Interactions between Hot Jupiters and their Host Stars

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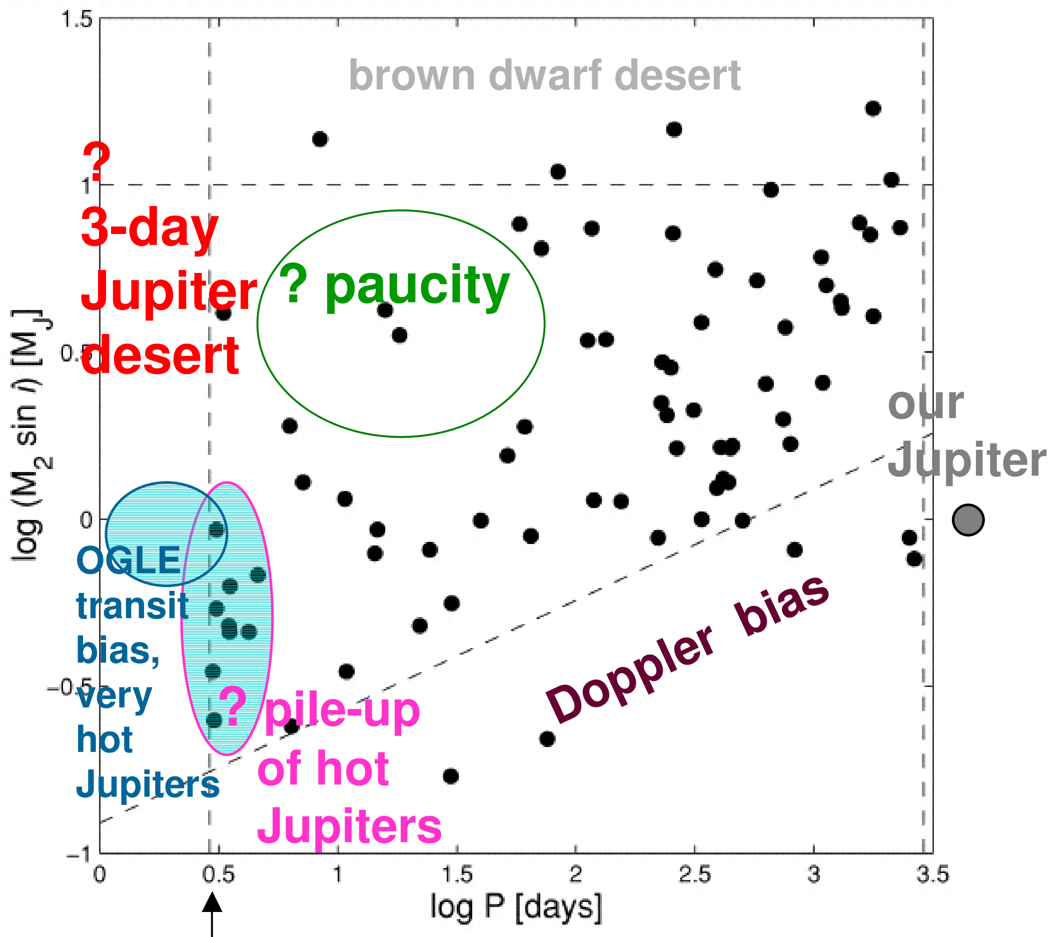
Type of Interactions

- ☐ gravitational (tides in hot Jupiters & in host stars)
- ☐ magnetic (planet-induced CaII emissions; planet inside the Alfven radius)
- ☐ stellar irradiation (planetary winds; Jupiter's size)

3-day Jupiter Desert

- tidal inflation instability (Gu, Lin, & Bodenheimer 2003, 2004): requires critical eccentricities, difficult for massive planets, location of dissipation
- inner disk truncated by stellar magnetic fields (Lin et al. 1996): why 3 days? Or by MRI (Kuchner & Lecar 02): handwaving. Or by evaporation (Johnstone)
- Roche-overflow driven by disk migration w/o tidal inflation (Trilling et al. 1998): requires very large planet sizes
- **orbital decay due to the spin-orbit tidal interaction (Rasio et al. 96; Patzold & Rauer 02; Jiang et al. 02): Q value of a star? Metallicity enhancement? Faster stellar spin? Why is there a pile-up?**
- orbital decay due to magnetic interaction (Shkolnik et al. 2005)
- evaporation by stellar irradiation/winds (Vidal-Madjar et al. 2003): source of neutral hydrogen? Magnetosphere of a hot Jupiter? Why pile-up? c.f. black widow pulsar?



cutoff period → Q_{star} ~ $10^{5\sim6}$ (consistent with stellar binaries)

→ faster rotating stars with higher metallicity?

stars having very hot or massive Jupiters rotate faster?

OGLE Bias

1) Gaudi et al. 2004

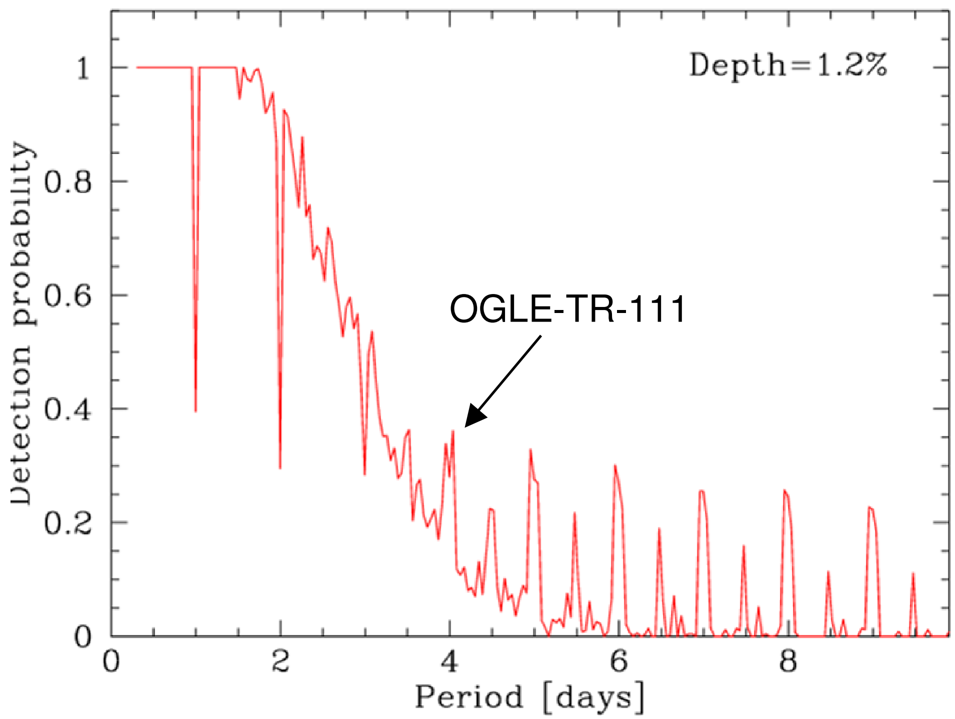
Radial Velocity Survey:
fixed sample size
detection probability

$$K \propto (M_p \sin i) P^{-1/3}$$

Transit Survey:
fixed S/N
detection probability

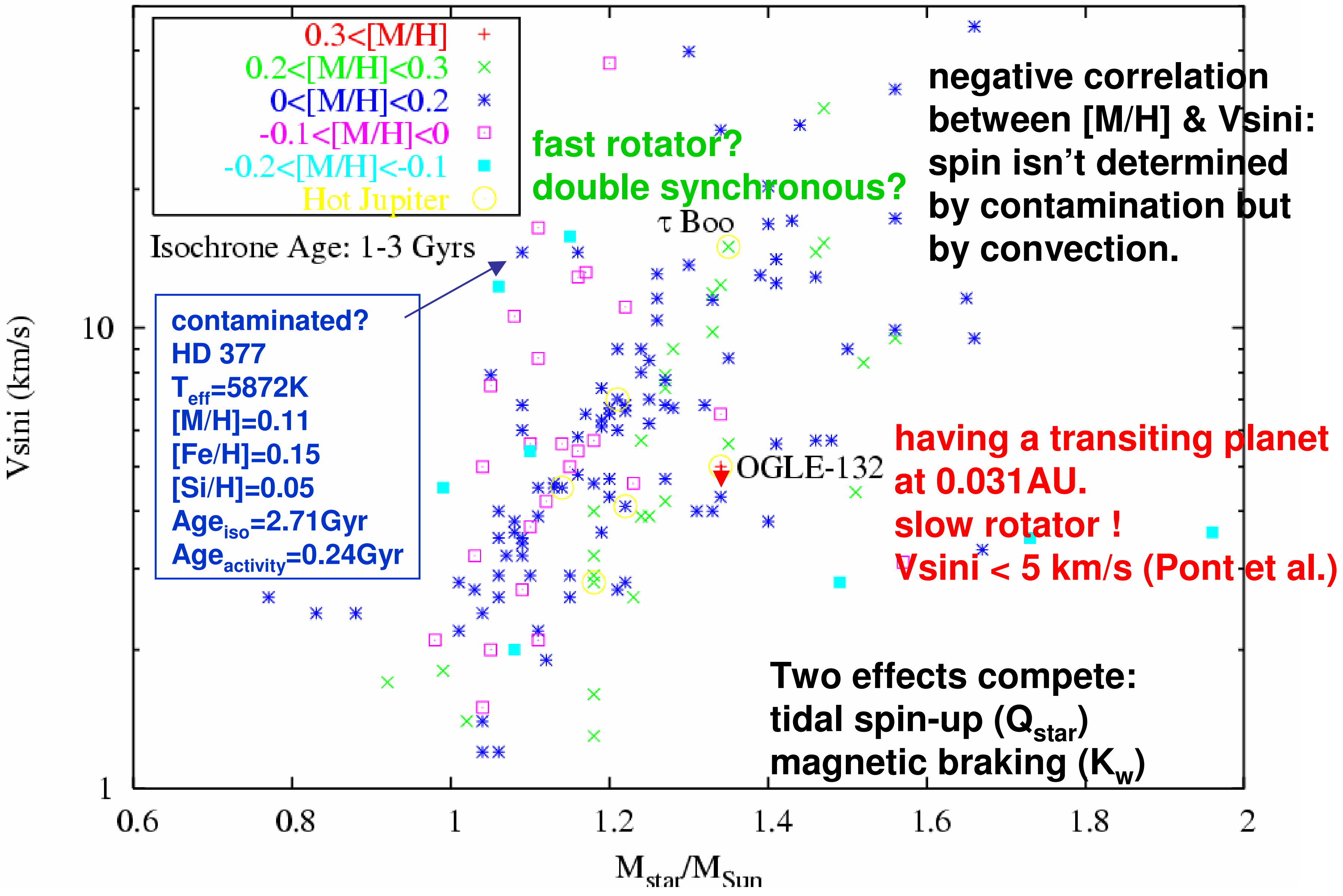
$$\underset{\text{geometric}}{\underset{\uparrow}{(a^{-1})}}\underset{\text{\# of stars}}{\underset{\nwarrow}{(d^{3})}} \propto (P^{-2/3})\underset{\text{S/N}}{\underset{\nwarrow}{(P^{-1})}} \propto P^{-5/3}$$

