Star-planet magnetic interactions and the misalignment of planetary orbits

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Examples of magnetic interactions in the Solar System (and beyond)

- Jupiter-Io "unipolar induction"
  => flux tube linking Io and Jupiter
  => decameter radio emisson
  hot spots on Jupiter's surface

Piddington & Drake 1968; Goldreich & Nicholson 1969

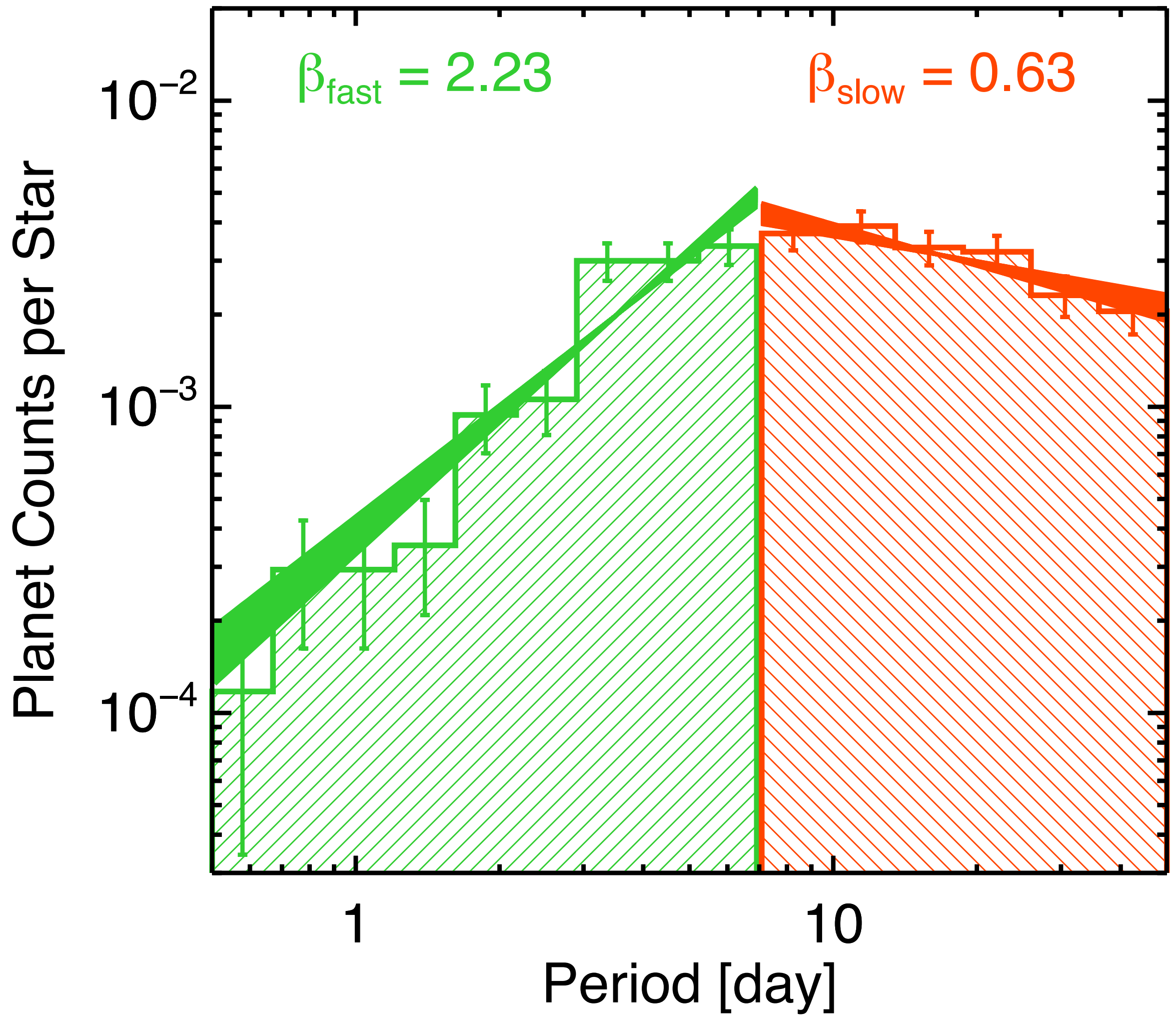
  - also discussed in context of white dwarf ultracompact binaries   Wu 2009
  - and most recently neutron star- black hole interaction during a merger (EM counterpart to GW)

