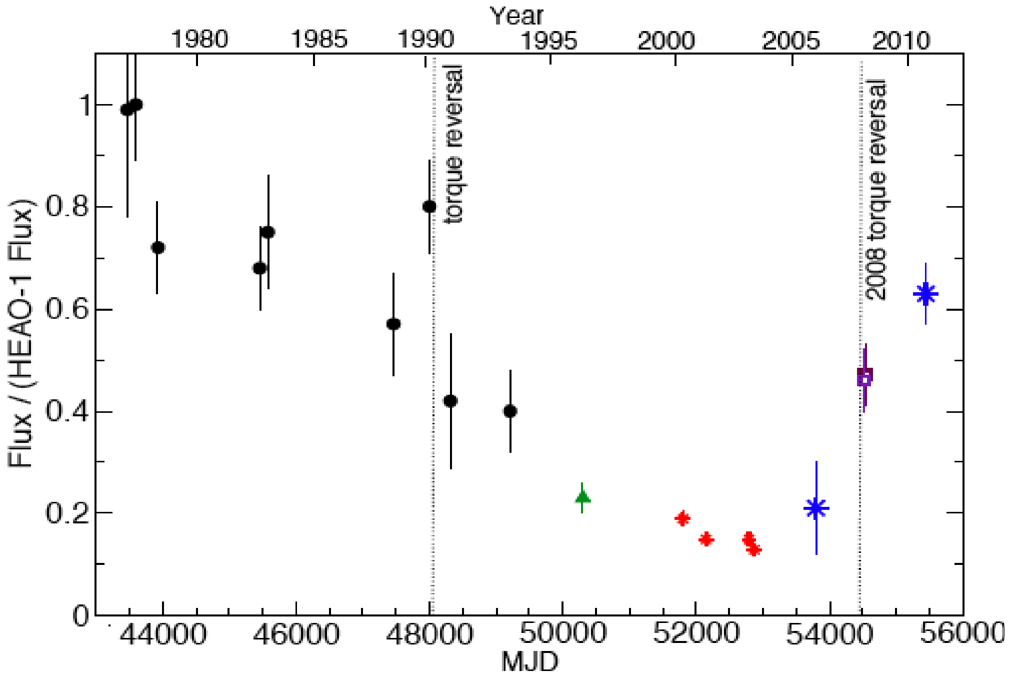


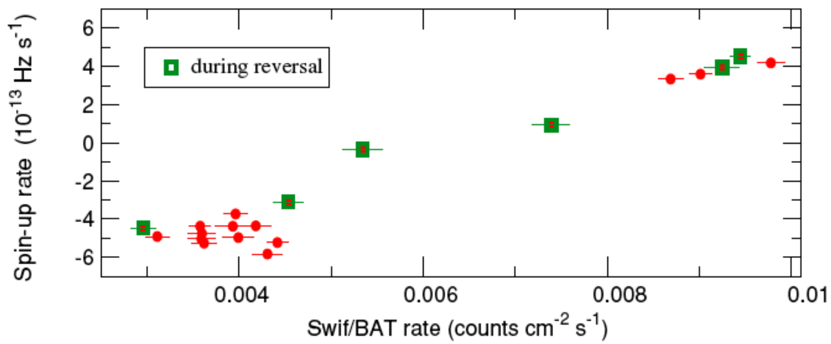
4U1626-67

7.66s

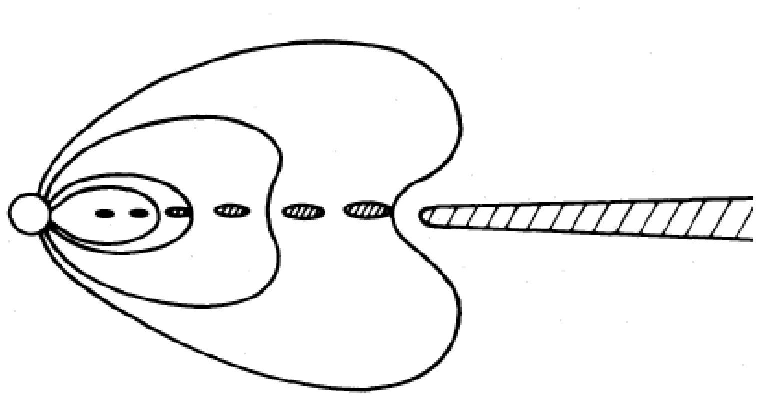
Transition lasted 150 days

Camero-Arranz et al. 2010,2012

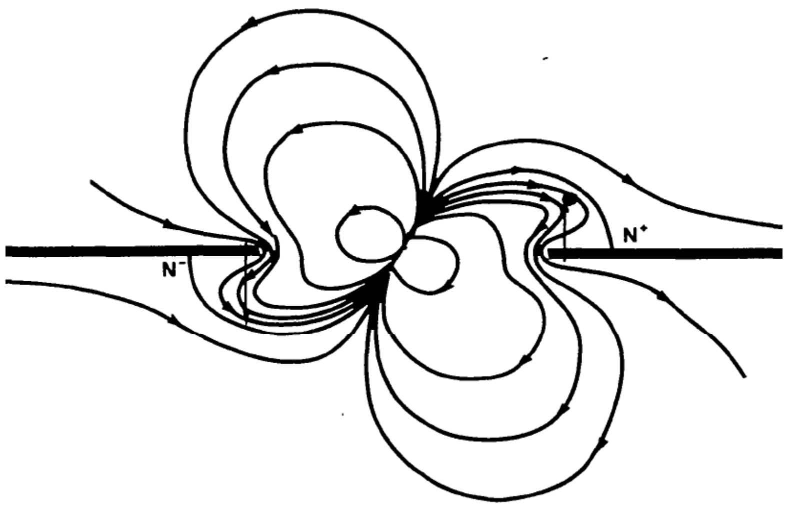




Misaligned Dipole



Accretion through instabilities



Funnel flow to polar caps

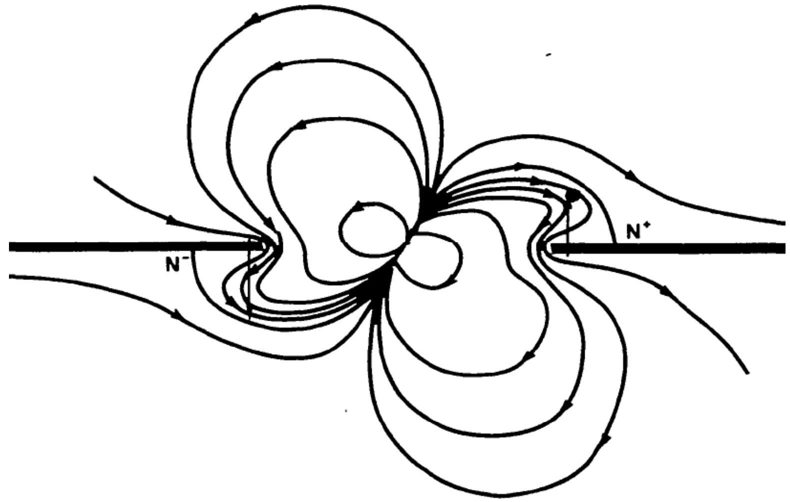
Misaligned Dipole: Exciting Waves in Disks