2) Pont et al. in preparation



RV survey is consistent with Transit survey

Vsini vs [M/H] (Gu, Li, Shkolnik, & Liu 2005 based on Valenti & Fischer 2005)



contaminated?
HD 377
T_{eff}=5872K
[M/H]=0.11
[Fe/H]=0.15
[Si/H]=0.05
Age_{iso}=2.71Gyr
$Age_{activity}$=0.24Gyr

fast rotator?
double synchronous?

negative correlation between [M/H] & Vsini: spin isn't determined by contamination but by convection.

having a transiting planet at 0.031AU.
slow rotator !
Vsini < 5 km/s (Pont et al.)

Two effects compete:
tidal spin-up (Q_{star})
magnetic braking (K_w)

Spin Evolution

$$\frac{\dot{\Omega}}{\Omega} = \frac{1}{\tau_{tide,\Omega}} - \frac{1}{\tau_{wind}} + \frac{1}{\tau_{magnetic}} \qquad \frac{\dot{a}}{a} = -\frac{1}{\tau_{tide,a}} - \frac{1}{\tau_{magnetic}}$$

where

wnd parameter:
calibrated for different spectral types

$$\tau_{wind} \approx 0.19 \left(\frac{I}{0.1 M_{sun} R_{sun}^2}\right) \left(\frac{2\pi/3\,\mathrm{days}}{\Omega}\right)^2 \boxed{\left(\frac{2.7\times10^{47}\,\mathrm{g\,s/cm^2}}{K_w}\right)} \left(\frac{M_{star}}{M_{sun}}\right)^{1/2} \left(\frac{R_{sun}}{R_{star}}\right)^{1/2} \mathrm{Gyrs}$$

$$\tau_{tide,\Omega} \approx 18.15 f \left(\frac{I}{0.1 M_{sun} R_{sun}^2}\right) \boxed{\left(\frac{Q_{sun}}{10^6}\right)} \left(\frac{M_{star}}{M_{sun}}\right)^{3/2} \left(\frac{a}{0.04\mathrm{AU}}\right)^{9/2} \left(\frac{M_J}{M_p}\right)^2 \left(\frac{R_{sun}}{R_{star}}\right)^3 \left(\frac{1}{n/\Omega - 1}\right) \mathrm{Gyrs}$$

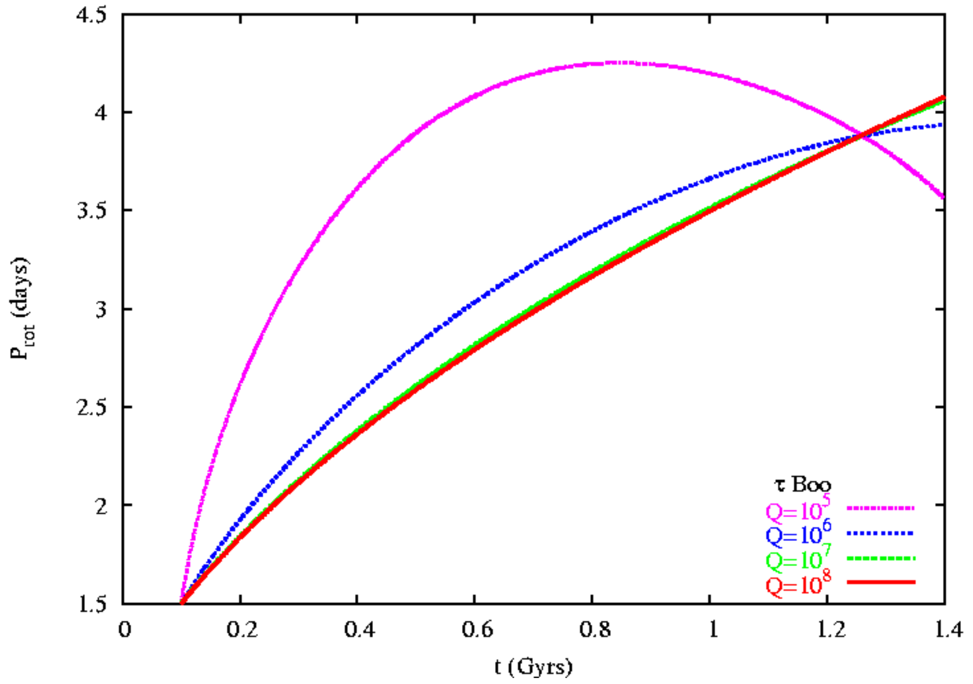
$$\tau_{tide,a} = \tau_{tide,\Omega} \left(\frac{M_p \sqrt{G M_{star} a}}{2 I \Omega}\right)$$

$\propto$ 1/viscosity (for beginners),
constrained conventionally by binary stars
or by star-hot Jupiter systems?

key issues:

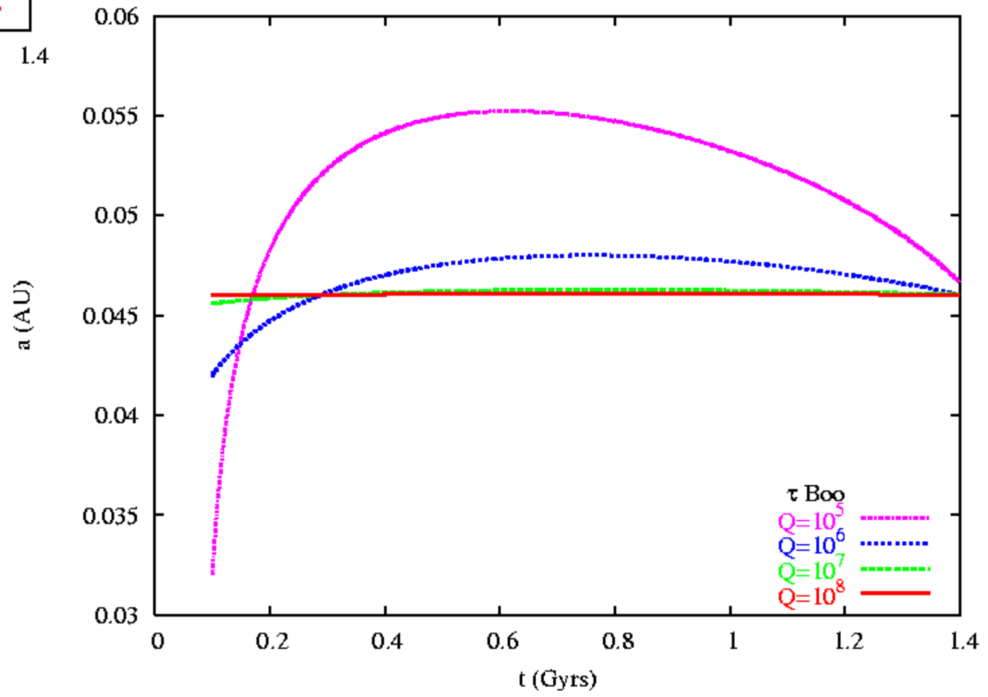
- **magnetic braking (theory: dynamo & wind velocity,**
  observation: Skumanich relationship $P_{rot} \propto t^{1/2}$)
- **tidal dissipation: circularization & synchronization**

P_{rot} evolution of τ Boo (Gu, Li, Shkolnik, & Liu 2005)