McWilliams & Levin 2011

- Induced currents in Europa
  => conductivity profile => ocean thickness

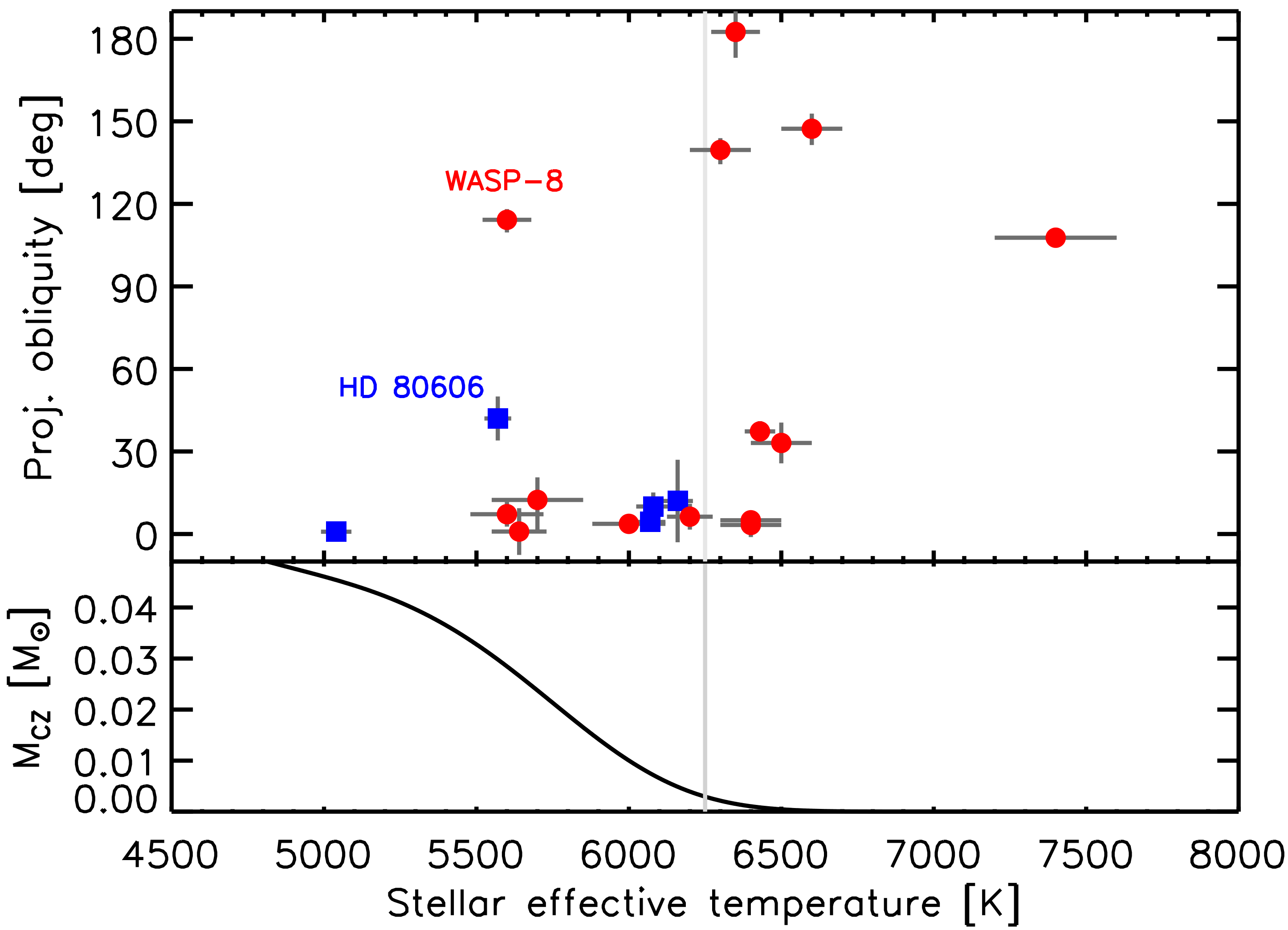
Schilling et al. 2007

Orbital period distribution close-in



Youdin 2011

Rossiter-McLaughlin measurement of misaligned orbital and spin angular momentum



Winn et al. 2010

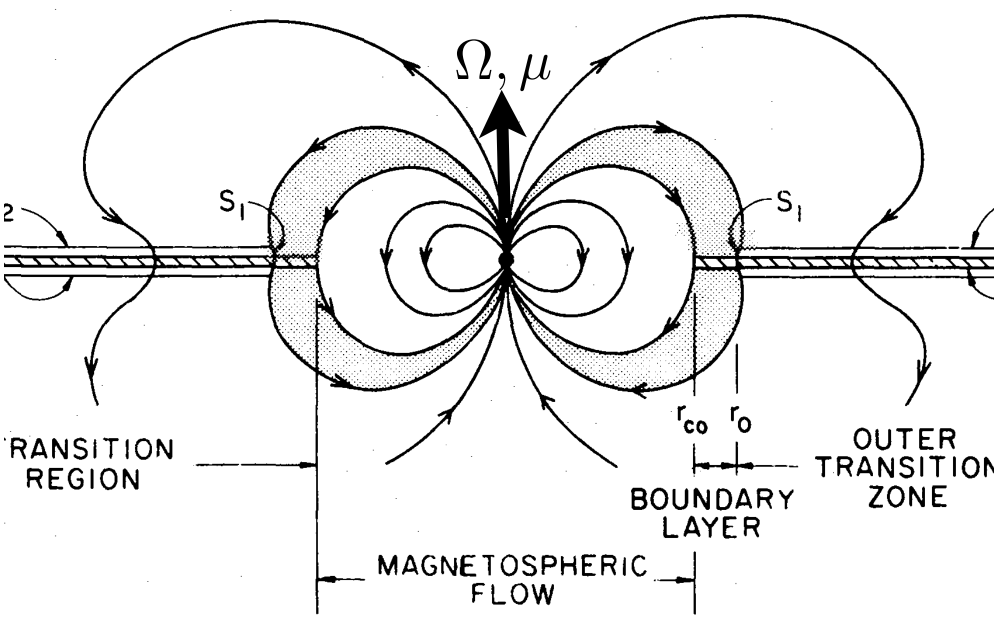
Could magnetic interactions be important in exoplanet systems, especially early on when the star is highly magnetized?

- magnetic torques modify orbits
- heating from e.g. ohmic dissipation

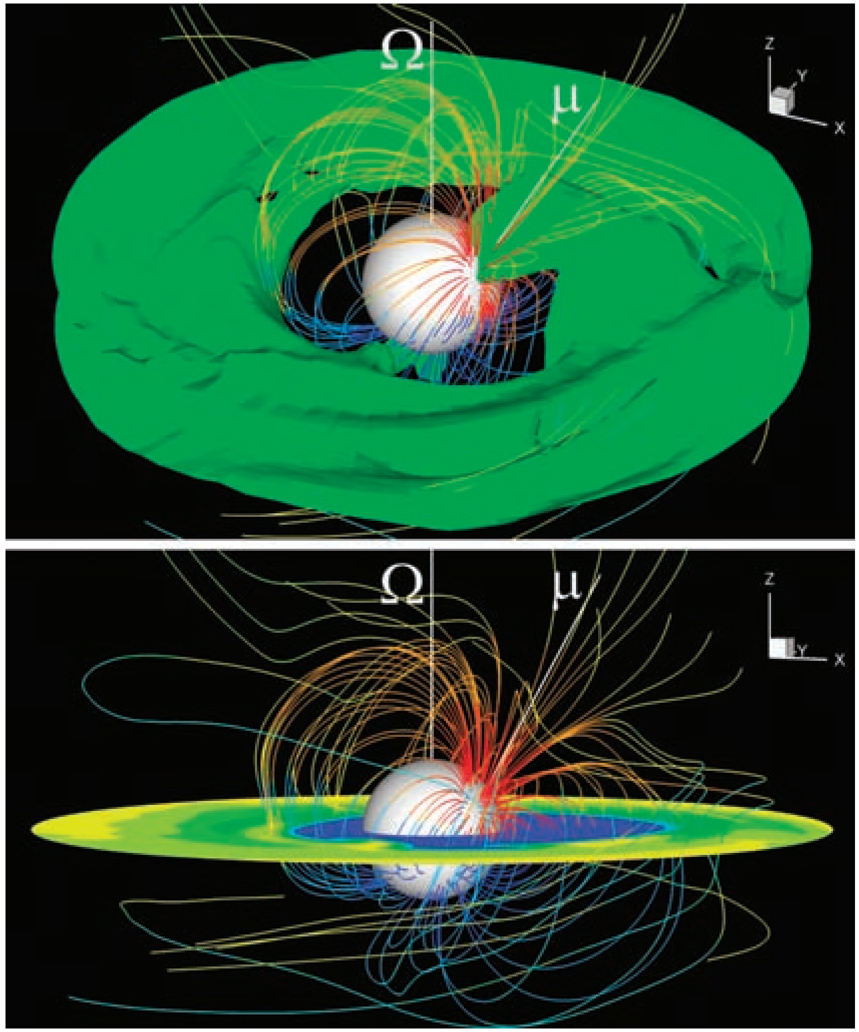
Alignment torques from misaligned magnetic dipoles

- Single objects with misaligned spin and magnetic dipole
  - Radio pulsars: Davis & Goldstein (1970)
    spin and magnetic axes tend to align over time
  - Stellar spin down with inclined dipole
    Mestel (1968a,b) Mestel & Selley (1970)
    spin axis moves to location of magnetic flux maximum
- Magnetic accretion with spin-orbit misalignment
  Lai (1999) showed that in addition to the spin up/down torque there are also two other torque components that cause alignment and precession