Vertical force on disk:

$$F_z(r,\varphi,t) = F_\omega(r)\exp(im\varphi - i\omega t)$$

$$m = 1, \quad \omega = \Omega_\star, 2\Omega_\star$$

➔ Excitation of Bending waves in the disk



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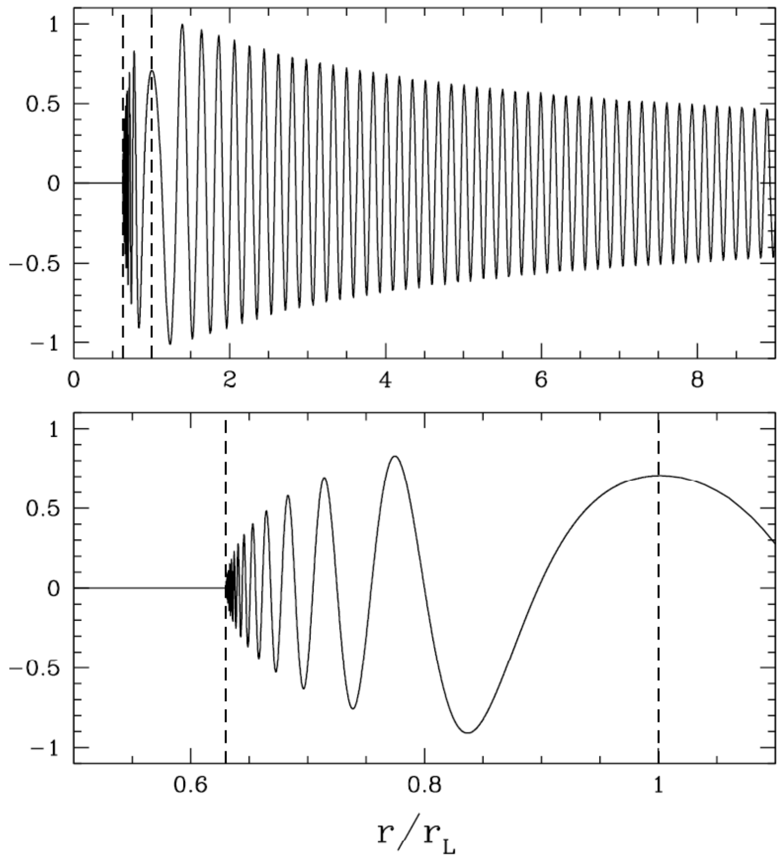
➔ Excitation of Bending waves in the disk

Perturbations most "visible" at Lindblad/Vertical Resonance

$$\omega - \Omega = \Omega_\perp \simeq \Omega$$

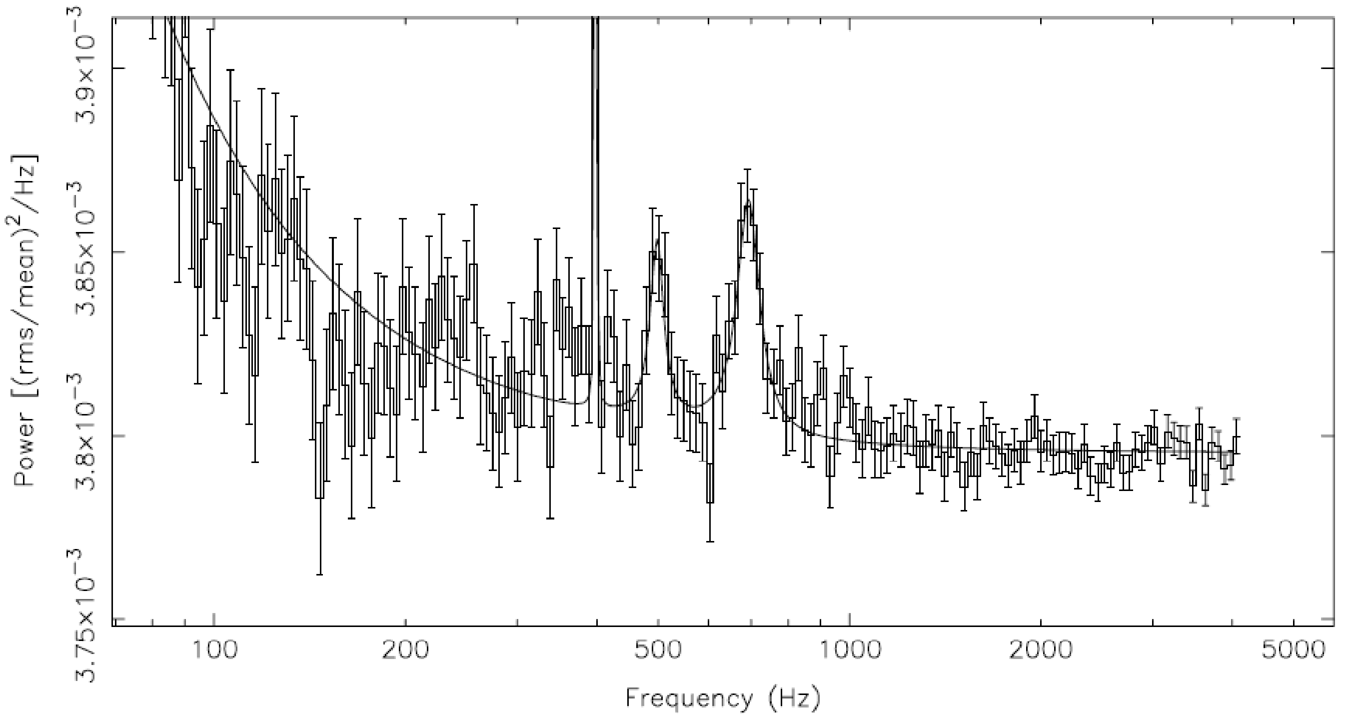
➔ $$\Omega(r_L) = \frac{\omega}{2} = \frac{\Omega_\star}{2}, \Omega_\star$$