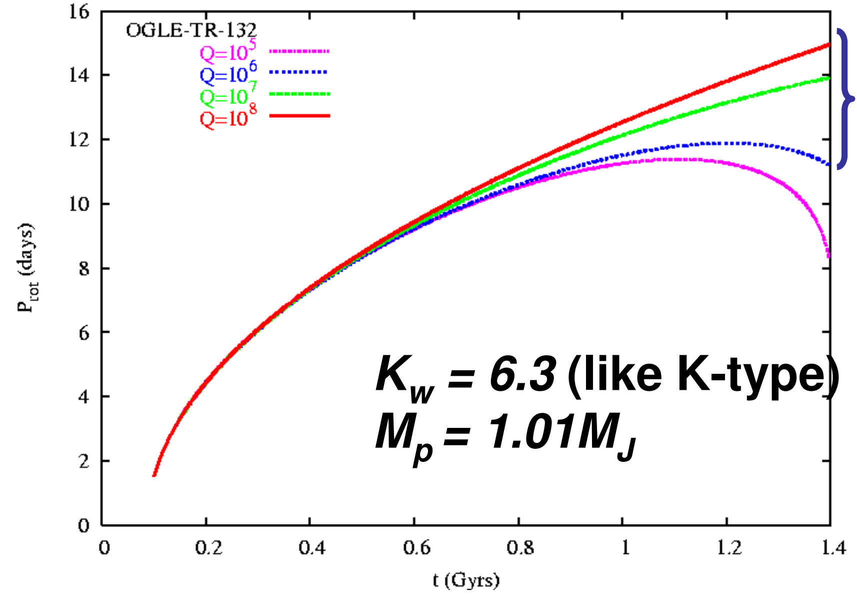


wind parameter: $K_w = 0.4$
$M_p = 5\ M_J$

Hard to discriminate
different Q-values →
Hard to say τ Boo
is tidally locked by its
planetary companion
unless $P_{rot}=P_{orb}$
(waiting for MOST results)



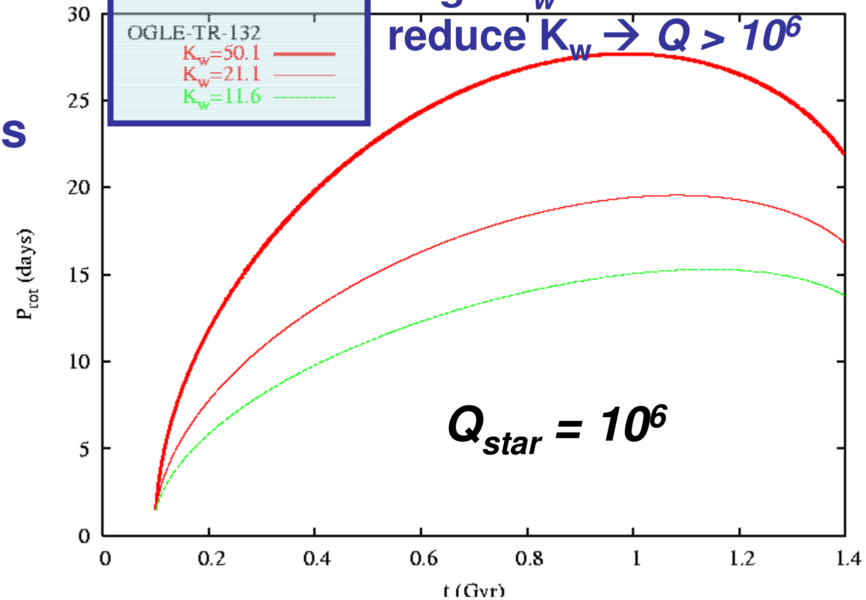
P_{rot} evolution of OGLE-TR-132 (Gu, Li, Shkolnik, & Liu 2005)



$K_w = 6.3$ (like K-type)

$M_p = 1.01 M_J$

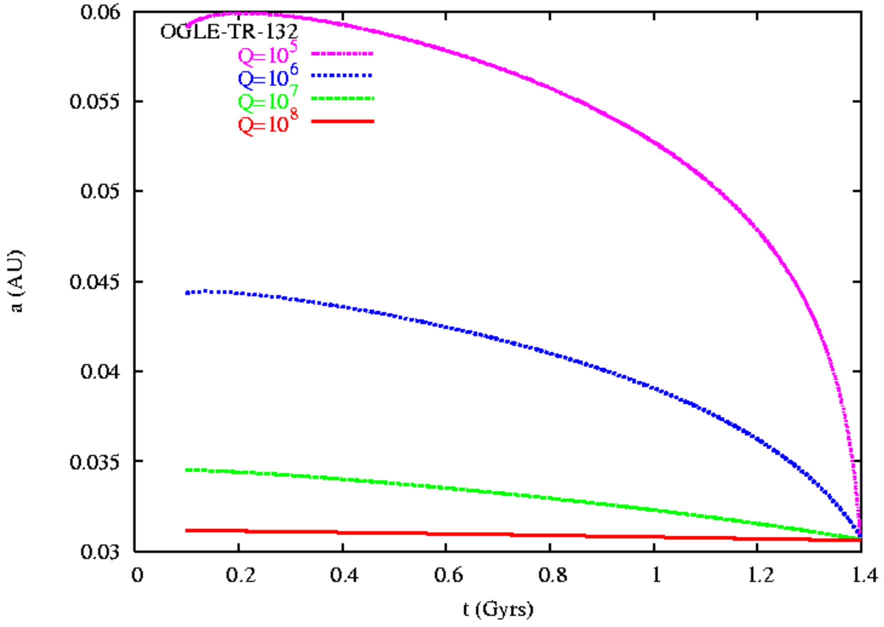
4 days

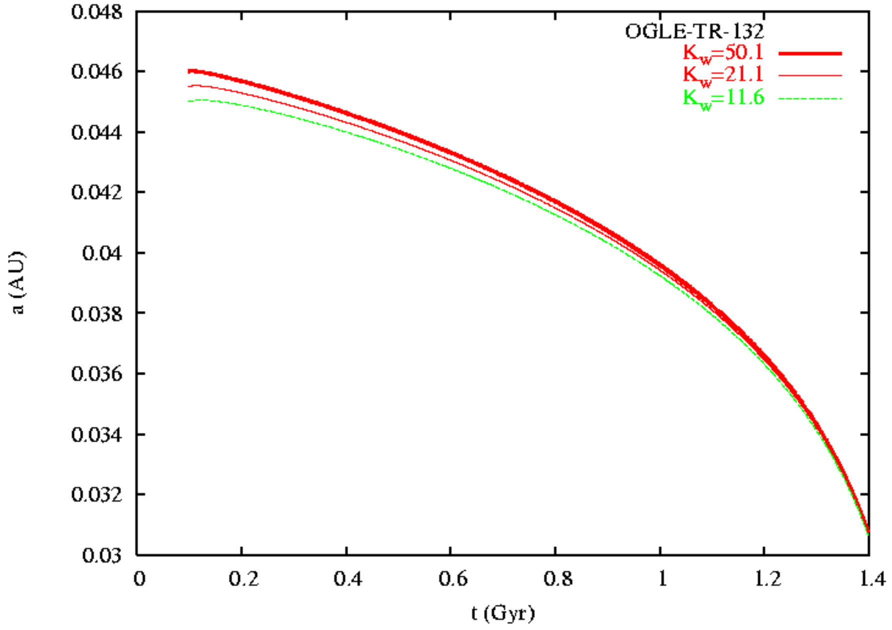


large K_w

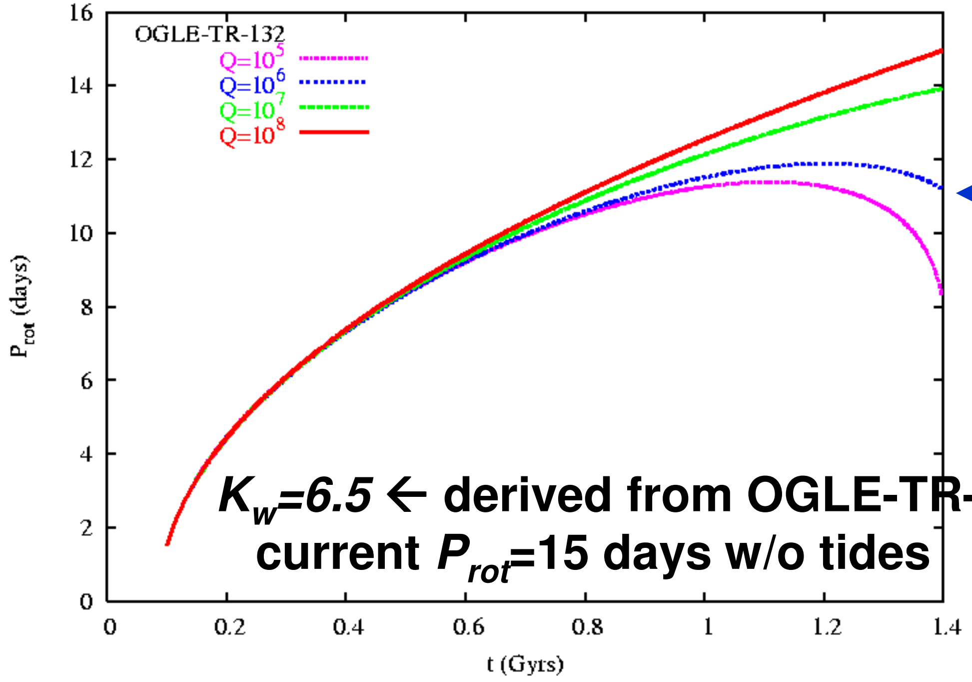
reduce K_w → $Q > 10^6$

$Q_{star} = 10^6$





Q value of a solar-type star (Gu, Li, Shkolnik, & Liu 2005)