Alignment torques from misaligned magnetic dipoles

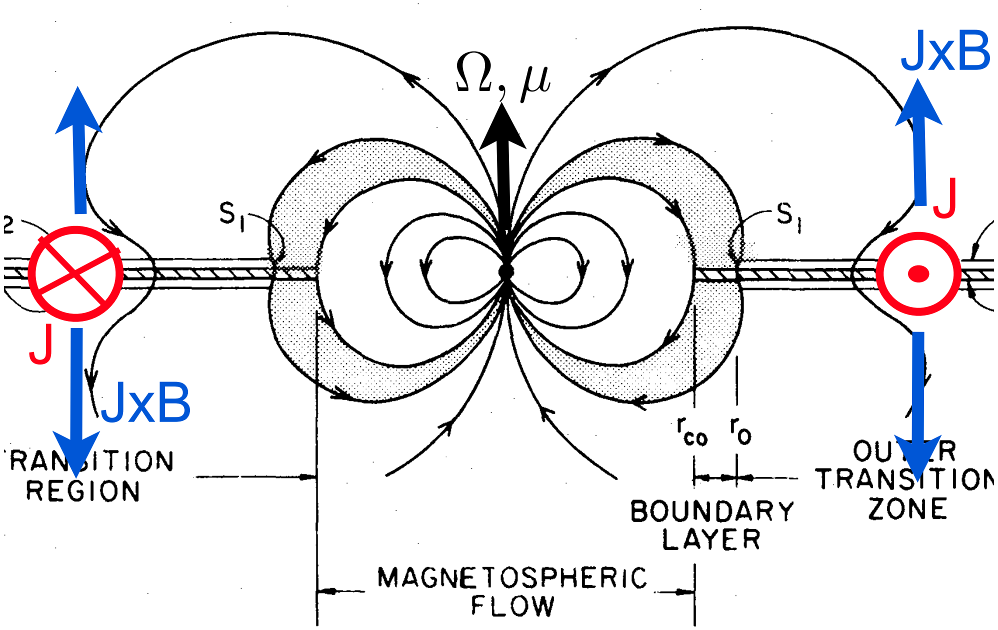


Ghosh & Lamb (1979)



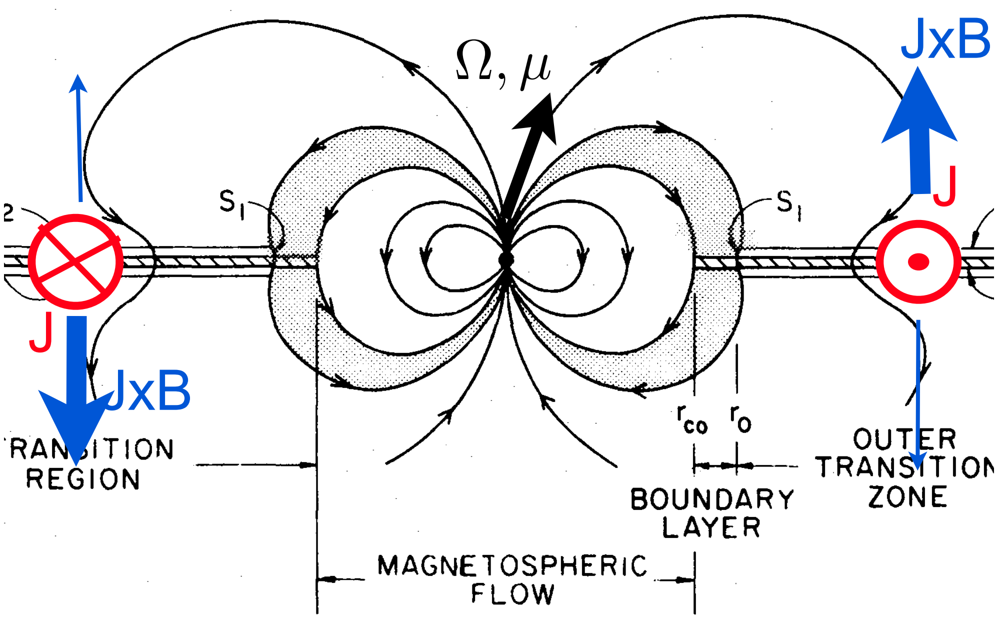
Long, Romanova et al. (2008)

Alignment torques from misaligned magnetic dipoles



Ghosh & Lamb (1979)

Alignment torques from misaligned magnetic dipoles



Ghosh & Lamb (1979)

a net torque when B is inclined relative to the disk orbital angular momentum

$J_r \times B_\phi$ warping

$J_\phi \times B_r$ precession

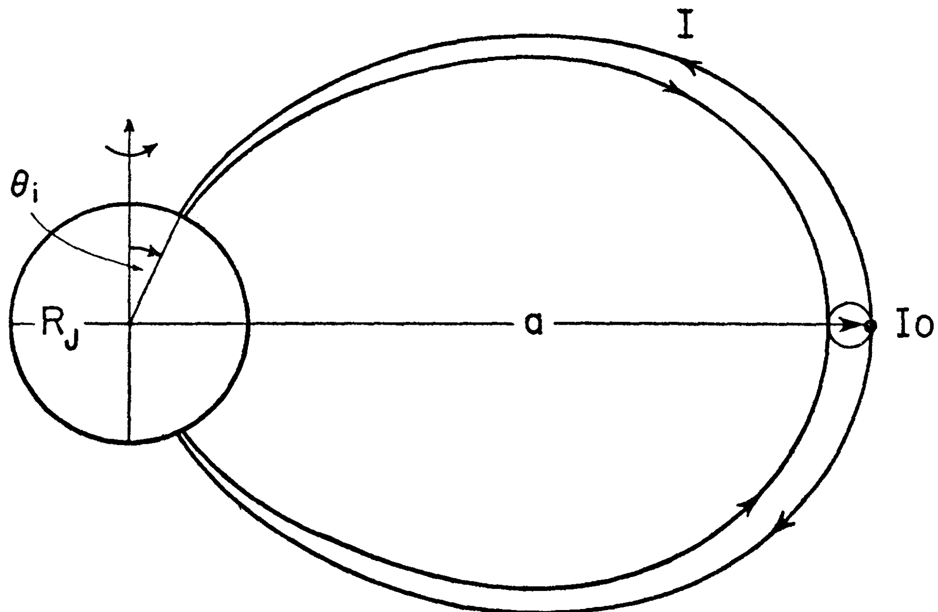
Final state:

- With no accretion torque, spin and orbital angular momentum want to be perpendicular
- But accretion torques try to keep orbital angular momentum fixed

Lai (1999)

Lai, Foucart & Lin (2010)

A unipolar inductor model for star-planet interaction



Goldreich & Lynden-Bell 1969

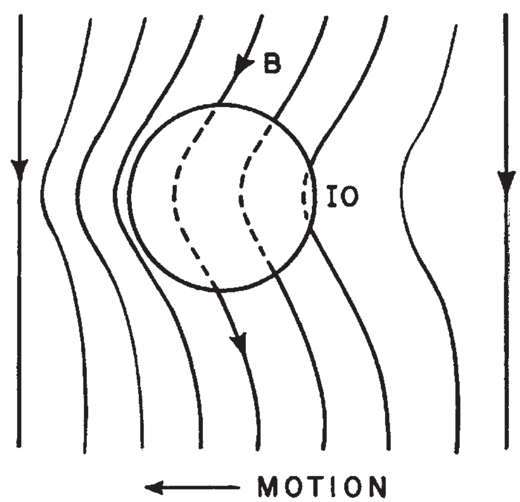
emf

$$\mathcal{E} = \int dr\ v \times B$$

force on the plane

$$\int d^3r\ J \times B$$

distorted field =>
magnetic pressure
gradient across the
planet



Piddington & Drake 1968

Requirement to
maintain the circuit:
Alfven travel time short
compared to time for
field lines to slip
through the planet

Timescale depends on the resistance of the circuit

torque on the orbit $\mathcal{T}_p = BIr_p a$

the current is
$$I = \frac{\mathcal{E}}{\mathcal{R}} = \frac{2(n-\omega_s)aB_z r_p}{c\mathcal{R}}$$

