Dissipation in resonant systems: Implications of observed orbital configurations

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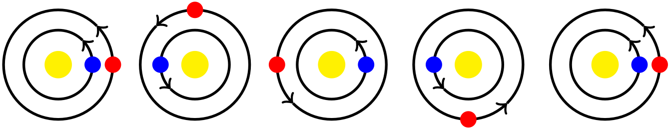
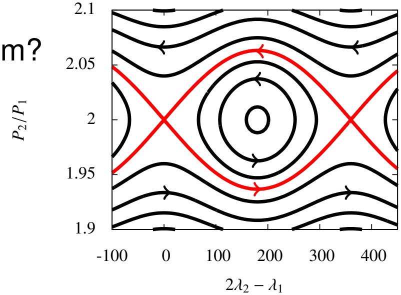
Resonant/near resonant systems

- What is a resonance between 2 planets?
  - $P_2/P_1 = p/q$ (p, q integers)
  - Example: 2/1



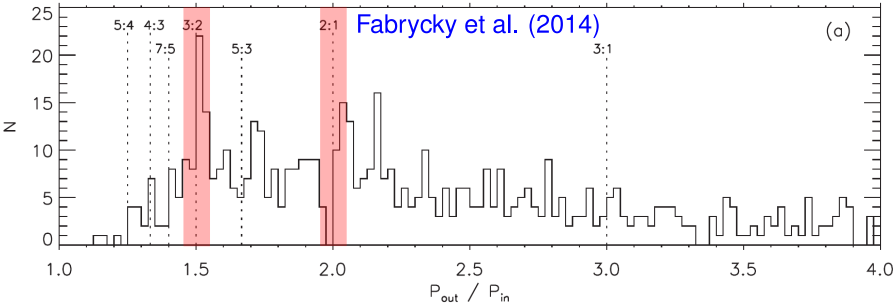
- Resonant or near resonant system?

Resonance width
depends on m_i, e_i



Kepler near-resonant planets

- Distribution of period ratio in Kepler data



- Peaks at resonances $\longrightarrow$ convergent migration ($P_2/P_1 \searrow$)
- Peaks slightly shifted to the right (Systems near but outside of resonances) $\longrightarrow$ tidal dissipation?

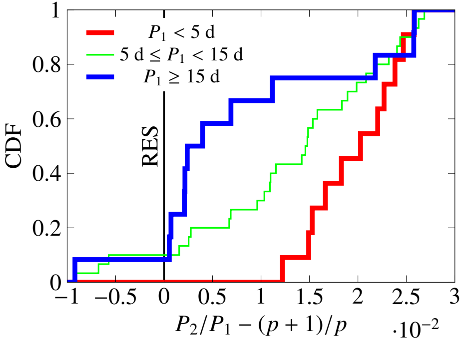
Lissauer et al. (2011), Fabrycky et al. (2014)

Kepler near-resonant planets

- Other possible explanations for the shift:
  - protoplanetary disk - planets interactions
    Rein (2012), Baruteau & Papaloizou (2013)
  - planetesimals - planets interactions
    Chatterjee & Ford (2015)
  - in-situ formation of planets
    Petrovitch, Malhotra, Tremaine (2013), Xie (2014)

Why tidal dissipation?

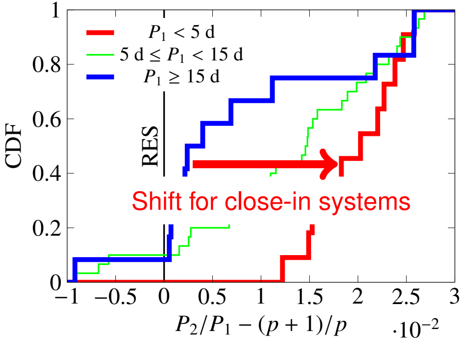
- Distribution of period ratio close to resonances (2:1 + 3:2)



Delisle, Laskar (2014)

Why tidal dissipation?

- Distribution of period ratio close to resonances (2:1 + 3:2)



Evidence for tidal dissipation

- KS-tests
  - Close-in vs Farthest: 0.08%
  - Close-in vs Intermediate: 3.5%
  - Intermediate vs Farthest: 10%

Delisle, Laskar (2014)

Analytical model of resonances

- First order resonances (2/1, 3/2, etc.)

  Integrable approximation is straightforward

  Sessin & Ferraz-Mello (1984), Henrard et al. (1986), Wisdom (1986), Batygin & Morbidelli (2013)

- Higher order resonances (3/1, 5/2, etc.)

  2 degrees of freedom (not integrable)

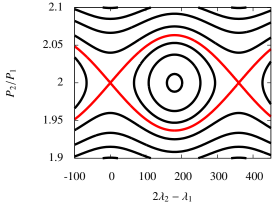
  - New simplifying assumption

  $e_1/e_2 \approx (e_1/e_2)_{forced}$ (ecc. ratio at resonance center)

→ Integrable pendulum-like approx.