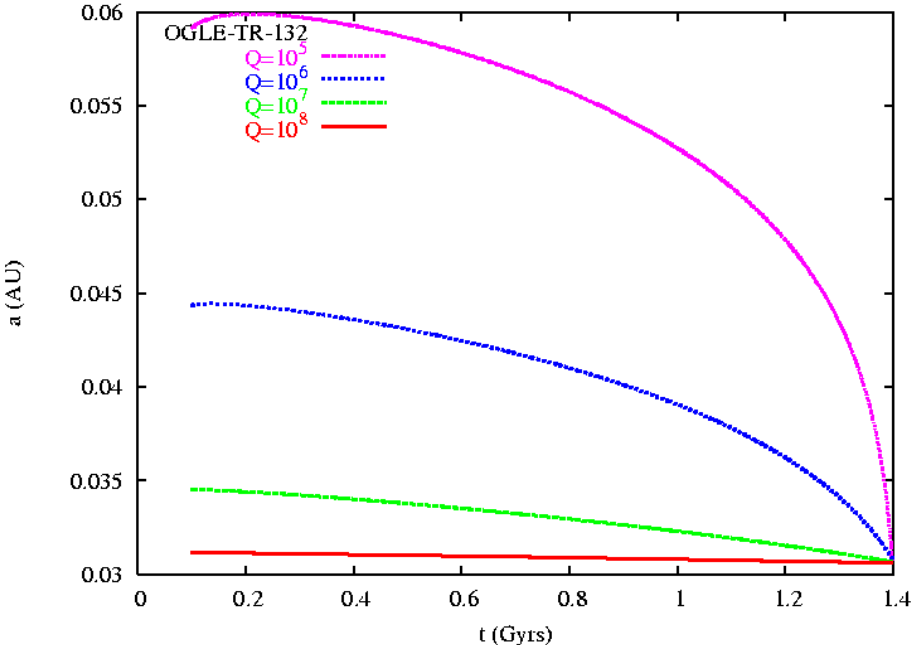


$K_w=6.5$ ← derived from OGLE-TR-132's current $P_{rot}=15$ days w/o tides

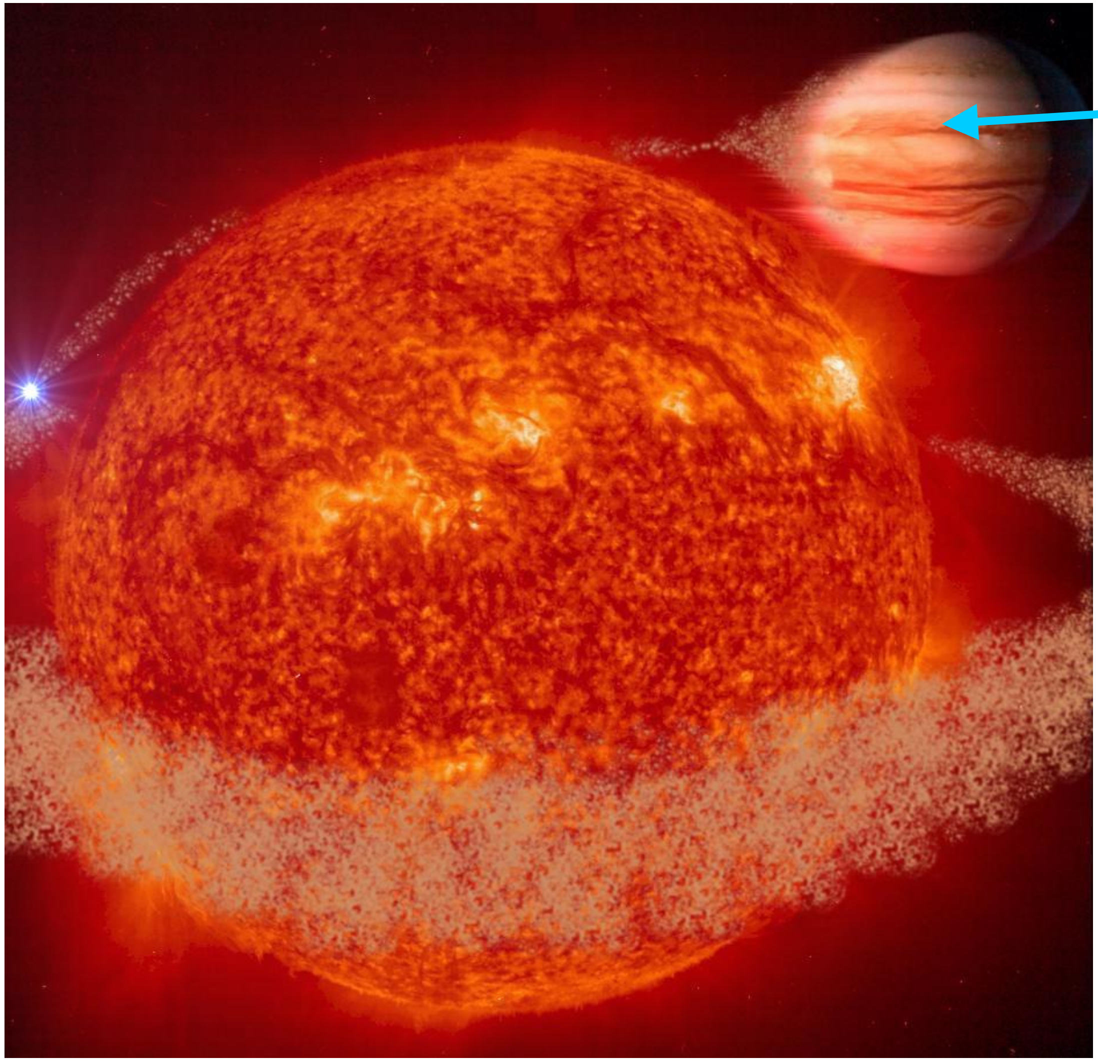
Can $Q=10^6$ in a star driven by a hot Jupiter be ruled out?

$Q=10^6$ driven by a stellar companion (Mathieu et al. 2004);

need another late-F type star to constrain the wind parameter K_w and then constrain the Q value of a solar-type star.



Tidal Inflation
(Gu, Bodenheimer, Lin 2003, 2004)



mini interacting binaries!

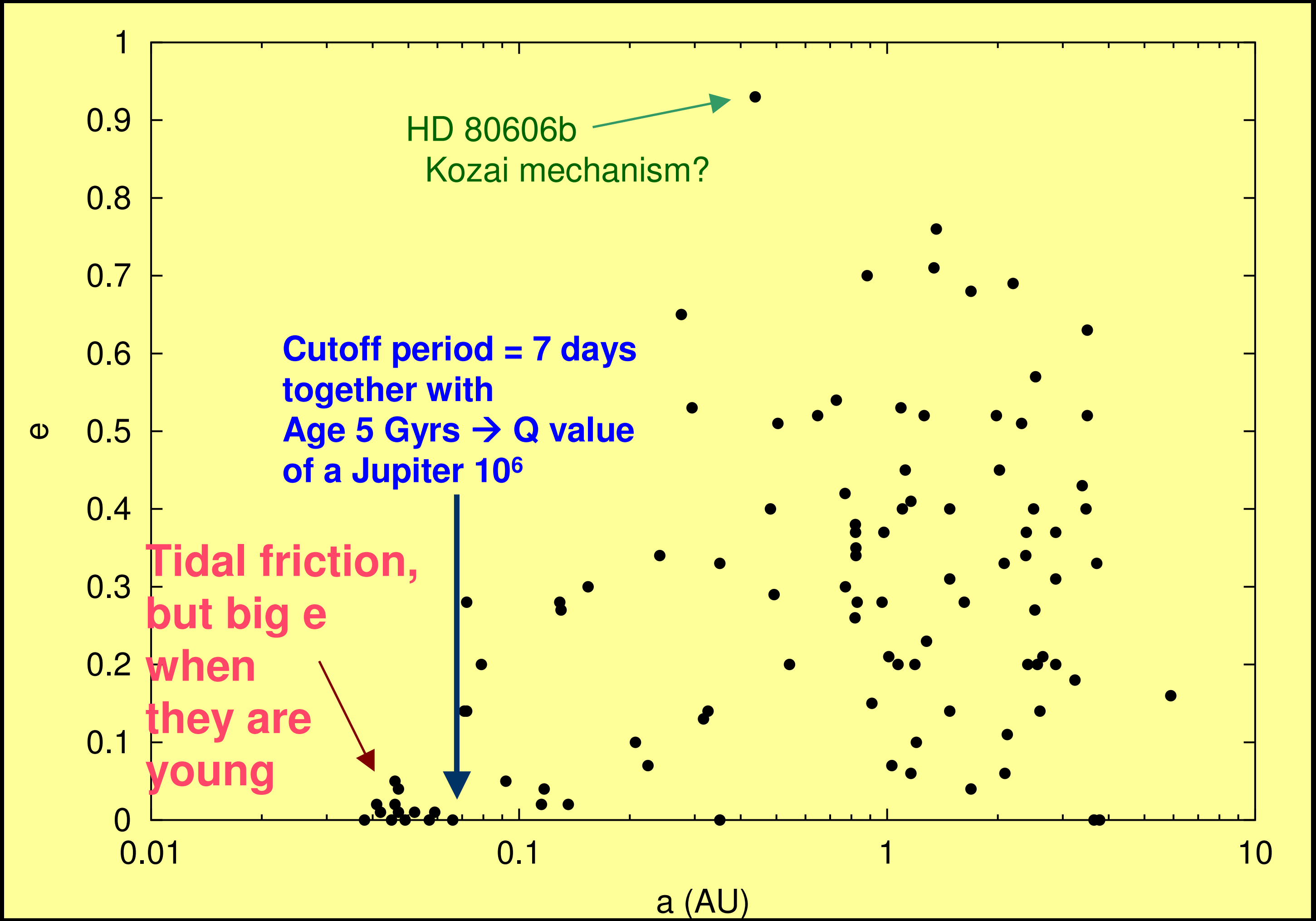
tidal heating →
EoS evolves →
thermal instability →
runaway inflation →
Roche-lobe overflow →
outward migration &
mass loss

Roche-lobe overflow
threshold:
$Q_p=10^6$, $M_p=1M_J$, $R_p=2R_J$
uniform heating in mass:
$e \geq 0.2$ at $a=0.04$AU
Heating focused on $m/M_p=0.9$
$e \geq 0.28$ at $a=0.04$AU

Key Words:
Tidal Interaction
Polytrope
Density Ionization

Most exoplanets are eccentric (not due to observational bias!)