DL & Zhang 08
Romanova et al 2012

Question: QPOs….

kHz QPOs in Accreting Millisecond Pulsars



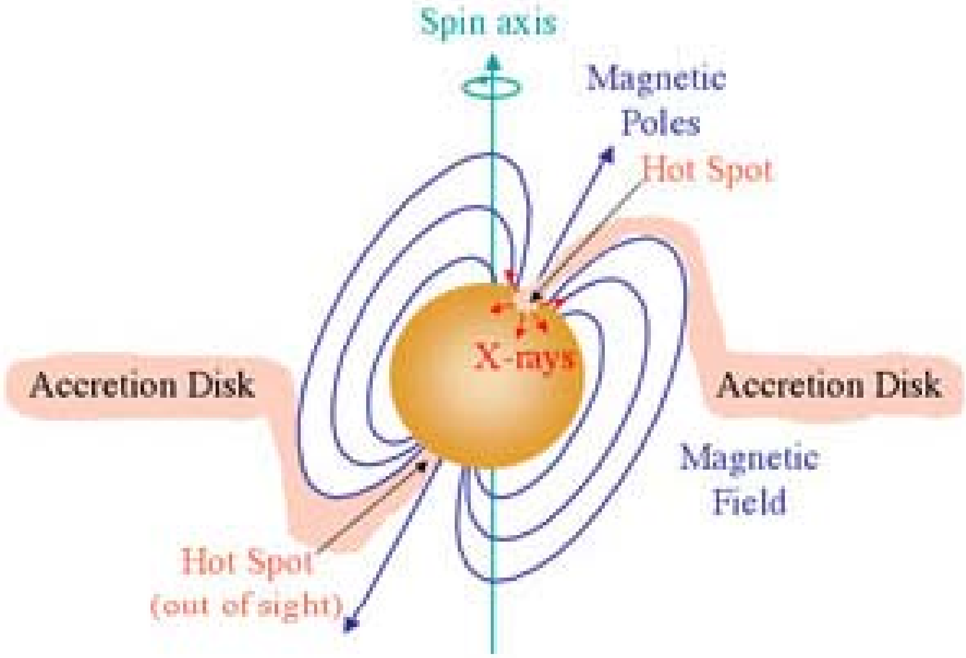
Van der Klis 2005

SAX J1808.4-3658 $\nu_s = 401$ Hz, $\nu_h - \nu_l \simeq \nu_s/2$ ($\pm$a few Hz)

XTE J1807.4-294: $\nu_s = 191$ Hz, $\nu_h - \nu_l \simeq \nu_s$

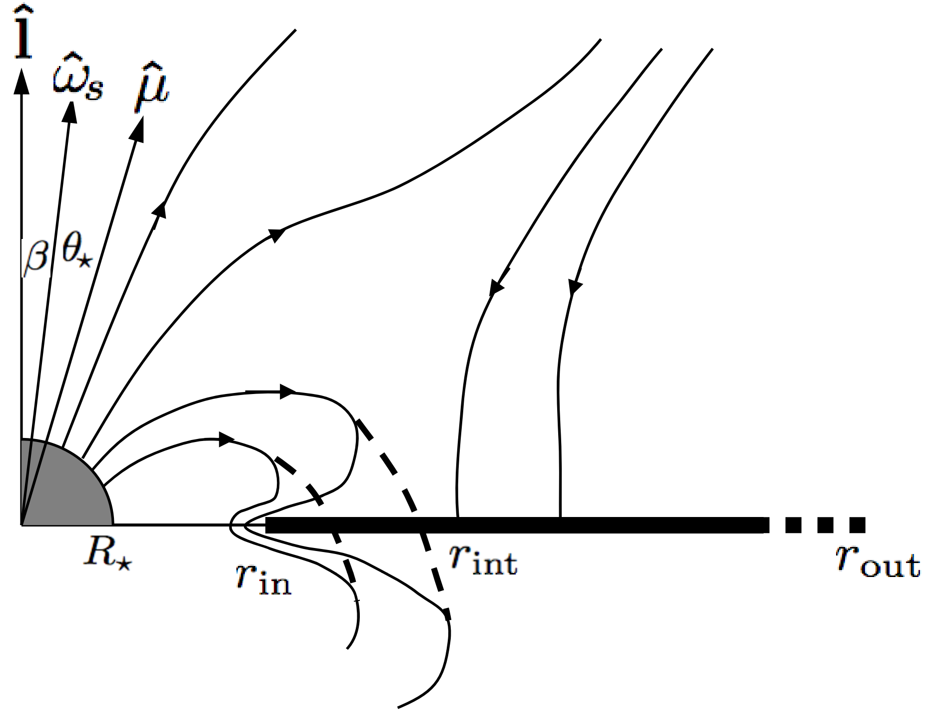
Beating of high-freq. QPO with perturbed fluid at L/VR ?

