Problem I: Hot Jupiters lack close companions

Kepler-detected single-, double- and triple-transit systems from the Q1-Q16 data, with known false positives removed and cuts on period and SNR applied as in Lissauer et al. (2011). Super-Earth planets are very common, yet almost never are they seen in systems with hot Jupiters. Systems marked in blue. Kepler-18, -23, -38 and -339, are studied below…

Solution: Other planets destroyed by high-eccentricity migration of the hot Jupiter

Giant planets may migrate when their orbital eccentricity is excited to near-unitary values. Tidal dissipation at periapsis leads to shrinkage and circularisation of the orbit, forming a hot Jupiter. The initial eccentricity excitation may be caused by other planets or a binary companion.

If the inner system already contains other planets, we may expect violent interactions.

Two examples: an eccentric giant planet is thrown from $a = 10$ au at the Kepler-18 system. In panel A the inner system is destroyed, the planets colliding with the star or the giant planet. In panel B the three inner planets merge and the giant is ejected.

Integrations are performed with the MERCURY package.

By varying the inner system and the initial giant’s periapsis $q$ and semimajor axis $a$ we can see the occurrence rate of different outcomes. After 1 Myr of integration time, most systems have ejected the giant (red-orange), possibly with a reduction in the number of inner planets; or they have lost all the inner planets (blue), possibly being accreted by the giant. Coexistence of the giant and the inner planets after 1 Myr is possible, but not when the giant has the very small periapses required for tidal circularisation ($q < 0.03$ au).

After the scattering interactions are complete we evolve the surviving giant planets’ orbits under tidal forces. Many of the giants retain a sufficiently small periapsis that permits tidal circularisation and hot Jupiter formation. A number have their $a$ and $e$ lowered to below the tidal circularisation track, forming a population of eccentric warm Jupiters in a region hard to populate by in situ scattering.


Problem II: There are “too many” single planets

Single-transit systems are far more prevalent than multi-transit systems in the Kepler data. Johansen, Davies, Church & Holmelin (2012) showed that this excess cannot be explained by:

- seeing large numbers of multi-transit systems as single-transit systems owing to unfavourable viewing geometry (high mutual inclinations)
- instabilities in close-in triples

Solution I: Inner systems are destabilised by outer systems

In the previous study, we found that systems that eject the giant planet can be reduced in multiplicity. We now try treating the dynamics of the outer system consistently: planet–planet scattering, Kozai cycles and explore a range of giant planet masses. In the top panels 2 Jovian and 2 Neptune–mass planets exterior to the Kepler-18 system undergo scattering. In the bottom panels, a Jovian planet undergoes Kozai cycles forced by a binary companion.

Varying the outer system configuration suggested that a binary companion forcing Kozai cycles would be the most efficient way to generate single planets from the triples, and we explored this scenario in more detail. With randomly-generated populations of inner triple systems, giant planets and binary companions (initial conditions shown), the latter isotropically distributed in inclination, we find only 1 in 4 of the inner systems are destabilised by perturbations of the giant planets. Hence we turn to another source of instability…

Solution II: High-multiplicity inner systems are self-unstable

Recently, Pu & Wu (2015) and Volk & Gladman (2015) showed that Kepler quintuple systems are much closer to the boundary of instability than the triples. We therefore explore the multiplicities arising from unstable tightly-packed quintuple systems. Unstable quintuples reduce to doubles or triples under the regular MERCURY assumption of perfect merging in collisions. However, as Volk & Gladman point out, impact velocities at fractions of an au can significantly exceed the escape velocity, and collisions will often be erosive. A crude “grinding” model where each collision removes half a planet’s mass is efficient at producing single detectable planets, while grinding others down below the threshold of detectability (above). This proof-of-concept motivates a more realistic collision algorithm based on Leinhardt & Stewart (2012), which we are currently implementing into MERCURY (right).