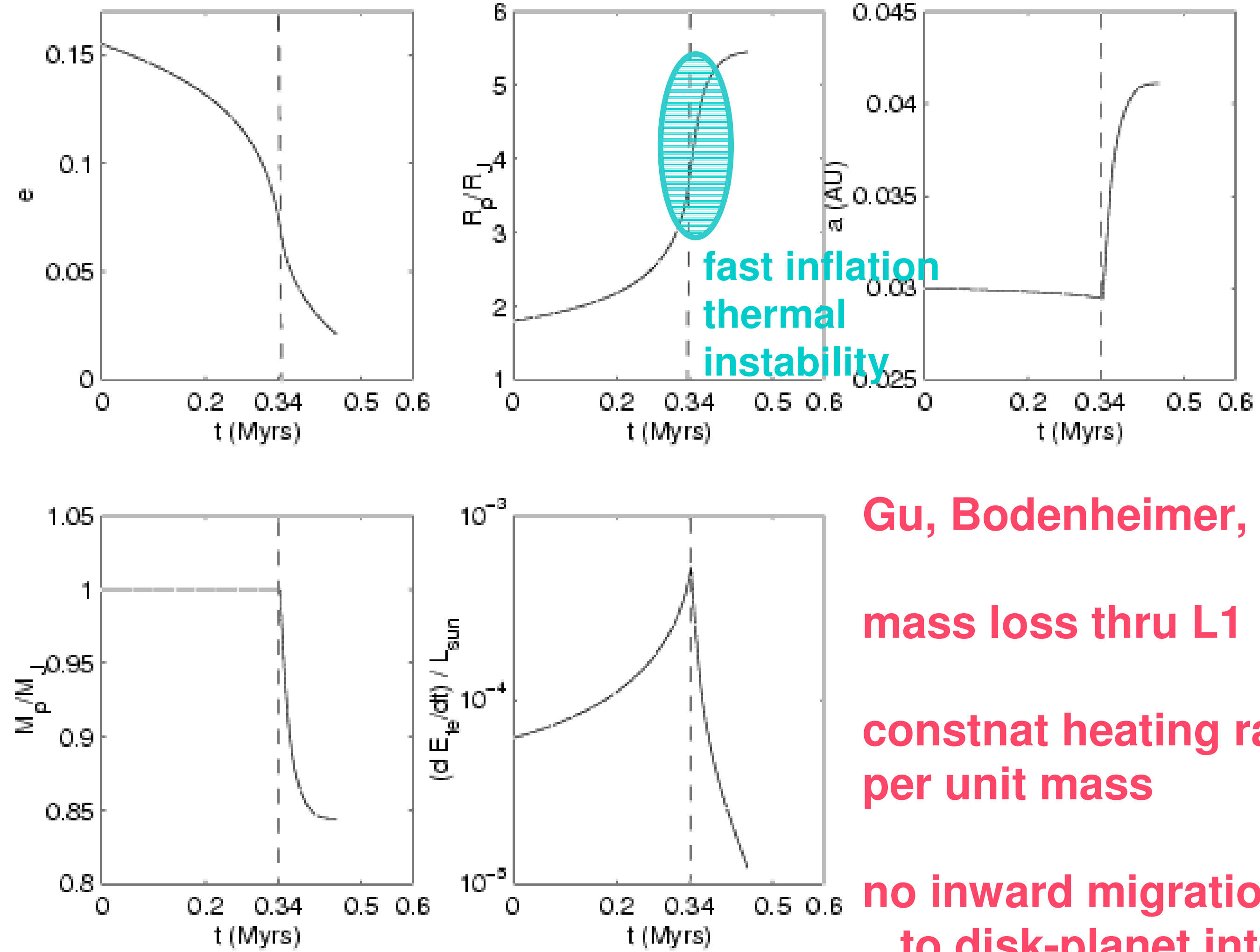
- planet-disk interaction (Goldreich & Sari; Ogilvie & Lubow 2003)
- planet-planet interaction (Fort & Rasio)



HD 80606b
Kozai mechanism?

Cutoff period = 7 days together with Age 5 Gyrs → Q value of a Jupiter 10^6

Tidal friction, but big e when they are young



fast inflation
thermal
instability

Gu, Bodenheimer, & Lin 2003

mass loss thru L1

constnat heating rate
per unit mass

no inward migration due
to disk-planet interaction

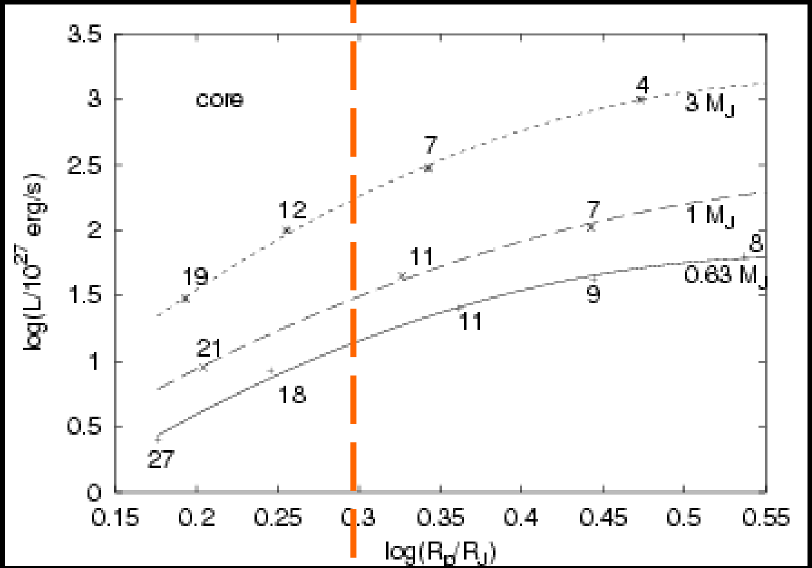
Fig. 2.— Time evolution of e, R_p, M_p, and $\dot{E}_{te}$ for a planet of a original $M_p = 1 M_J$ without a solid core initially located at 0.03 AU. The mass loss is calculated by using equation (74) with the condition that $\lambda = 2$. The moment $t = 0.34$ Myrs marked by a vertical dashed line indicates the beginning of the Roche overflow phase.

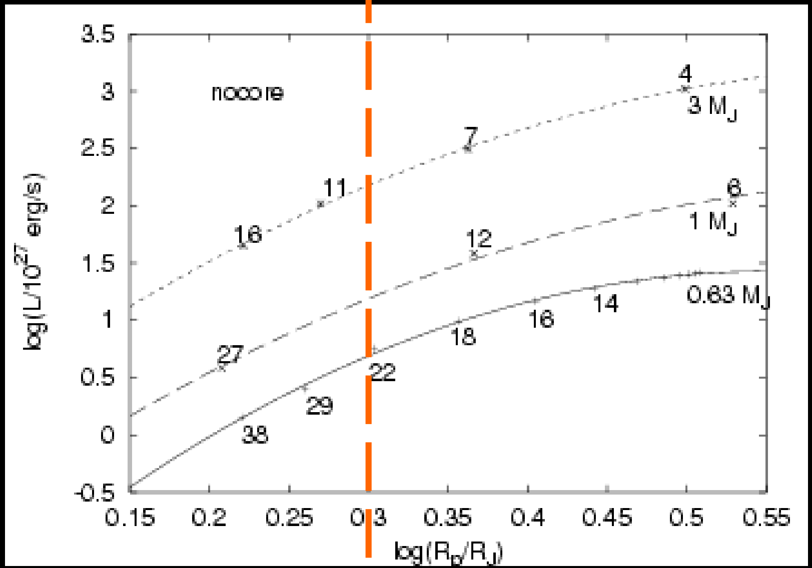
Luminosity-Radius Relation (Gu et al. 2003, 2004)

$H\,(\text{heating rate}) \propto R_p^5 e^2 / Q_p, \quad L(\text{cooling rate}) \propto R_p^{\gamma}$

$\text{Degeneracy} \equiv \frac{E_{Fermi}}{kT} \cong \frac{\rho}{6\times10^{-9}T^{3/2}}$

Degeneracy and γ decreases as R_p increases.