Stellar Spin – Disk Misalignment

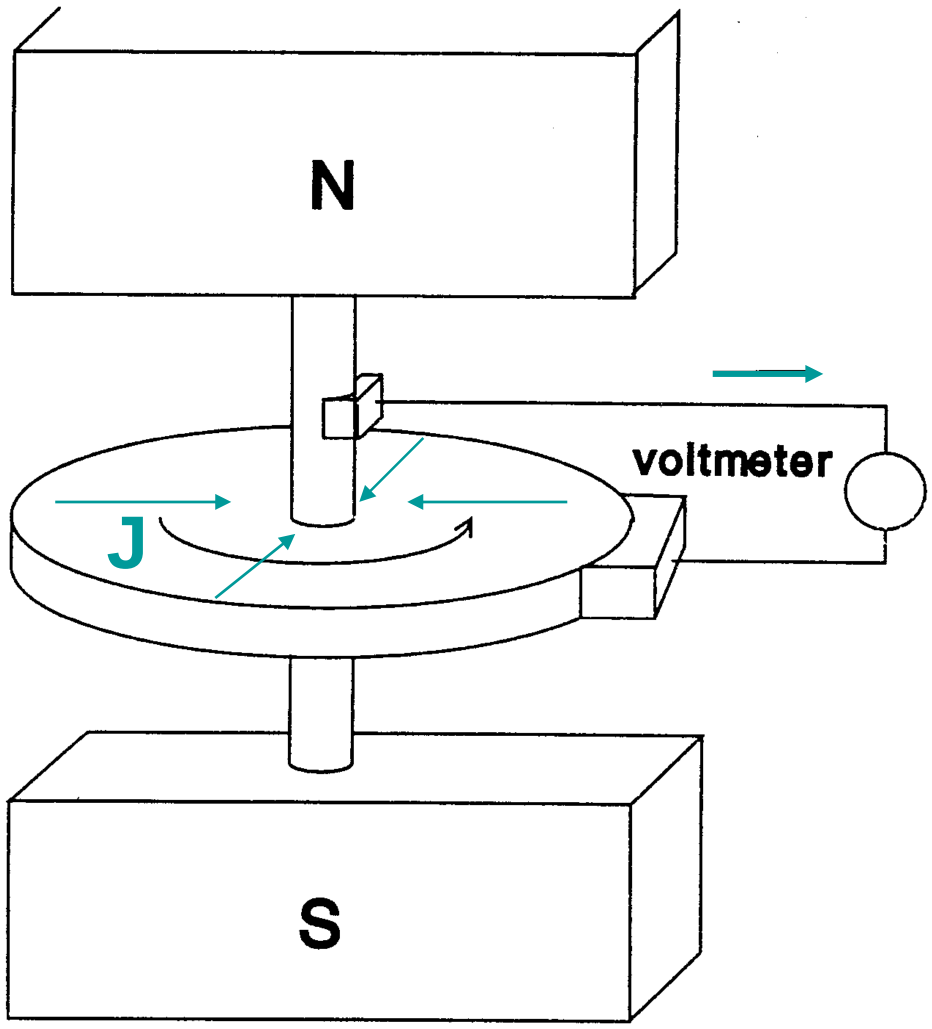


Standard story: **S//L**

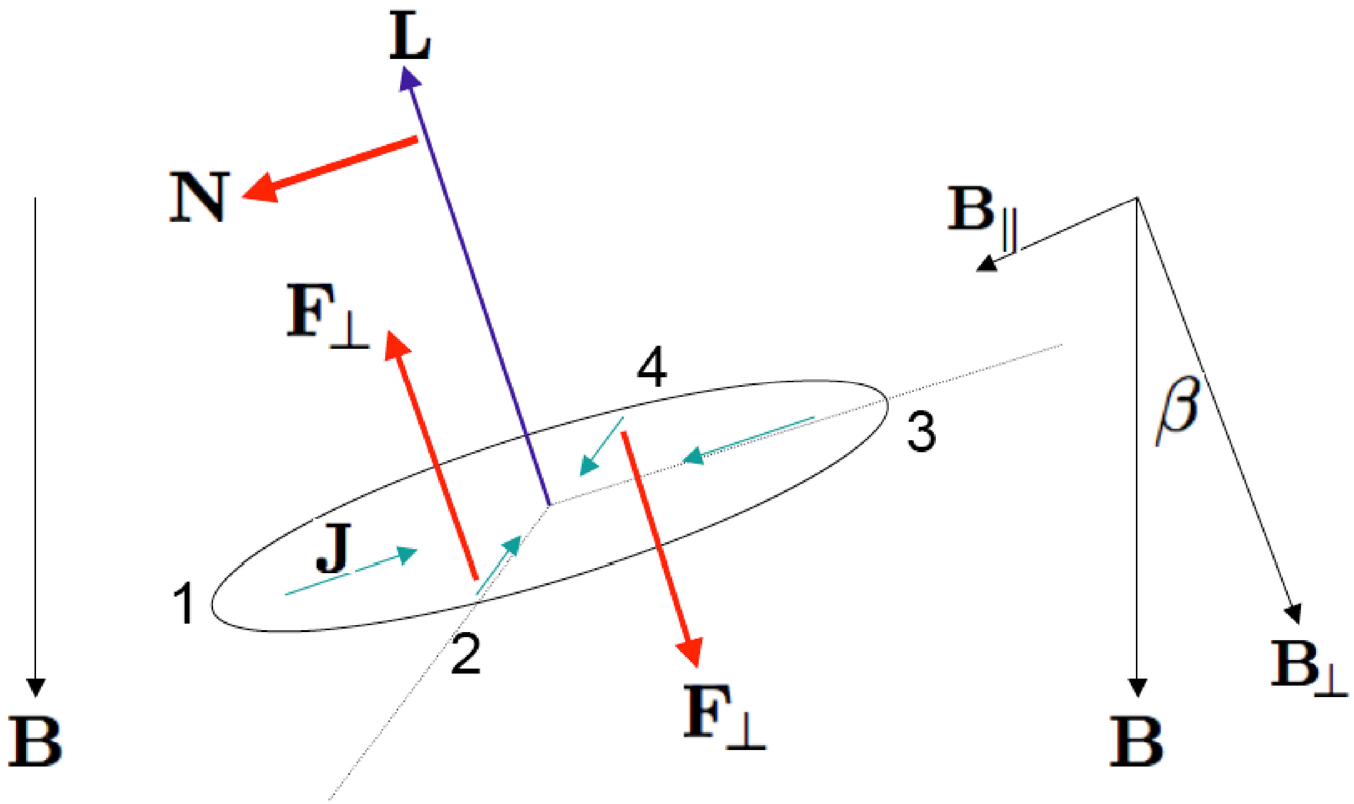
There is a magnetic torque which tends to make the inner disk warp on timescale >> dynamical time (rotation/orbital period)