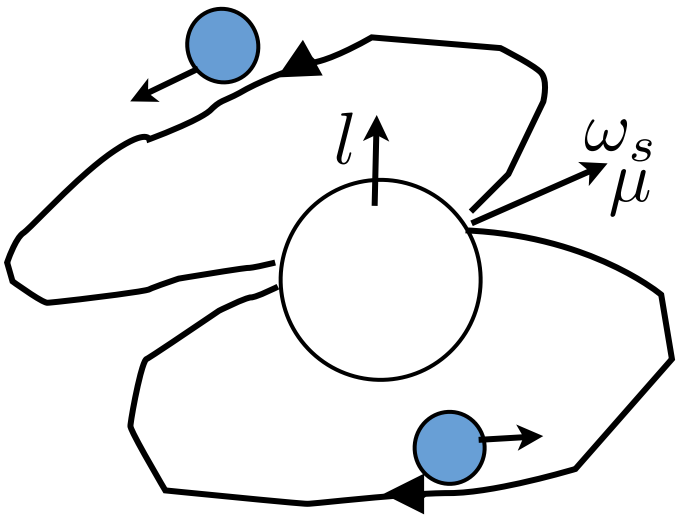
timescale
$$\tau_a^{-1} = -\frac{\dot{a}}{a} = \frac{2\mathcal{T}_p}{M_p\sqrt{GM_\star a}}$$

$$\tau_a = 1.5 \text{ Myrs } \left(\frac{a}{10r_\star}\right)^6 \left(\frac{\mathcal{R}}{10^{-5}\text{ ohm}}\right)\left(\frac{1\text{ kG}}{B_\star}\right)^2 \left(\frac{R_J}{r_p}\right)^2 \left(\frac{M_p}{M_J}\right)\left(\frac{n}{n-\omega_s}\right).$$

Laine & Lin 2010
For rocky planets,
resistance dominated
by the star

(timescale about the same for super Earths)

There is an alignment torque when spin/magnetic axis and orbit are misaligned



inside corotation, the current points inwards towards the star

on one side of the orbit the $J_r B_\phi$ force is up; on the other side down => an x-component of the torque

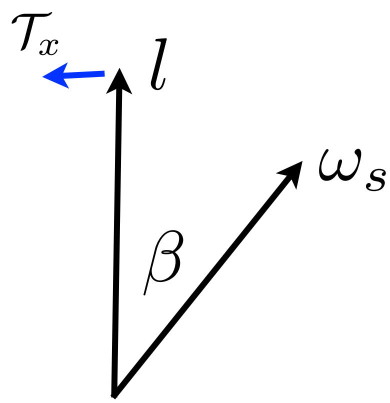
after time averaging

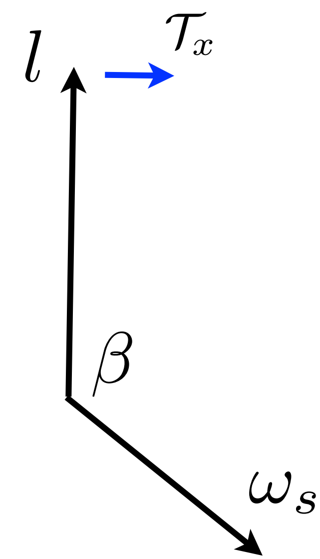
$$\langle \mathcal{T}_x \rangle = -\frac{1}{2}\mathcal{T}_p \cos\theta_\star \sin\beta$$

$$\langle \mathcal{T}_z \rangle = -\mathcal{T}_p \cos\theta_\star \cos\beta$$

Evolution of obliquity

1. fix spin

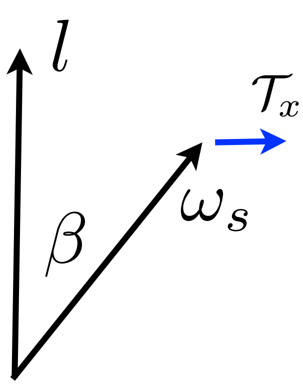




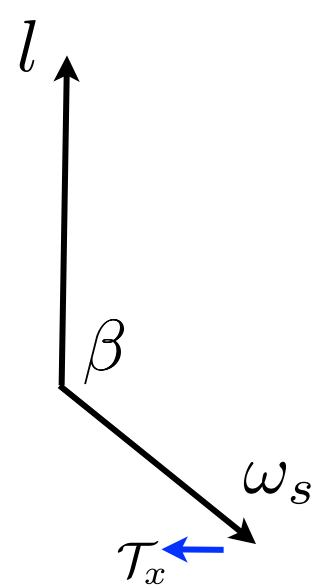
=> move to the perpendicular state

$$\frac{d\beta}{dt} = -\frac{\mathcal{T}_x}{l}$$

2. fix orbital ang.mom.