γ >5 thermally stable

R_p≈$2R_J$

γ <5 thermally unstable

γ >5 thermally stable

R_p≈$2R_J$

γ <5 thermally unstable

Polytrope and Planet Compressibility
(Gu et al. 2004)

$P = K\rho^{\Gamma} \equiv K\rho^{1+1/n}, \quad K = k_n M_p^{1-1/n} R_p^{-1+3/n}, \quad s(\text{entropy}) \propto \ln K$

$\Rightarrow d\ln R_p = C_M d\ln K + C_K d\ln M_p,$

$$\text{where } C_M \equiv \left(\frac{d\ln R_p}{d\ln K}\right)_{M_p} = \frac{n}{3-n}, \quad C_K \equiv \left(\frac{d\ln R_p}{d\ln M_p}\right)_K = \frac{1-n}{3-n}$$

completely degenerate gas : $K = \text{const.}, \quad n = 1.5 \Rightarrow C_K = -1/3$

terrestrial planets/asteroids : $n = 0, \ C_K = 1/3, \ C_M = 0, \ \Gamma = \infty$

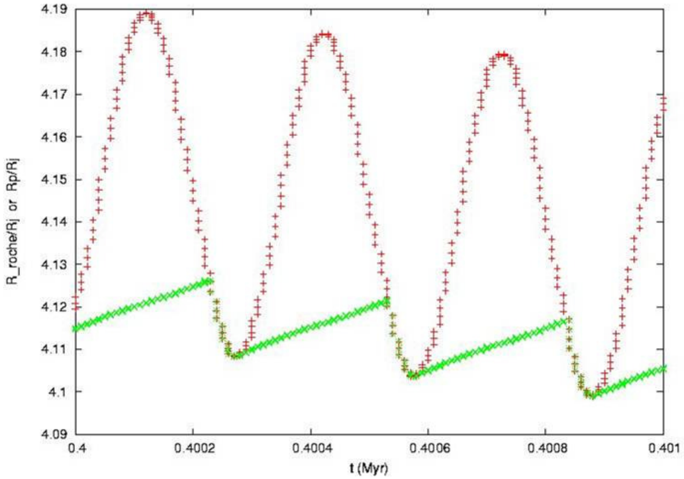
partial degeneracy : $n \approx 1, \ C_K \approx 0$ (max size at const. entropy), and

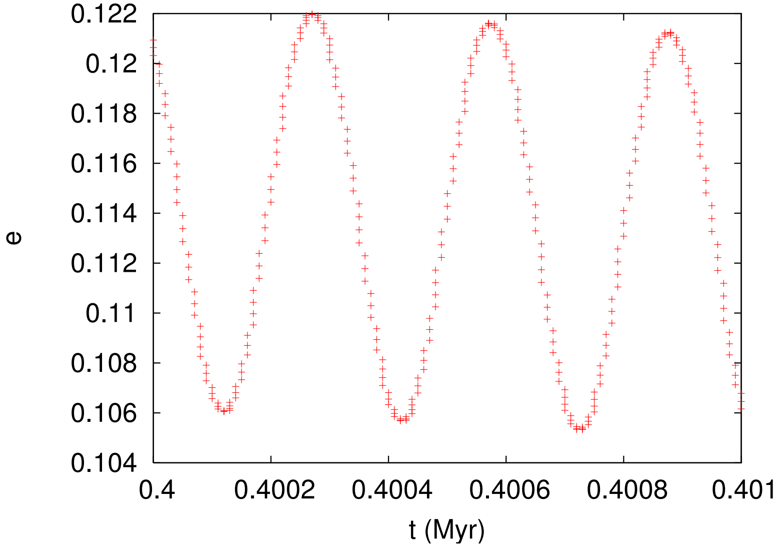
C_M increases as n rises from 1.

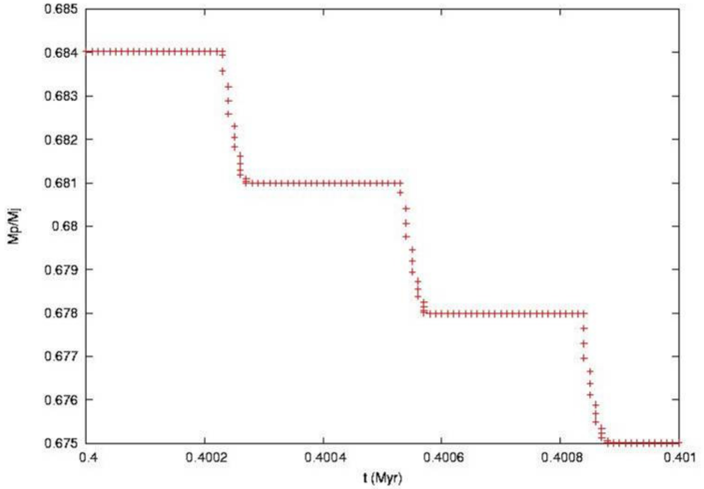
Note that $\dfrac{1}{C_M} = 3\left(\Gamma - \dfrac{4}{3}\right)$; i.e. the adiabatic bulk modulus Γ_{ad} decreases as the planet's elasticity C_M increases due to the reduction of electron degeneracy and non - ideal effects.

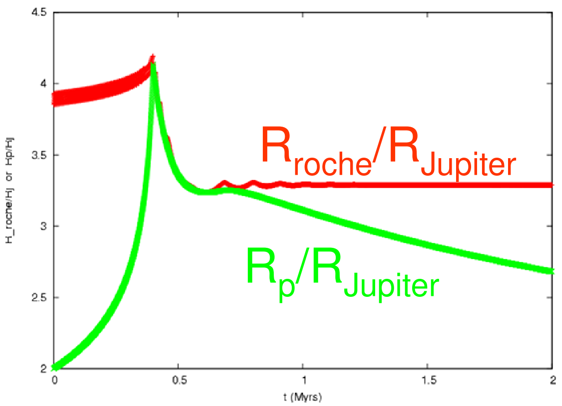
Formation of Hot Neptune in 55 Cnc (preliminary)

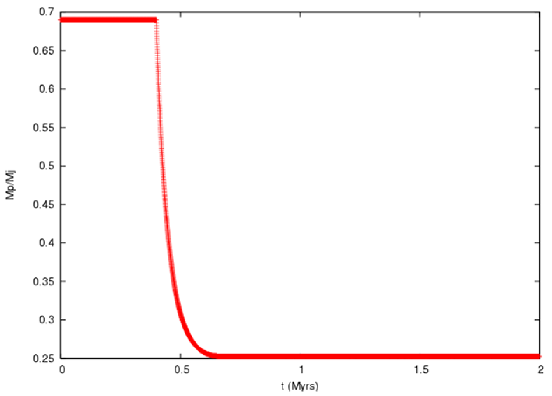
Progenitor might be a hot Jupiter.
intermittent mass loss due to tide + secular perturbation











Secular resonance should be included (Nagasawa & Lin 2005)