A Laboratory Experiment



A Laboratory Experiment



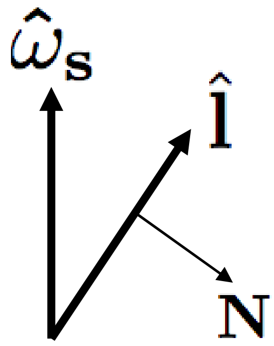
DL, Foucart & Lin 2011

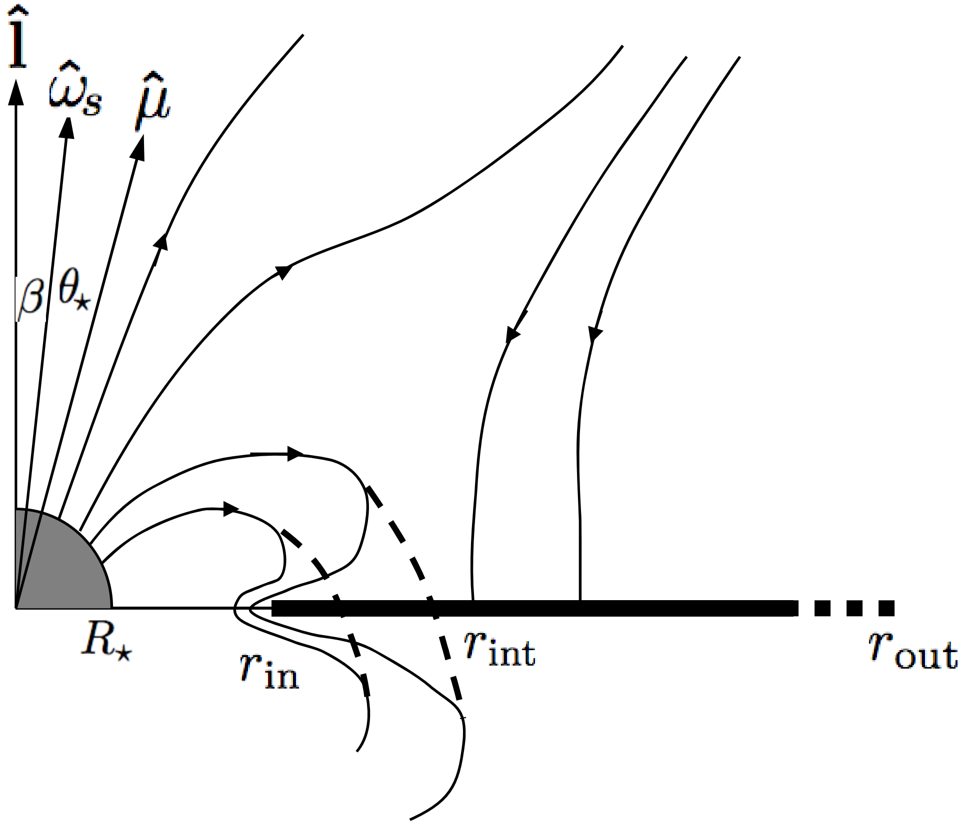
Magnetically Threaded disk:

Torque on disk (per unit area): $\mathbf{N} \propto -\hat{\mathbf{l}} \times (\hat{\mu} \times \hat{\mathbf{l}})$

Averaging over stellar rotation: $\mathbf{N} \propto -\hat{\mathbf{l}} \times (\hat{\omega}_s \times \hat{\mathbf{l}})$