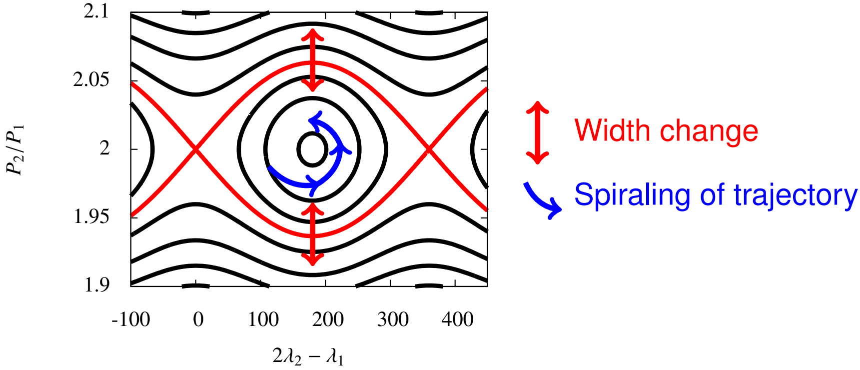
$$H = -(I - \delta)^2 + 2R\cos(q\theta)$$

Delisle, Laskar, Correia, Boué (2012)
Delisle, Laskar, Correia (2014)



Dissipative evolution in resonance

- Dissipation affects the resonant motion in 2 ways



- Relative amplitude: $A = \frac{\text{Amplitude}}{\text{Width}}$
  - if $A \searrow$ Locked in resonance, $P_2/P_1 \approx p/q$
  - if $A \nearrow$ Escape from resonance, P_2/P_1 no more locked

Migration in protoplanetary disk

- $A \nearrow$ (unstable res.) $\Longleftrightarrow \frac{T_{e,1}}{T_{e,2}} < \left(\frac{e_1}{e_2}\right)^2_{forced}$

  ecc. damping timescales
  (by disk-planet interactions)

  $\longrightarrow$ Escape with $P_2/P_1 \searrow$ (convergent migration)

- Observed resonant systems

  $\longrightarrow$ constraints on disk properties
  (ex: surface density profile)

Delisle, Correia, Laskar (2015), accepted to A&A

Tidal dissipation

$$\tau = \frac{T_1}{T_2} \qquad \tau_c \approx L\left(\frac{e_1}{e_2}\right)^2 \frac{4+|k_2|(1+L)}{4L-|k_1|(1+L)} \qquad \tau_\alpha = \left(\frac{e_1}{e_2}\right)^2$$

$$L \approx \frac{m_1}{m_2}\left|\frac{k_1}{k_2}\right|^{1/3}$$

- $\tau < \tau_c$: Amplitude ↗ ⟶ separatrix crossing possible
  - $\tau < \tau_\alpha$: Diverging $P_2/P_1 > k_2/k_1$ EXT
  - $\tau > \tau_\alpha$: Converging $P_2/P_1 < k_2/k_1$ INT
- $\tau > \tau_c$: Amplitude ↘ ⟶ evolution close to libration center
  - $q = 1$: Diverging $P_2/P_1 > k_2/k_1$ EXT
  - $q > 1$: Staying in resonance $P_2/P_1 \approx k_2/k_1$ RES

Delisle, Laskar, Correia (2014)

Who's who? Constraints on planets nature

ex: GJ 163

Parameter	[unity]	b	c	d
$m \sin i$	$[M_\oplus]$	**10.661**	**7.263**	22.072
P	[days]	**8.633**	**25.645**	600.895
a	[AU]	**0.06069**	**0.12540**	1.02689
e		**0.0106**	**0.0094**	0.3990

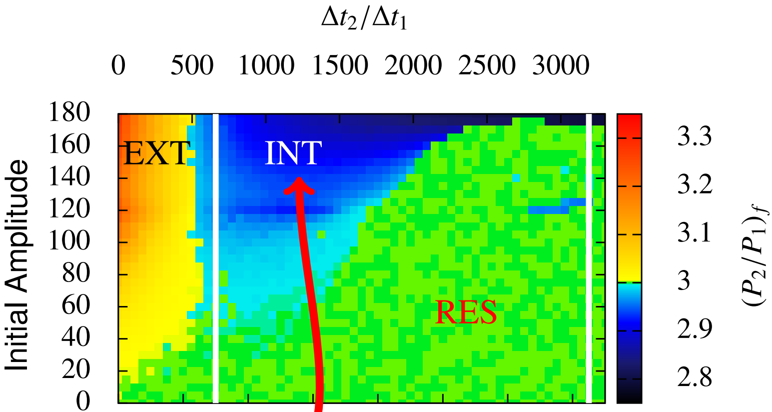
- Planets b, c close to 3:1 MMR (order 2)

  $\frac{P_2}{P_1} = 2.97 < 3$ Internal circulation (converging)

$$\tau_\alpha < \tau < \tau_c$$

Delisle, Laskar, Correia (2014)

Who's who? Constraints on planets nature



GJ 163b, c are here

GJ 163b: gaz

GJ 163c: rock

Delisle, Laskar, Correia (2014)

Conclusion

- Classification of outcome of dissipative process in resonance
- Constraints on systems properties from period ratio
  - Disk properties (disk-planet interactions)
  - Planets nature (tidal dissipation efficiency)
- Analytical model
  - Better understanding of these complex process
  - First approximation of constraints
  - Need numerical simulations for precise constraints