Short-period planetary systems and their mysteries

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Some open questions: gas giants

- How do hot jupiters arrive at their orbits?

- Are systems multiple systems containing hot jupiters rare (e.g., Upsilon Andromeda)?
  - was their formation mechanism different to 51 Peg’s?

- What is the main bloating mechanism for hot jupiters?

- What causes spin-orbit misalignment of hot jupiters?
  - can we distinguish between mechanisms?

- How are tidal disturbances dissipated inside stars and planets?

- Are resonant pairs of gas giants more common than resonant low-mass pairs?

- Why do orbits of gas giants tend to be more eccentric than those of low-mass planets?

- What does this tell us about the formation process?
Some open questions: low-mass planets

* How do ultra-short period low-mass planets arrive at their orbits?
* Is the formation mechanism of low-mass planets different to that of gas giants?
* Why are most low-mass planet pairs not in resonance?
* Are low-mass planets formed in situ?
* Is there a way to break the mass-radius-composition degeneracy
  * Can PLATO help to do this?
How to break the mass-radius degeneracy

The key is the link between
the physics of tides
and
the dynamics of multi-planet systems
and ...
How to break the mass-radius degeneracy

PLATO
The physics of stellar & planetary tides

Variations in the orbital elements and spins caused by

1. Non-spherical distributions of matter

2. Dissipation due to friction between fluid elements
The physics of stellar & planetary tides

1. Non-spherical distributions of matter cause:
   • Rotation of orbit in the orbital plane (apsidal motion)
   • Rotation of spin and orbit normals around $\mathbf{J}_{\text{tot}}$ (precession)
The physics of stellar & planetary tides

2. Dissipation inside bodies causes:

- Orbit to shrink or expand
- Spins rates to decrease or increase
- Spins to align with orbit normal
- Eccentricity to decrease or increase
Stellar & planetary tides: the minimum energy state

1. spin-orbit alignment

\[ \Omega_* < n \]

2. spin-orbit synchronization

\[ \Omega_* = n \]

3. orbital circularization
Spin-orbit coupling: the Darwin instability

2. spin-orbit synchronization

It is not possible to achieve the state $\Omega_* = n$ when $J_{\text{spins}} > \frac{1}{3} J_{\text{orb}}$

Hut 1980
Spin-orbit coupling: spin-orbit synchronization

It is not possible to achieve the state \( \Omega_* = n \) when \( J_{spins} > \frac{1}{3} J_{orb} \)

Hut 1980

Damiani & Lanza 2014
Key aspects of tidal physics: 1. apsidal motion

Tidally distorted distributions of matter cause apsidal motion.

The rate of apsidal advance depends on the Love numbers of the bodies AND general relativistic potential of star

Love number of fluid body (=2 x apsidal motion contant)

-- depends on density profile of body including whether or not it has a core
Key aspects of tidal physics: 1. apsidal motion

Tidally distorted distributions of matter cause apsidal motion.

The rate of apsidal advance depends on the Love numbers of the bodies AND general relativistic potential of star.

Love number of solid body

-- depends on RIGIDITY of body - its resistance to being tidally distorted

-- Rigidity depends on composition of body  (Goldreich & Soter 1966)
Key aspects of tidal physics: 2. Circularization

The minimum energy state of an isolated two-body system is a circular orbit.

The minimum energy state of a short-period planet being forced by a companion is an *eccentric orbit* with apsidal lines of orbits aligned.
Key aspects of tidal physics: 2. Circularization

Measuring this non-zero eccentricity is the key to breaking the mass-radius-composition degeneracy

Accurate measurements of eccentricity are difficult

PLATO will allow us to do this
Dynamics of coplanar two-planet systems

Secular evolution, no tides
Secular evolution with tides:
The system relaxes to a non-circular state

``Equilibrium eccentricity``

Mardling 2007
Equilibrium eccentricity

Solve \[
\frac{de_b}{dt} = 0, \quad \frac{d\varpi_b}{dt} = \frac{d\varpi_c}{dt}
\]

to get \[
e_{eq} = \frac{(5/4)(a_b/a_c)e_c}{1 - \sqrt{a_b/a_c\left(m_b/m_c\right)} + \gamma}
\]

\(\gamma\) contains information about internal structure of planet:
measuring \(e_{eq}\) gives Love number of planet

Batygin et al 2009
Mardling 2010
We can measure all parameters and deduce $\gamma$

$$e_{eq} = \frac{(5/4)(a_b/a_c)e_c}{1 - \sqrt{a_b/a_c} (m_b/m_c) + \gamma}$$

$e_{eq}$: transit and secondary eclipse, RV

semimajor axes (periods): transits and RV

planet masses: RV, Gaia, TTVs

$e_c$: RV (and maybe transits)

mutual inclination: Gaia, RV (transits)

Note: $e_{eq}$ depends on ratio of planet masses and does not depend on the mass of the star or the dissipation rate (Q-values of star and planet)
what is $\gamma$?

$$e_{eq} = \frac{(5/4)(a_b/a_c)e_c}{1 - \sqrt{a_b/a_c (m_b/m_c)} + \gamma}$$

$$\gamma = \gamma_*^{GR} + \gamma_b^{tide} + \gamma_b^{spin} + \gamma_*^{tide} + \gamma_*^{spin}$$

$\gamma$ is the ratio of the rate of apsidal advance due to, eg., tidal bulge, to rate of apsidal advance due to second planet

$$\dot{\omega}_{GR} = 3 \left( \frac{v_{orb}}{c} \right)^2 n_b$$

eg: $v_{orb}/c = 0.001$ for 3 day solar orbit
Example: HAT-P-13

\[ e_{eq} = \frac{(5/4)(a_b/a_c)e_c}{1 - \sqrt{a_b/a_c} (m_b/m_c) + \gamma} \]

\[ \gamma = \gamma^G_R + \gamma^tide + \gamma^{\text{spin}}_b + \gamma^{\text{spin}}_* + \gamma^tide_* \]

\[ \gamma_{\text{HP13}} = 1.9 + 4.6 + 0.3 + 0.04 + 0.05 \]

\[ = 7.0 \]

\[ m_c = 15 \, M_J \]

\[ e_b = 0.02 \]

\[ m_b = 0.9 \, M_J \]

\[ e_c = 0.7 \]

\[ a_c/a_b = 30 \]
small denominator = large $e_{eq}$

$$e_{eq} = \frac{(5/4)(a_b/a_c)e_c}{1 - \sqrt{a_b/a_c} (m_b/m_c) + \gamma}$$

good to have $m_c < m_b$

large $e_c$

not too big $a_c/a_c$
Suitable systems may be rare...

But PLATO will find them around bright stars if they exist

Breaking the mass-radius-composition degeneracy may be possible with PLATO!