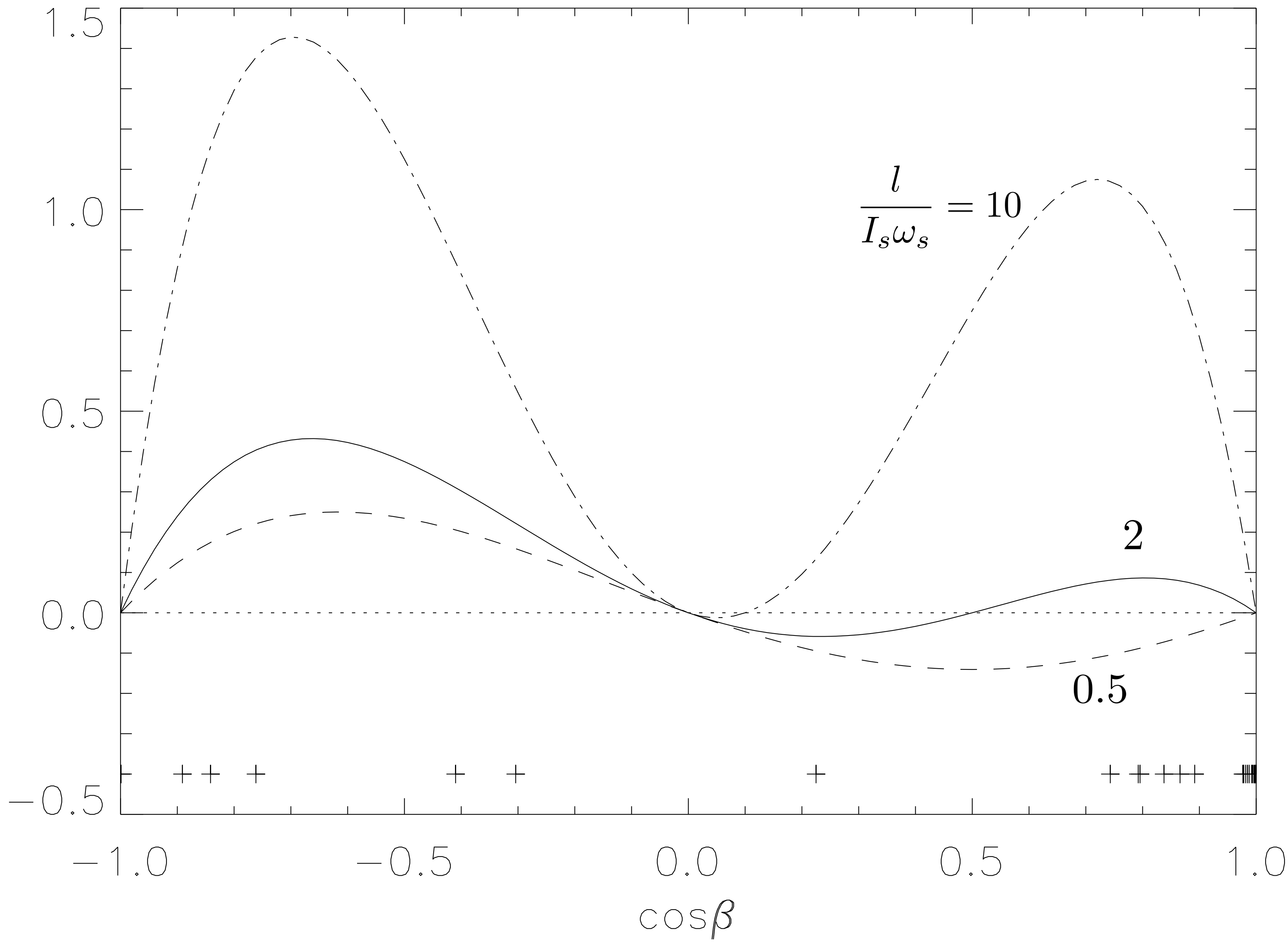


wants to go to 90°

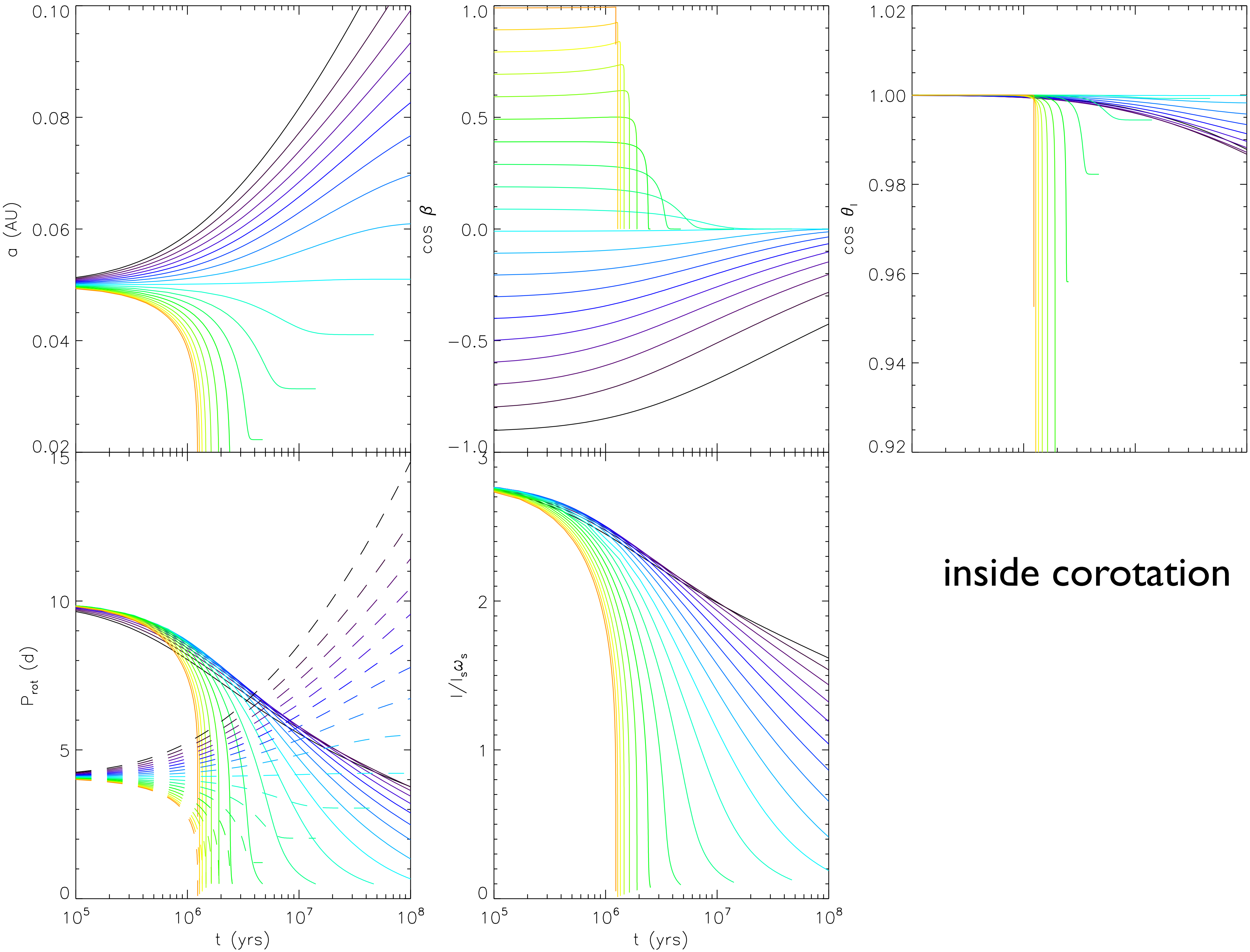


$$\frac{d\beta}{dt} = -\frac{\mathcal{T}_x \cos\beta}{I_s \omega_s}$$

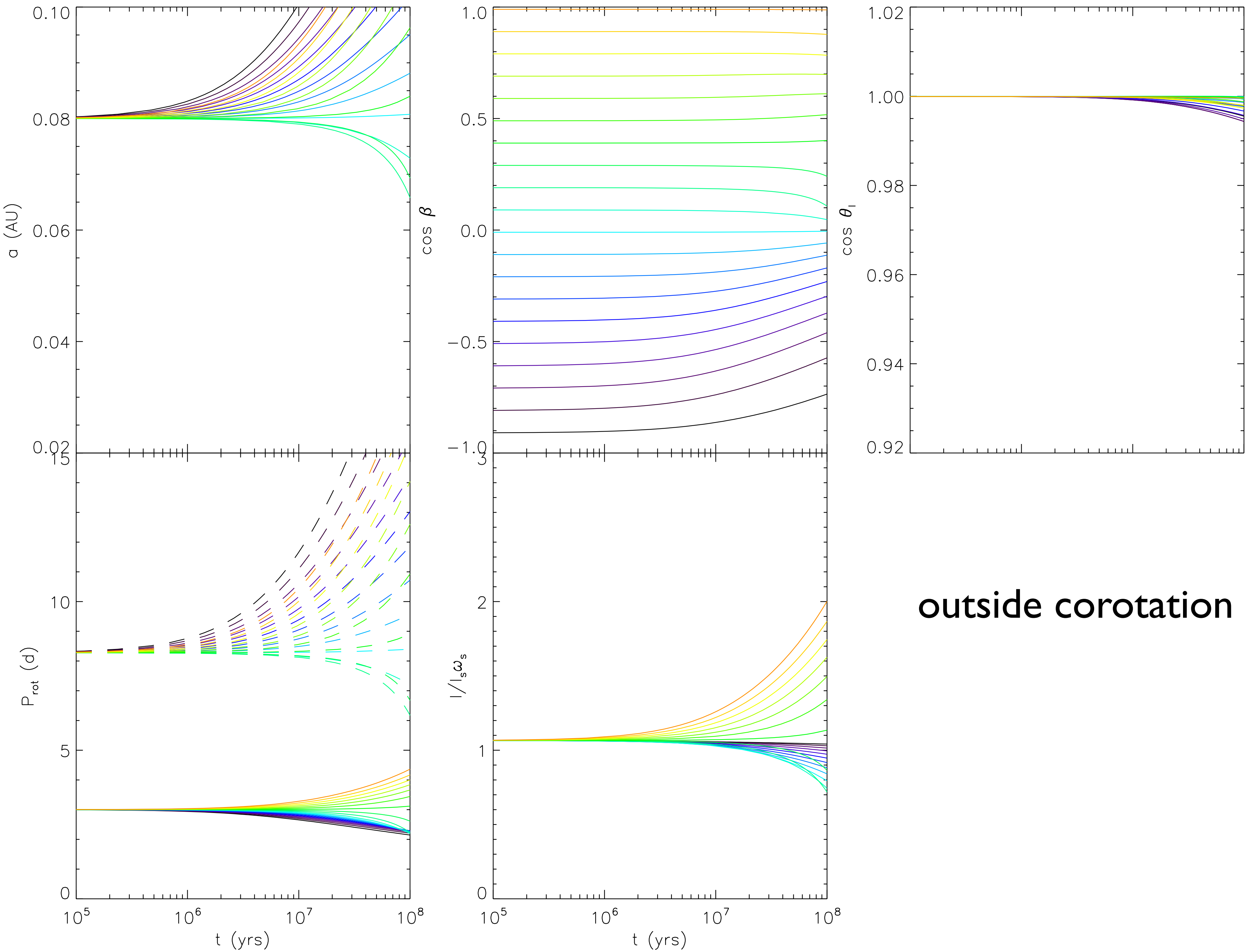
wants to go to 180°



1.5
1.0
0.5
0.0
−0.5
τ_a dcosβ/dt
$\frac{l}{I_s\omega_s} = 10$
2
0.5
−1.0
−0.5
0.0
0.5
1.0
cosβ



inside corotation



outside corotation

Electrical conductivity

"terminal velocity"

1. relaxation time approximation

$$J = \sigma E = n_e e v_{\rm drift} = n_e e \left(\frac{eE}{m_e \nu} \right)$$

$$\Rightarrow \sigma = \frac{n_e e^2}{m_e \nu}$$

collision frequency ν

2. strong B field

cyclotron frequency $\omega_e = \dfrac{eB}{m_e c}$

$$\vec{J} = \sigma \cdot \vec{E}$$

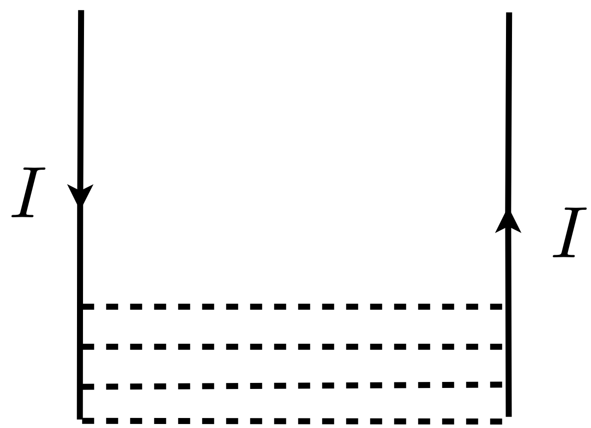
$$\sigma_\parallel = \sigma_0$$