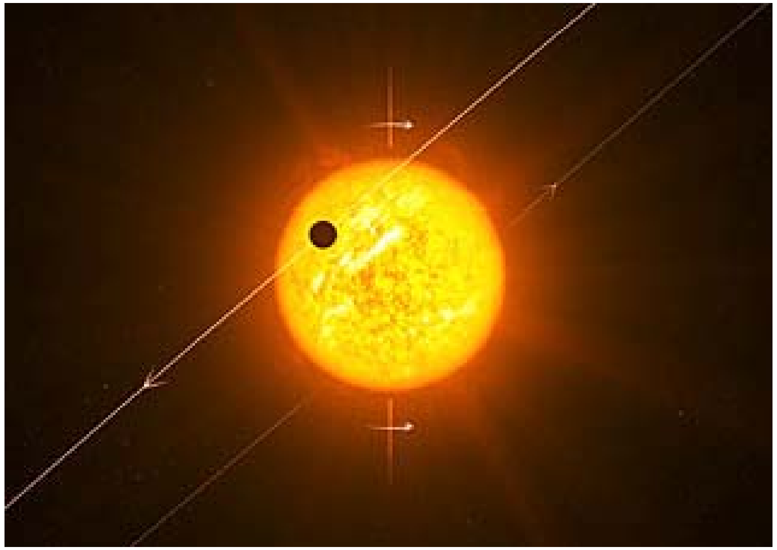
Warping torque

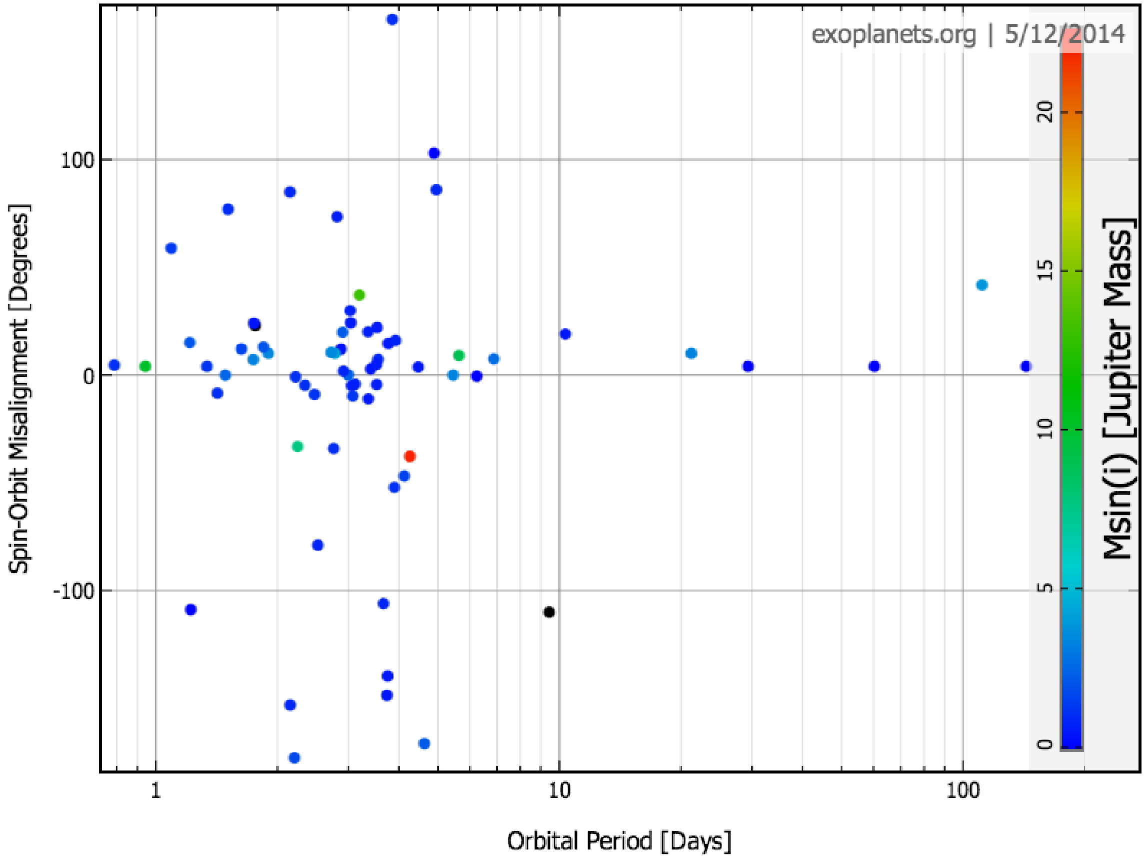




Possible Connection to (Exo)Planetary Systems

Many “hot Jupiters” have Misaligned S^*-L_p

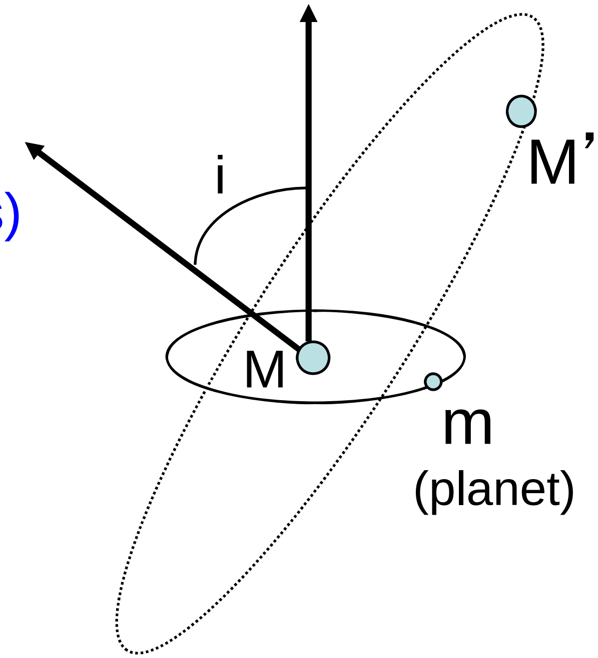




S_*-L_p misalignment in Exoplanetary Systems
➔ The Importance of few-body interactions

1. Kozai + Tide migration by a distant companion star/planet
   (e.g., Wu & Murray 03; Fabrycky & Tremaine 07; Naoz et al.12, Katz et al.12)

2. Planet-planet Interactions
   -- Strong scatterings
   (e.g., Rasio & Ford 96; Chatterjee et al. 08; Juric & Tremaine 08)
   -- Secular interactions ("Internal Kozai", chaos)
   (e.g Nagasawa et al. 08; Wu & Lithwick 11)



-- Chaotic stellar spin evolution during Kozai
   (Storch, Anderson & DL 2014)

Is “High-e Migration” the whole story for producing hot Jupiters and S-L misalignments?

Likely NO.

-- Companion? Initial conditions? (e.g., Knutson et al. 2014)

-- Can produce distribution of period, ecc, misalignment? (Naoz+12,Petrovich+14)

-- Paucity of high-e proto-hot Jupiters (Socrates et al.2012; Dawson et al.2012)

-- Stellar metallicity trend of hot Jupiters ➔ Two mechanisms of migrations (Dawson & Murray-Clay 2013)

-- Misaligned multiplanet systems:

Kepler-55 (2 planets 10.5 & 21 days ➔40-55 deg from seismology; Huber et al 2013)
Kepler-9 (3-planets; Walkowicz & Basri 2013) ?
Other Candidates: Hirano et al. 2014

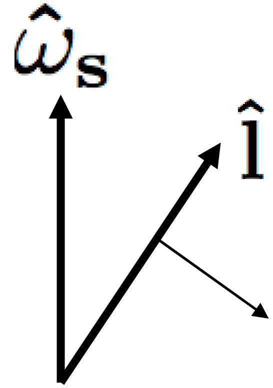
Alternative: Primordial Misalignments

between Stellar Spin and Protoplanetary Disk

-- **Magnetic Star – Disk Interaction** (Lai, Foucart & Lin 2011)

-- **Perturbation of Binary on Disk** (Batygin 2012; Batygin & Adams 2013; **Lai 2014**)

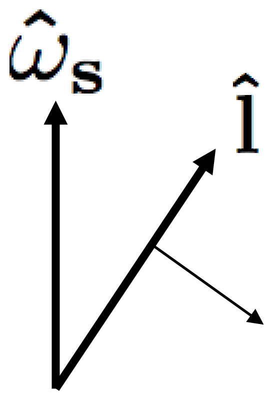
Recall: Magnetic toques from the star **want** to make the inner disk warp and precess…



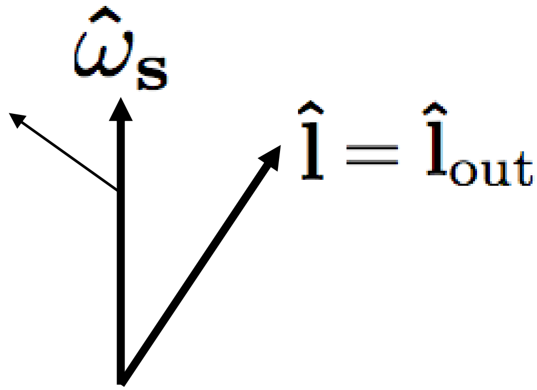
But disk will **want** to resist it by internal stresses (viscosity or bending wave propagation)

$$\frac{\partial}{\partial t}\left(\Sigma r^2 \Omega \hat{\boldsymbol{l}}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(\Sigma V_R r^3 \Omega \hat{\boldsymbol{l}}\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(Q_1 I r^2 \Omega^2 \hat{\boldsymbol{l}}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(Q_2 I r^3 \Omega^2 \frac{\partial \hat{\boldsymbol{l}}}{\partial r} + Q_3 I r^3 \Omega^2 \hat{\boldsymbol{l}} \times \frac{\partial \hat{\boldsymbol{l}}}{\partial r}\right) + \mathbf{N}_m$$

Back-reaction Torque on Star:
What is happening to the stellar spin direction?
(Is there secular change to the spin direction?)