Call from Hot Jupiter Host Stars

Shkolnik, Walker, Bohlender, Gu, & Kurster 2005

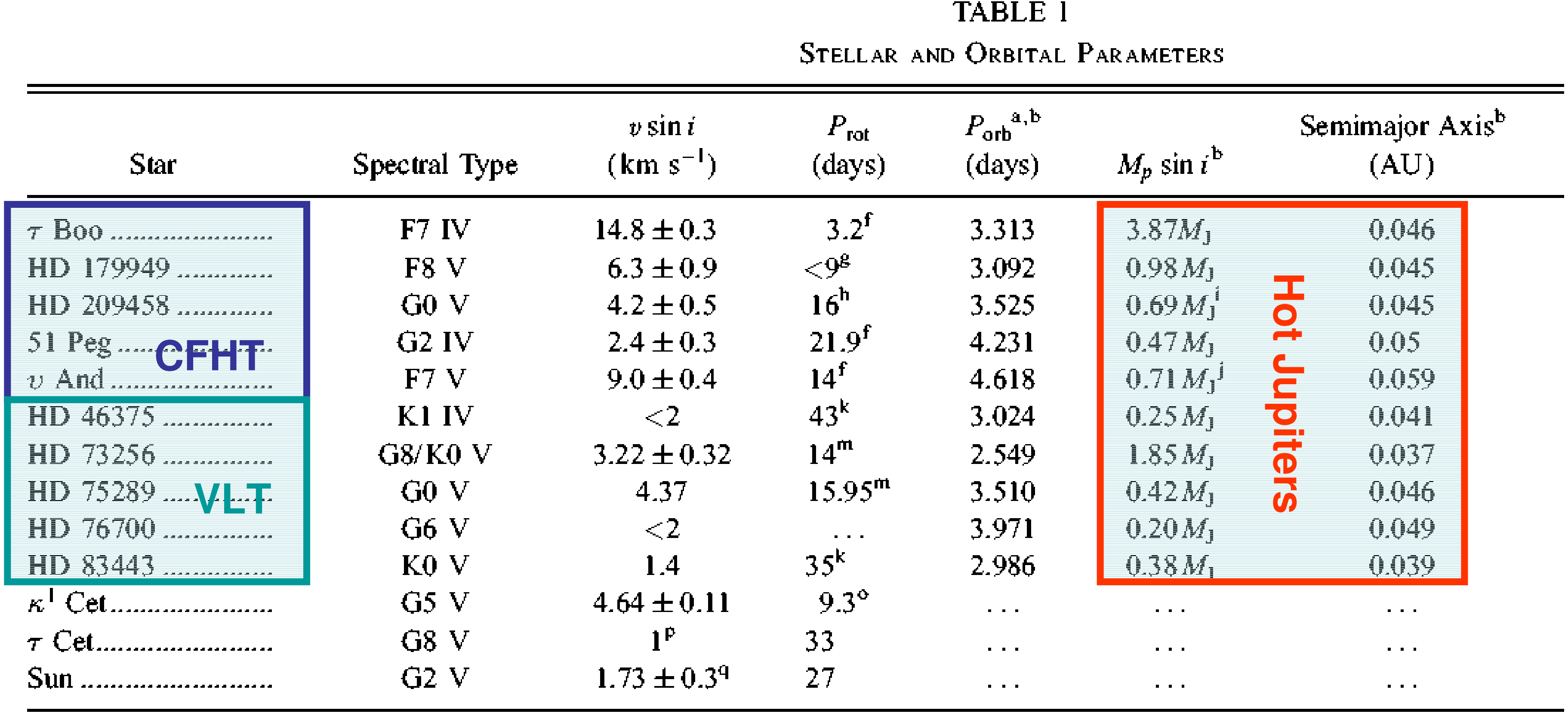


TABLE 1

STELLAR AND ORBITAL PARAMETERS

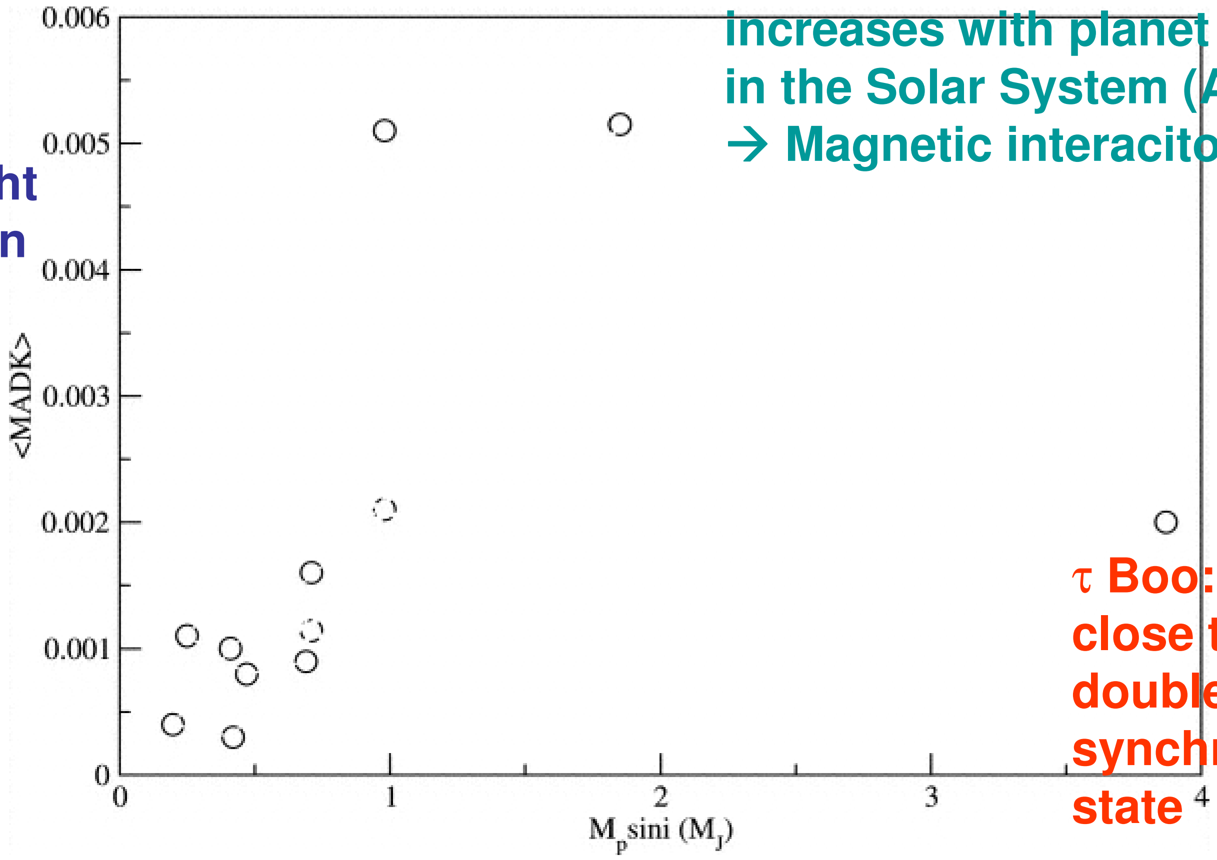
Star	Spectral Type	$v \sin i$ (km s^{-1})	P_{rot} (days)	P_{orb}^{a,b} (days)	$M_p \sin i$^{b}	Semimajor Axis^{b} (AU)
τ Boo	F7 IV	14.8 ± 0.3	3.2^{f}	3.313	$3.87 M_J$	0.046
HD 179949	F8 V	6.3 ± 0.9	$<9^{g}$	3.092	$0.98 M_J$	0.045
HD 209458	G0 V	4.2 ± 0.5	16^{h}	3.525	$0.69 M_J^{i}$	0.045
51 Peg	G2 IV	2.4 ± 0.3	21.9^{f}	4.231	$0.47 M_J$	0.05
υ And	F7 V	9.0 ± 0.4	14^{f}	4.618	$0.71 M_J^{j}$	0.059
HD 46375	K1 IV	<2	43^{k}	3.024	$0.25 M_J$	0.041
HD 73256	G8/K0 V	3.22 ± 0.32	14^{m}	2.549	$1.85 M_J$	0.037
HD 75289	G0 V	4.37	15.95^{m}	3.510	$0.42 M_J$	0.046
HD 76700	G6 V	<2	. . .	3.971	$0.20 M_J$	0.049
HD 83443	K0 V	1.4	35^{k}	2.986	$0.38 M_J$	0.039
κ^1 Cet......................	G5 V	4.64 ± 0.11	9.3^{o}	. . .	. . .	. . .
τ Cet.........................	G8 V	1^{p}	33	. . .	. . .	. . .
Sun	G2 V	1.73 ± 0.3^{q}	27	. . .	. . .	. . .

CFHT: 2001 Aug (3.5 nights), 2002 July (4 nights), 2002 Aug (2 nights)
2003 Sep (5 nights)

VLT: 2004 Apr (4x0.5 nights)

Planet Mass & CaII variation

Shkolnik, Walker, Bohlender, Gu, & Kurster 2005



night-to-night CaII variation

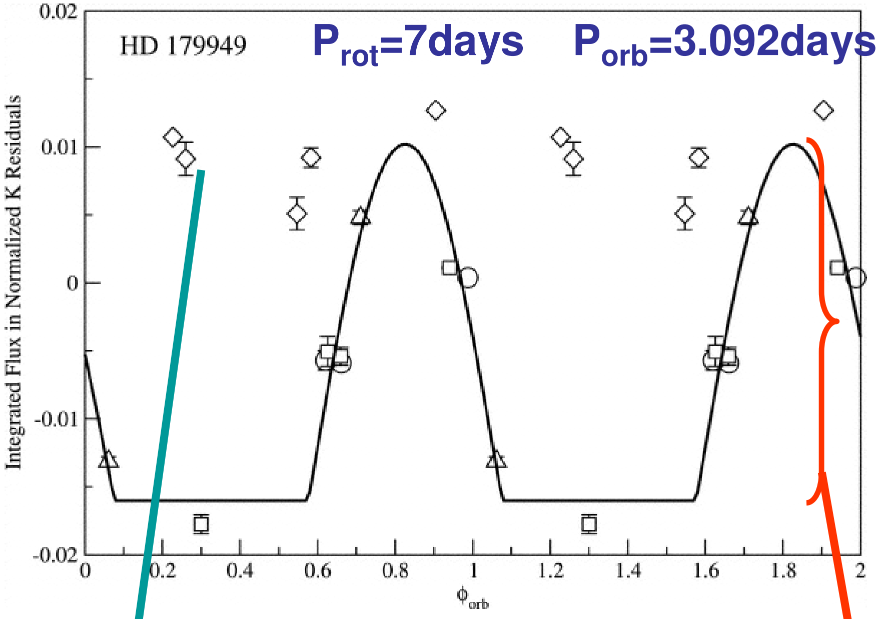
magnetic moment increases with planet mass in the Solar System (Arge et al. 95) → Magnetic interaciton?

τ Boo: close to double synchronous state

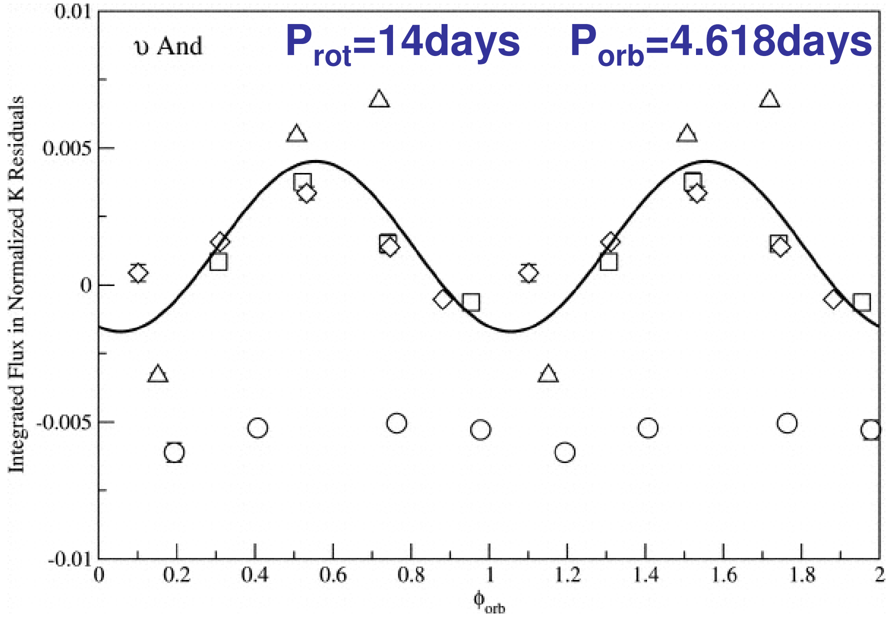
Synchronized Planet-induced Heating?