$$\sigma_\perp = \frac{\sigma_0}{1 + (\omega_e/\nu)^2}$$

$$\sigma_{\rm Hall} = \frac{\sigma_0(\omega_e/\nu)}{1 + (\omega_e/\nu)^2}$$

Resistance of the stellar atmosphere

Laine & Lin 2010



resistance of a wire

$$\mathcal{R} = \frac{L}{\sigma A}$$

$$\Rightarrow \mathcal{R}^{-1} = \int \sigma(r) dr$$

electron collision frequency
set by e-neutral collisions

$$\nu \sim n\sigma v \approx n_n \left(10^{-15}\ \mathrm{cm}^2\right) \left(\frac{k_B T}{m_e}\right)^{1/2}$$

(Draine)

$$\Rightarrow \quad \sigma = 3 \times 10^{15}\ \mathrm{s}^{-1} \frac{x}{T_4^{1/2}}$$

ionization fraction from Saha

$$x^2 = \frac{1}{n} \left(\frac{m_e k_B T}{2\pi \hbar^2}\right)^{3/2} \exp\left(-13.6\ \mathrm{eV}/k_B T\right)$$

$$\Rightarrow \quad \sigma_0 \propto \frac{1}{\sqrt{n}} \qquad \frac{\omega_e}{\nu} \propto \frac{1}{n}$$