Warping torque



Back-reaction torque

➔ **Stellar spin may be misaligned with disk axis**

Accretion tends to align S & L:

Accretion torque $\mathcal{N}_{\rm acc} \simeq \dot{M}\sqrt{GM_\star r_{\rm in}}$

Magnetic misalignment torque: $\mathcal{N}_{\rm mag} \sim \mu^2/r_{\rm in}^3$

For $r_{\rm in} \sim \left(\frac{\mu^4}{GM_\star \dot{M}^2}\right)^{1/7}$

➔ $\mathcal{N}_{\rm acc} \sim \mathcal{N}_{\rm mag}$

Evolution of the stellar spin

$$\frac{d}{dt}(J_s\hat{\boldsymbol{\omega}}_s) = \boldsymbol{\mathcal{N}} = \boldsymbol{\mathcal{N}}_{\rm acc} + \boldsymbol{\mathcal{N}}_m + \boldsymbol{\mathcal{N}}_{\rm sd}$$

$$\mathcal{N}_{\rm acc} = \lambda \dot{M}\sqrt{GMr_{\rm in}}\,\hat{l}_{\rm in}, \quad \lambda \sim 1 \text{ (or less)}$$

$\mathcal{N}_m$ =backreaction of magnetic (warping & precessional) torques

$$\mathcal{N}_{\rm sd} = -|\mathcal{N}_{\rm sd}|\,\hat{\omega}_s$$

(Each term is of order $\mathcal{N}_0 = \dot{M}\sqrt{GMr_{\rm in}}$)

$$\Longrightarrow \frac{d\cos\theta_{\rm sd}}{dt} = \frac{\mathcal{N}_0}{J_s}\sin^2\theta_{\rm sd}\left(\lambda - \tilde{\xi}\cos^2\theta_{\rm sd}\right)$$

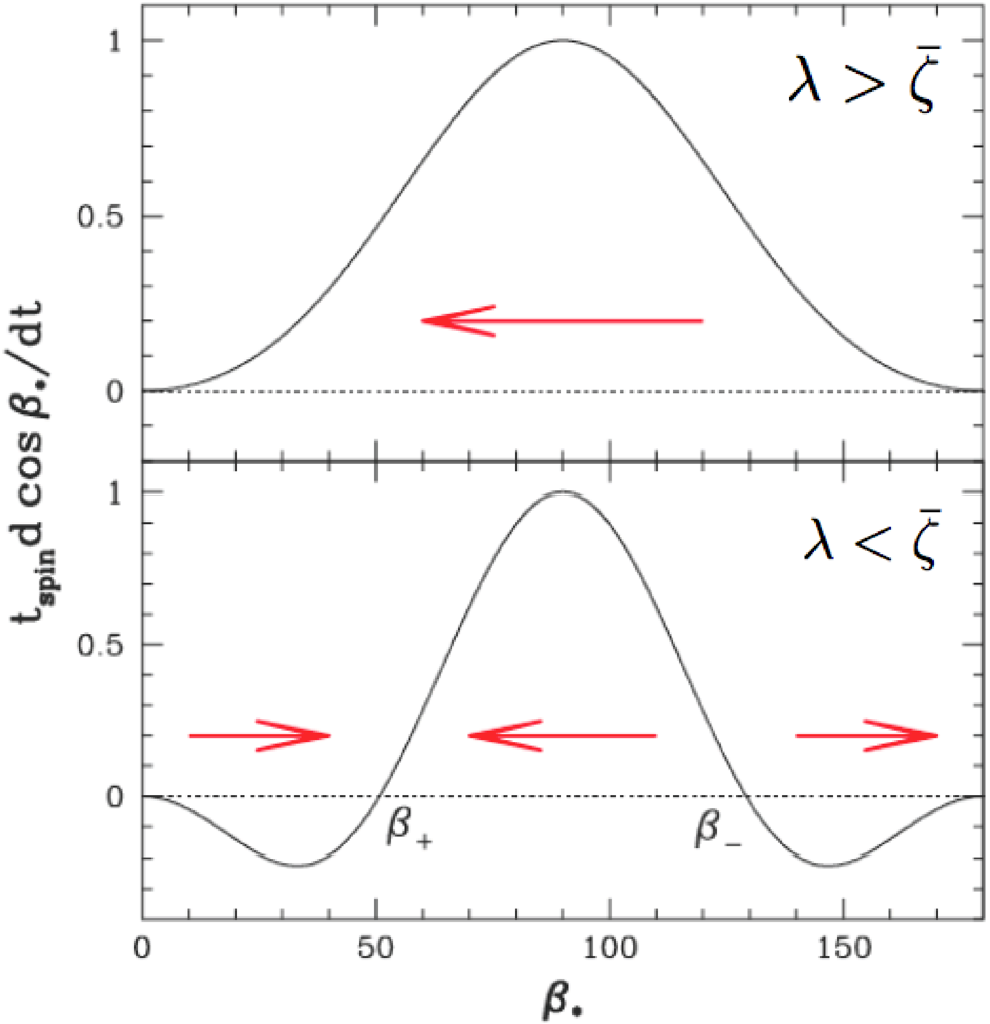
$$\bar{\zeta} = \frac{\zeta\cos^2\theta_\star}{6\eta^{7/2}} \ (\sim 1)$$

Spin evolution timescale:

$$t_{\rm spin} = (1.25\,{\rm Myr})\left(\frac{M_\star}{1\,M_\odot}\right)\left(\frac{\dot{M}}{10^{-8}M_\odot{\rm yr}^{-1}}\right)^{-1}\left(\frac{r_{\rm in}}{4R_\star}\right)^{-2}\frac{\omega_s}{\Omega(r_{\rm in})}$$

Evolution of the stellar spin

$$\frac{d\cos\theta_{\rm sd}}{dt} = \frac{\mathcal{N}_0}{J_s}\sin^2\theta_{\rm sd}\left(\lambda - \tilde{\xi}\cos^2\theta_{\rm sd}\right) \qquad \bar{\zeta} = \frac{\zeta\cos^2\theta_\star}{6\eta^{7/2}}\ (\sim 1)$$



"weak" warping torque

"strong" warping torque

For Isolated star-disk systems:

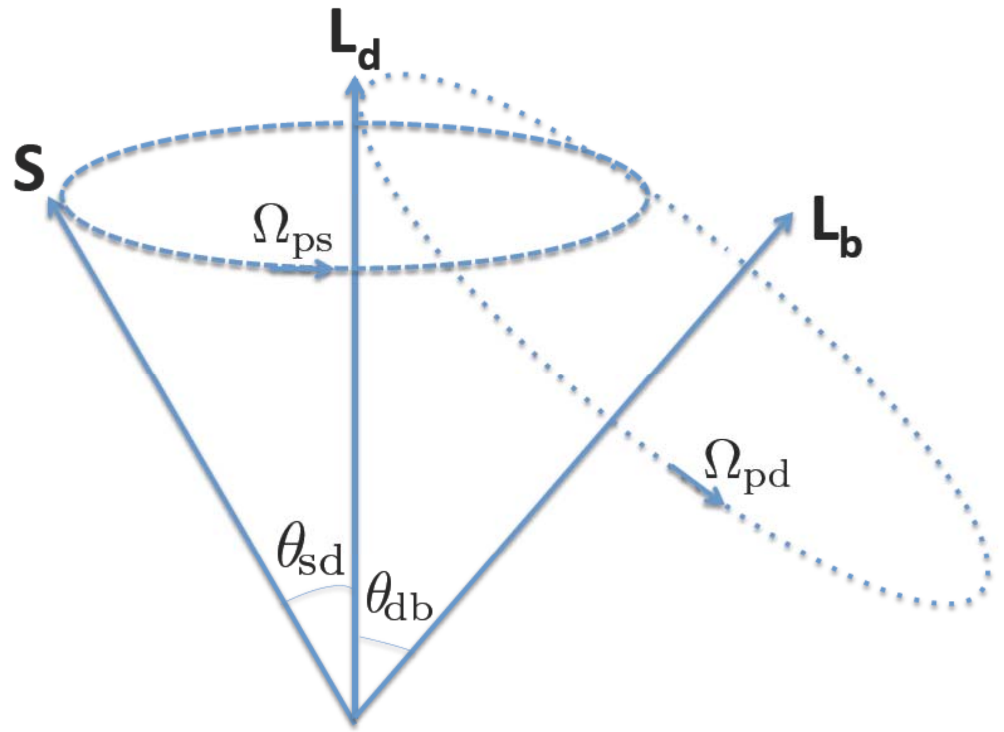
Magnetic torque tends to produce spin-disk misalignment,
But competes with accretion

➔May or may not produce small/modest misalignment

(e.g., Solar system 7 degree?)

Star-Disk-Binary Interactions

Gravitational interactions…

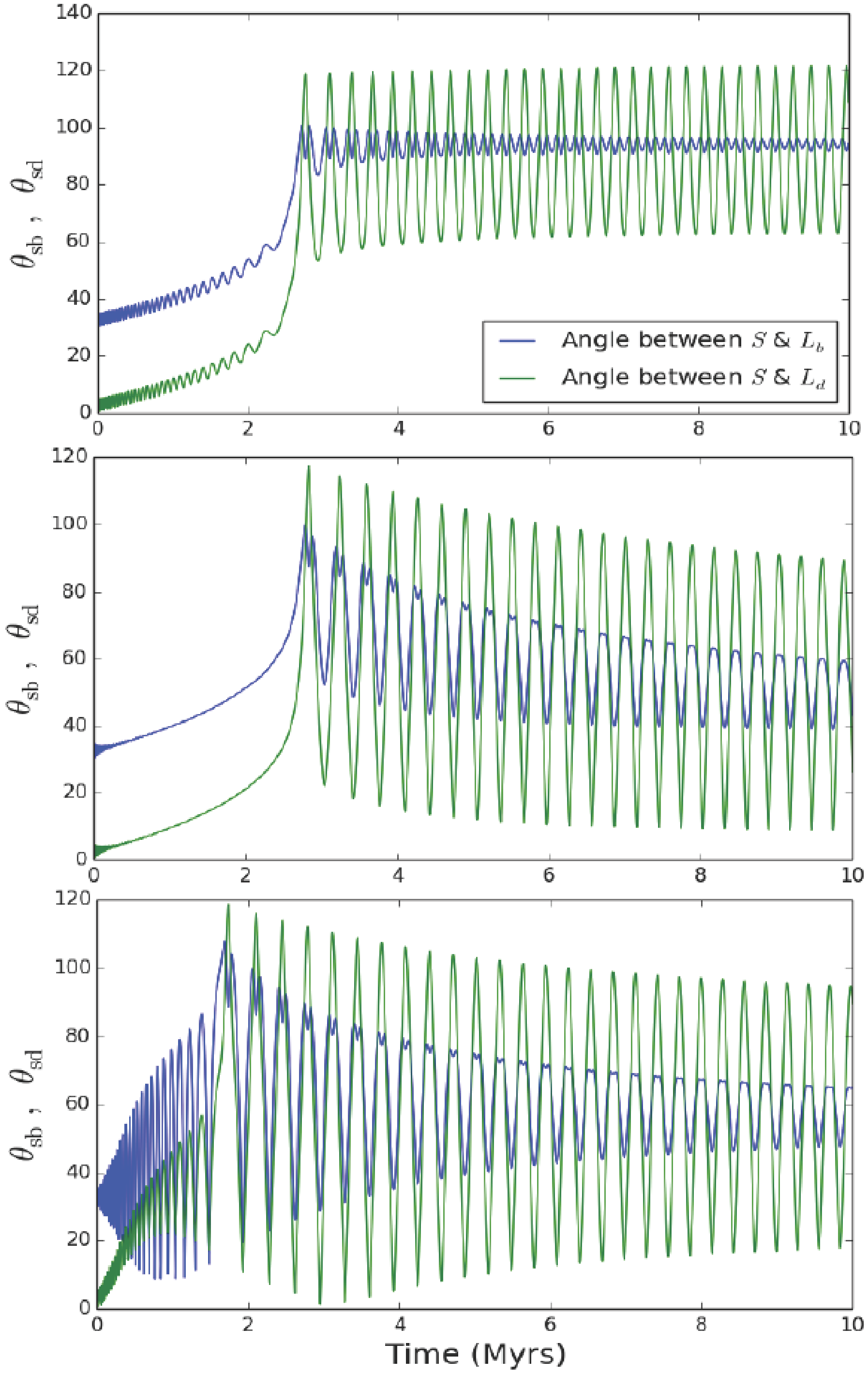


Now include Accretion and Magnetic Torques

No accretion/magnetic

Accretion/magnetic damps SL-angle

Accretion/magnetic increases SL-angle



DL2014

Summary

Magnetic star - disk interaction

Rich MHD and plasma physics: connection to other field

Interchange instabilities, reconnection, field winding/inflation, outflows, waves, resonances…

Wide Applications **(accreting NSs, WDs, protostars):**

Variabilities (QPOs), jets, spin equilibrium, spinup/down, warp/prcession, exoplanets, protoplanetary disks

THANKS