Shkolnik, Walker, Bohlender, Gu, & Kurster 2005

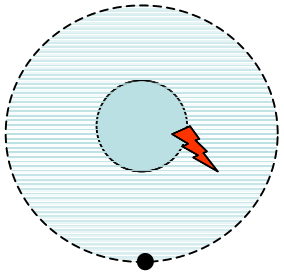
2001 Aug (circle), 2002 July (square), 2002 Aug (triangle), 2003 Sep (diamond)



P_{rot}=7days P_{orb}=3.092days

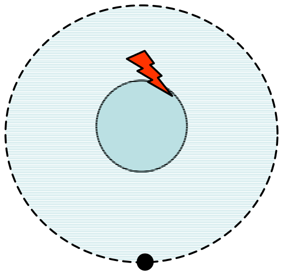


P_{rot}=14days P_{orb}=4.618days



due to
stellar
cycle?
more active
→ smaller corona hole
→ longer heating phase

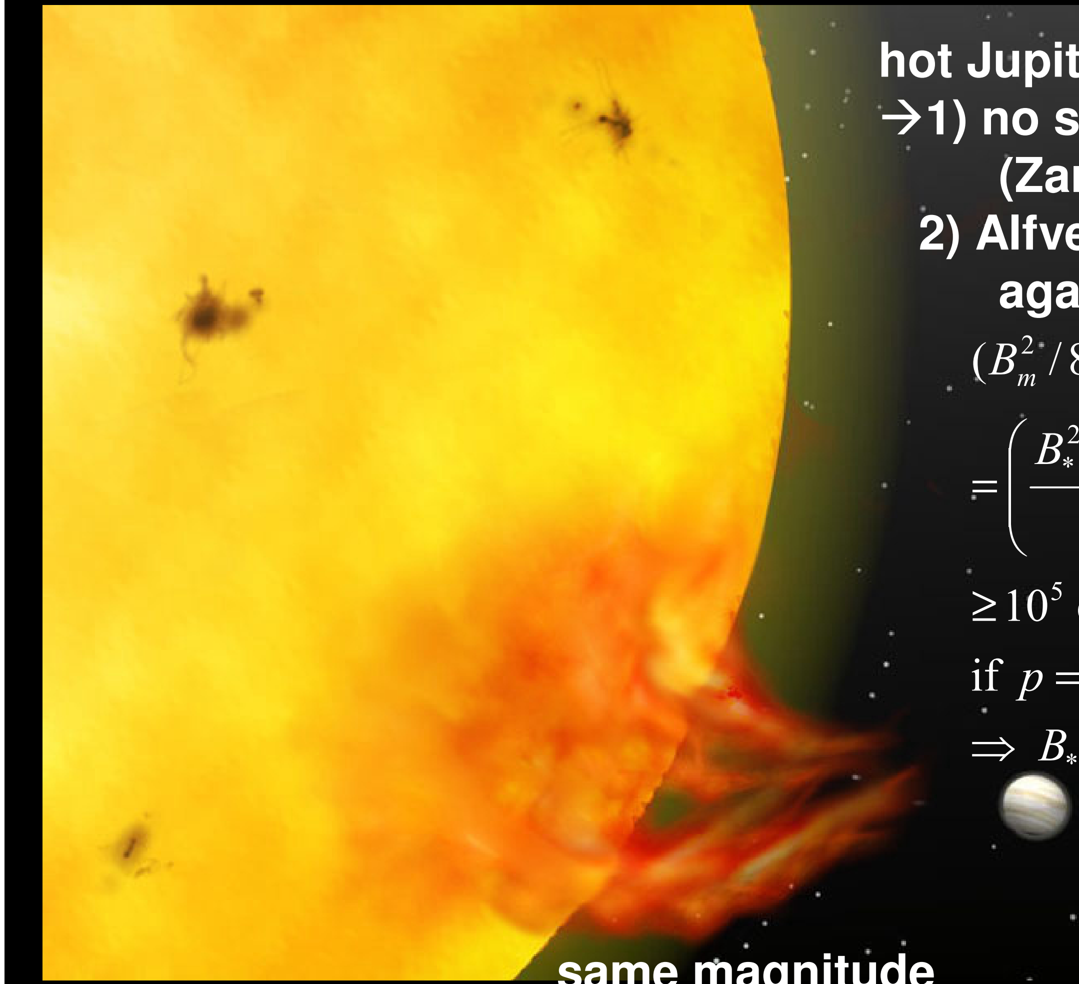
⚡ =
10^{27} erg/s
(1.5×10^{5} erg/cm^2 s)
comparable to a solar flare



winding field lines → phase difference

Planet-Induced Chromospheric (CaII H & K emission) Activity
(Shkolnik, Walker, Bohlender, Gu, & Kuerster 2005)

Shane Erno's conception of the flare



same magnitude of a typical solar flare

Magnetic Heating?

hot Jupiter inside the Alfven radius

→1) no shock caused by stellar winds
(Zarka et al. 2001, Ip et al. 2004)

2) Alfven wave packet travel inward against stellar winds

$$(B_m^2/8\pi)(V_{orb}-V_{\phi,wind})(r_m/R_*)^2$$

$$=\left(\frac{B_*^{2(1-1/q)}B_p^{2/q}}{8\pi}\right)a\left(\frac{2\pi}{P_{orb}}-\frac{2\pi}{P_{rot}}\right)\left(\frac{R_*}{a}\right)^{2p(1-1/q)}\left(\frac{R_p}{R_*}\right)^2$$

$$\geq 10^5\ \text{erg cm}^{-2}\ \text{s}^{-1}$$

if $p=2$ (open fields), $q=3$ (dipole fields)

$\Rightarrow B_* \approx 250\text{G},\ B_p \approx 10\text{G}$ for HD179979

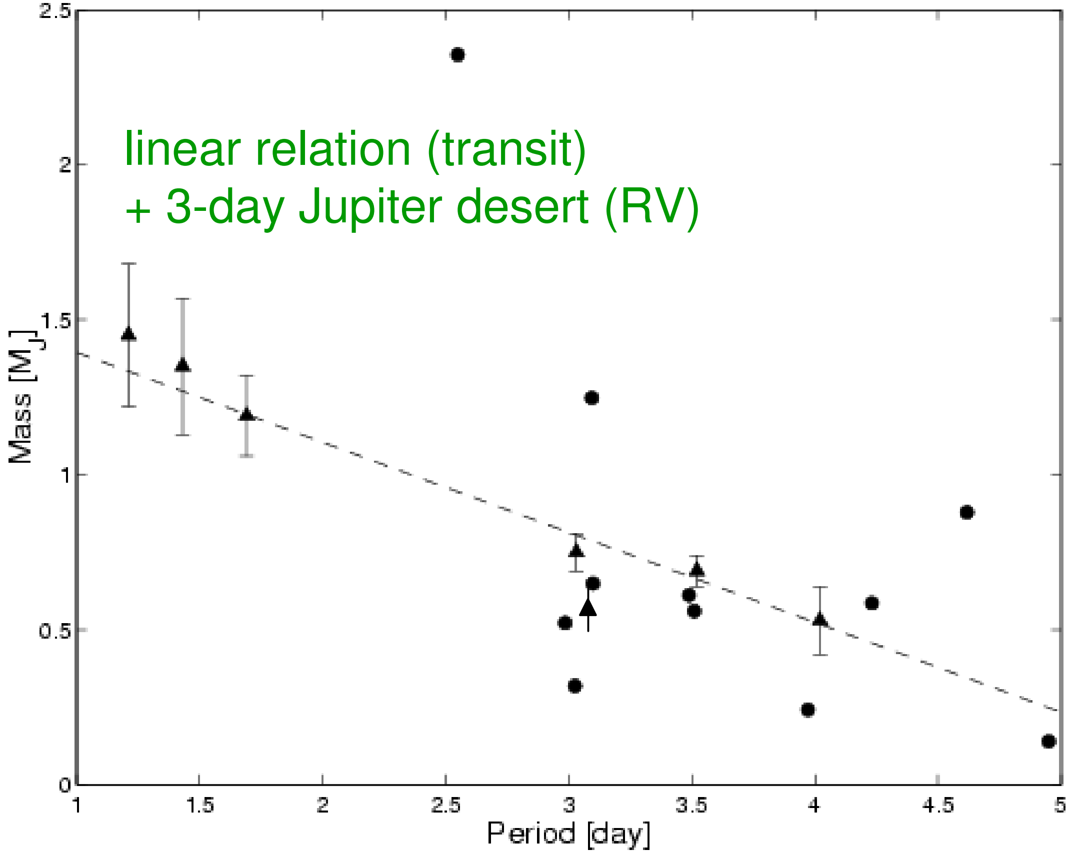
requires very large stellar fields + Alfven waves reflect back from the star →

Energy Budget Problem?

→Triggered Energy Release
(Gu, Li, Shkolnik, & Liu 2005)

Intriguing correlation for the transiting planets

Mazeh, Zucker, & Pont 2005



linear relation (transit)
+ 3-day Jupiter desert (RV)

Figure 2. The mass-period diagram of the short-period planets. The filled circles are the minimum masses multiplied by $4/\pi$.

evaporation instability

- if $M_p<M_{crit}$, $t_{evaporation}<t_{KH}$
- need reliable evaporation models;
- no correlation with L_*

Ω_* - *n* tidal interaction

- larger M_p → faster orbital decay
- but *vsini*<5 km/s for OGLE

$$P^{13/3}Q_* \propto -M_p t$$

If $Q_* \propto P^{-10/3}$ & same t.......

magnetic interaction

- larger Mp → stronger B?
- but *vsini*<5 km/s for OGLE
- Energy budget problem

Roche-lobe overflow

- overflow → reduce M_p & migrate outward

Summary

- **Gravitational Interaction:**
  tides in host stars: stellar models w/o considering the tidal effect seem to sufficiently explain Vsini/Prot → The tidal dissipation parameter *Q* in a solar-type star driven by a hot (very hot) Jupiter might be much larger than that driven by a stellar companion with longer orbital periods
  tides in a young Jupiter: tidal inflation instability → 1) a pile of hot Jupiters around 0.04-0.05 AU 2) mass-period relation for very hot Jupiters 3) formation of hot Neptunes 4) 90% of hot Jupiters might have perished (Ida & Lin 04)

- **Magnetic Interaction:**
  Observation: Call emissions from HD 179949 and υ And are synchronized with planet's orbital motion, but there are phase differences. The energy release is comparable to a typical solar flare.
  Possible scenario: Inward traveling Alfven waves along winding field lines trigger the magnetic energy already stored on the surface of the host star.