current flows where $\omega_e/\nu \sim 1$

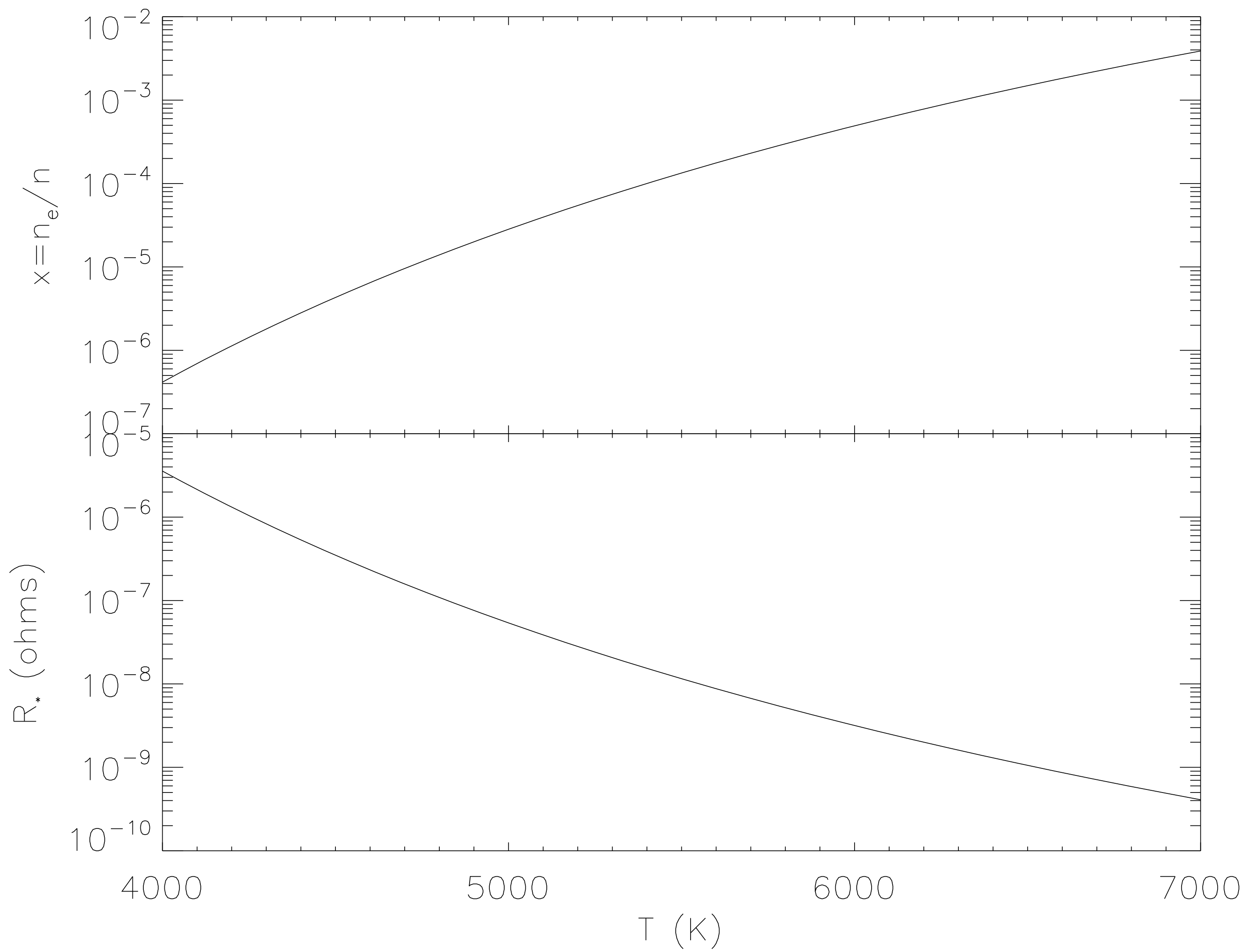
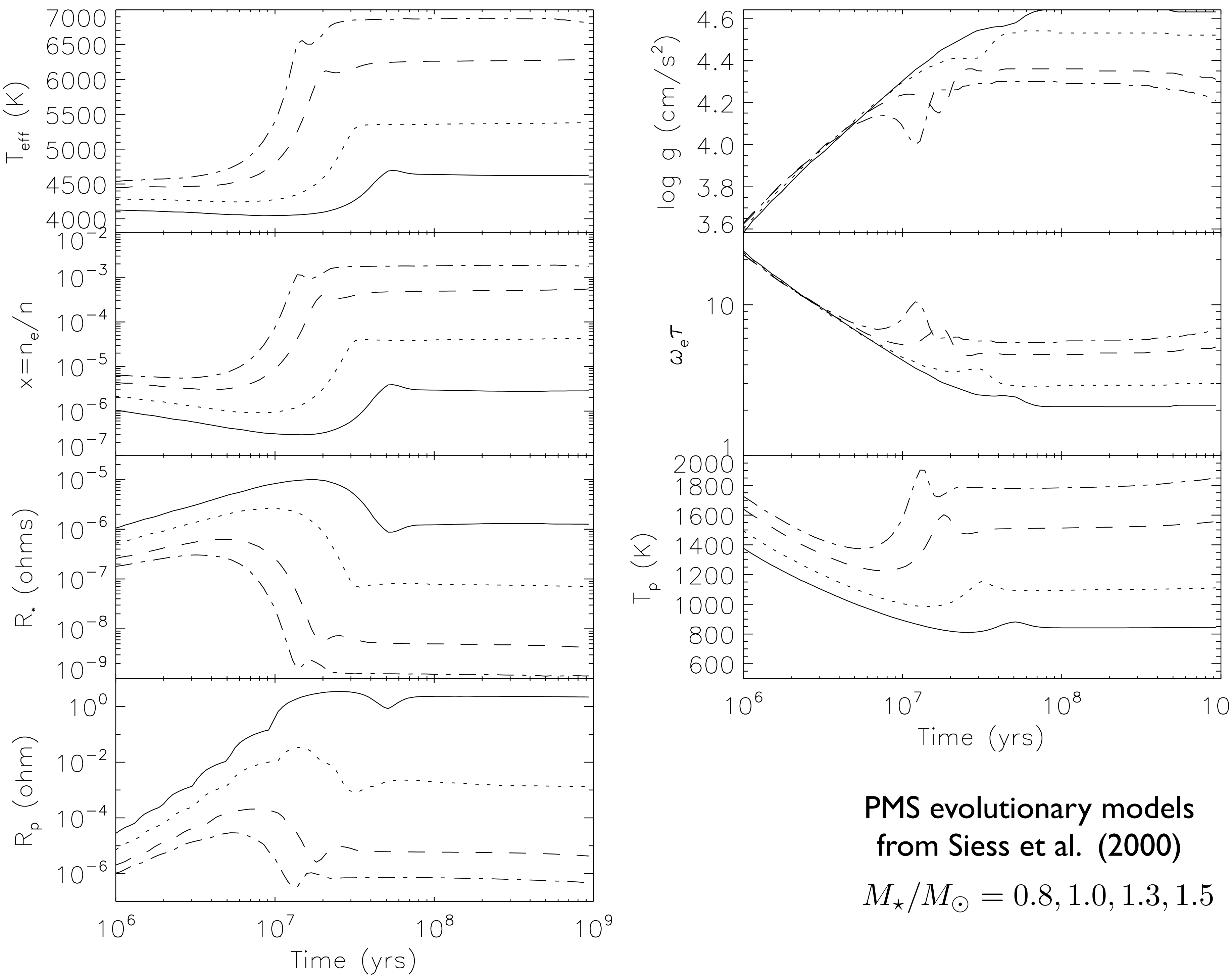


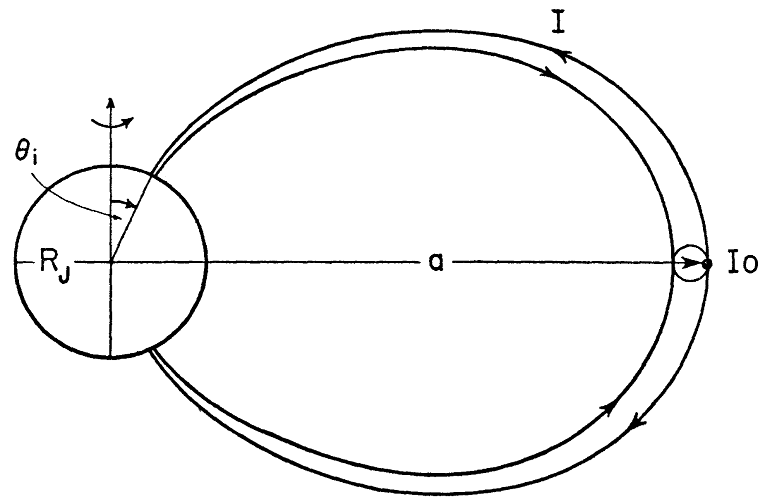
FIG. 4.— Ionization fraction of hydrogen at the photosphere as a function of temperature (top panel) and the resistance of the star (bottom panel).



PMS evolutionary models
from Siess et al. (2000)

$$M_\star/M_\odot = 0.8, 1.0, 1.3, 1.5$$

Limiting current from magnetic reconnection



$$\Delta\phi = \frac{4\pi\mathcal{I}}{r_P B_\star c}\left(\frac{a}{r_\star}\right)^3\left(1-\frac{r_p}{a}\right)^{1/2}$$

12° for Jupiter-Io
(Goldreich & Lynden_Bell 1969)

Winding angle is ~1 for $c\mathcal{R}_{\rm eff} = \frac{8\pi\,(n-\omega_s)\,a}{c} = \frac{8\pi\Delta v}{c}$

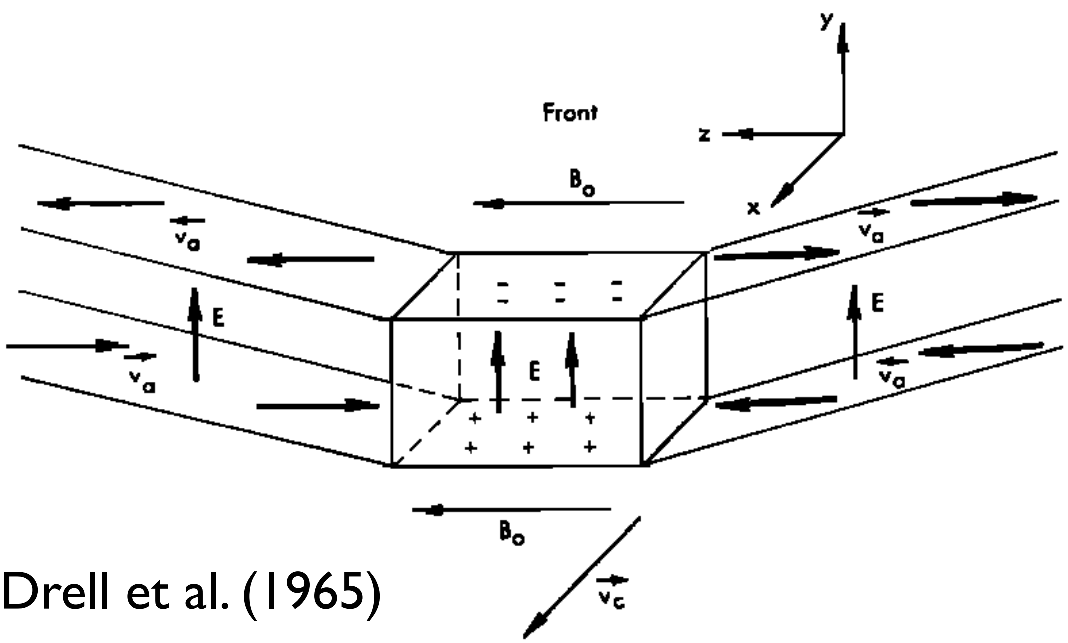
$$\mathcal{R}_{\rm eff} = 0.25\ {\rm ohm}\ \left(\frac{\Delta v}{100\ {\rm km\ s^{-1}}}\right)$$

Seems likely that the winding angle could not be much greater than ~unity => build up of current in the magnetosphere is limited

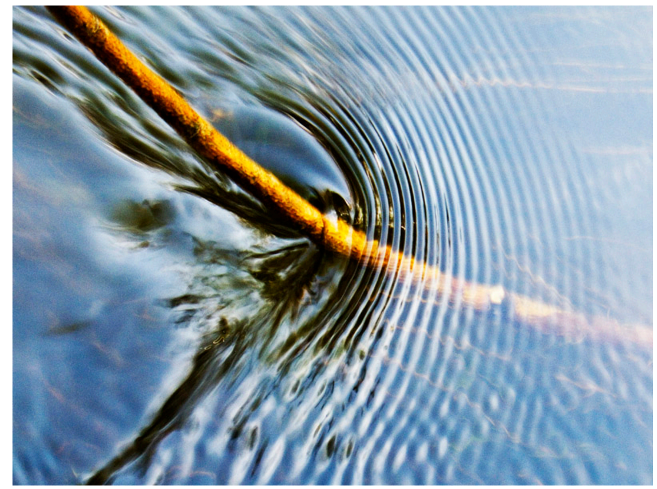
=> time dependence, effective mean resistance ~ 0.3 ohm

Maintaining a circuit requires the Alfven travel time between the star and planet to be short compared to the time on which the planet crosses field lines

If not, then the moving planet will excite Alfven waves



Drell et al. (1965)



Effective plasma impedance
(resistance in the circuit)

$$\mathcal{Z} \approx 2\pi v_A / c^2$$

.. but to exceed the reconnection-limited torque, can show that Alfven Mach number >1, so need to look more carefully

A second interaction is from the induced field in the planet in response to the time-varying stellar field

Laine & Lin (2008)

Model as a dipole-dipole interaction

Induced dipole moment $V\alpha \boldsymbol{B}$

in-phase and out-of-phase response $V\alpha = V(\alpha' + i\alpha'')$

Ratio of torque to the unipolar inductor torque

$$\frac{\langle \mathcal{T}_z \rangle}{\langle \mathcal{T}_z \rangle_u} = \frac{15\pi}{8} \left(\frac{\delta}{r_p} \right)^3 \left(\frac{r_p}{a} \right)^2 \tan^2 \theta_\star .$$

Energy dissipation rate

$$1.25 \times 10^{25} \text{ erg s}^{-1} \left(\frac{r_p}{R_J} \right)^3 \left(\frac{B_\star}{1 \text{ kG}} \right)^2 \left(\frac{2\pi/\omega}{1 \text{ day}} \right)^{-1} \left(\frac{10 r_\star}{a} \right)^6 (20\pi\alpha'')$$

(Inflated hot jupiters require 1e24-1e28 Ibgui et al. 2008)

Summary

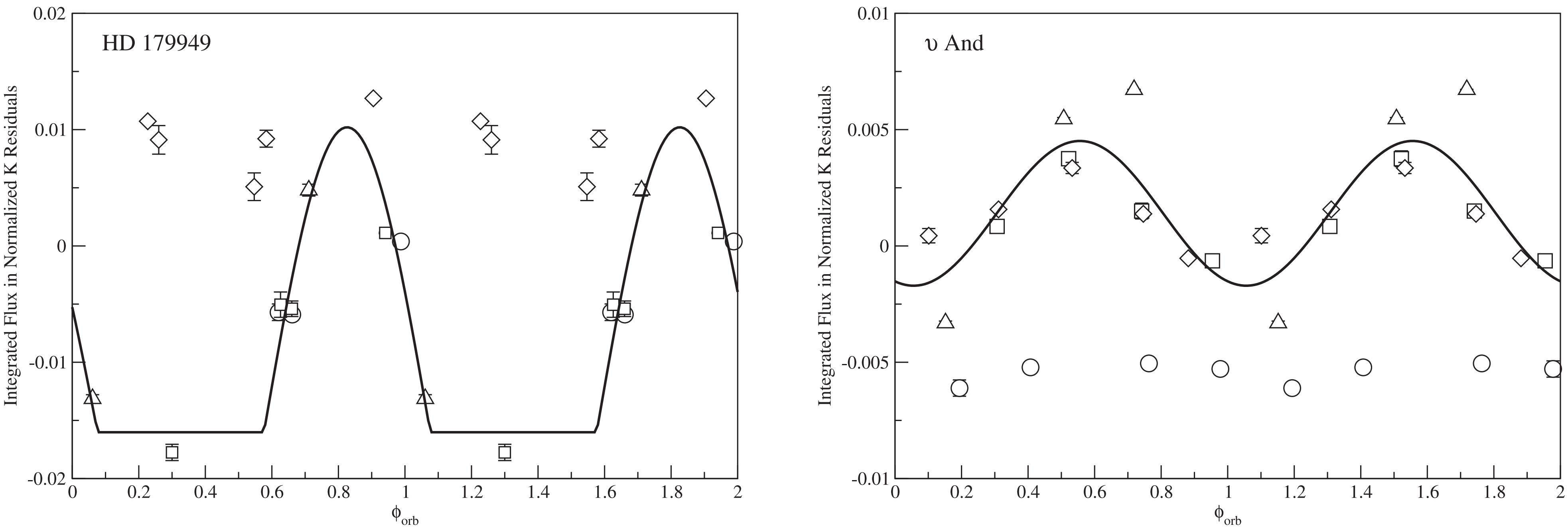
- If magnetic torques play a role in migration of closely orbiting planets, significant non-zero obliquities can be generated

- Uncertainties in the timescale:
  - In the exoplanet case, unipolar induction is likely limited by reconnection of the field
  - Effect of planetary magnetosphere, solar wind on the current paths
  - If Alfven travel time is too long, drag from excitation of Alfven waves

- Other observational signatures:
  - heating, hot spots, equivalent of Jupiters decametre emission..

Enhanced magnetic activity in hot jupiter hosting stars

Shkolnik et al. (2005) CaHK emission correlated with orbital phase



Also, some evidence for enhanced X-ray flux for stars with close planets (Kashyap et al. 2008; but see Poppenhaeger et al. 2010)