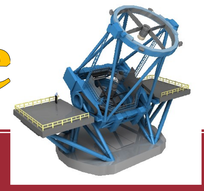
The New Norm in Exoplanets: Explaining the Impossible



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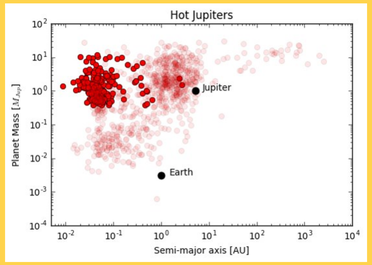
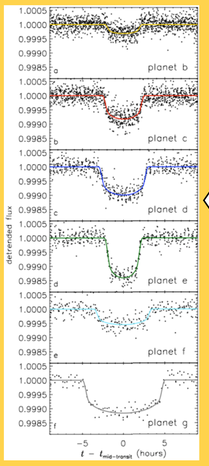
Hot Jupiters

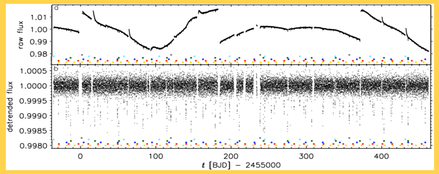
Most of the discovered planets by transit and RV techniques are hot-Jupiters (mass ~1 M_{Jup}, $a \leq 1$ AU). A gas giant with a 4-day orbit like 51 Peg b cannot be explained with in-situ planet formation as there is insufficient mass at such small radii and the temperature is too high to allow the formation of rocky or icy planetesimals .





Example: Kepler-11 compact system

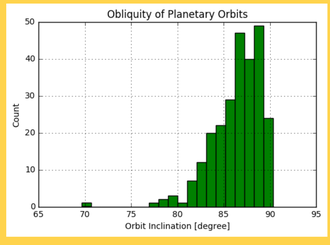
Six individual lightcurves extracted from the raw lightcurve below show 6 planets: Kepler-11 bcdefg (Lissauer et al. 2011)



A simple sketch of Kepler-11 architecture shows 6 close-in planets within the orbit of Venus, 5 of which are closer to the star than Mercury's orbital radius.

Properties of Hot Jupiters

- There is an excess of objects that have orbital p < 10 d and masses similar to that of Jupiter
- The objects rarely have companion planets on nearby orbits
- Nearly 1/3 of hot Jupiters have orbital paths that are inclined with respect to their star's equator, and several planets in the population rotate in the opposite direction to the star.

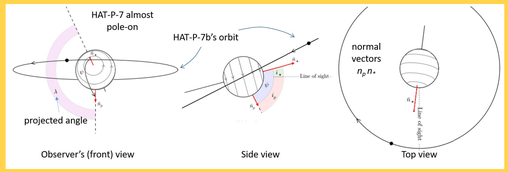


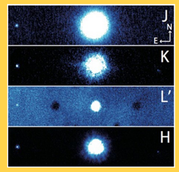
Origin of Hot Jupiters

1. In-situ formation at the distances at which they're currently observed
   - PRO: explains the frequency of observed additional low-mass planets with short periods
   - CON: not enough material orbiting close to the star to allow for in situ assembly of massive cores
2. Formation at a distance + inward migration
   - PRO: explains also the existence and properties of the Solar System's outermost regions
   - CON:

Planets in Retrograde Motion

HAT-P-7b (aka Kepler-2b) orbits its star in the opposite direction of the star's spin. Spin-orbit misalignment was determined from transit observation and asteroseismology.



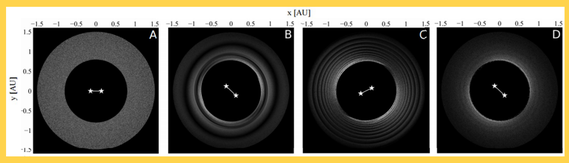


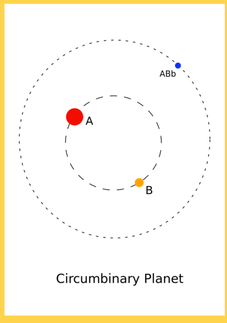
Sketch of HAT-P-7b's and its host star's 3D orbital parameters showing spin-orbit misalignment. A second star has been detected shown left in the near-IR image captured by the 8-m Subaru telescope.

A companion star (HAT-P-7B) could have pulled the inferred giant outer planet, HAT-P-7c, into a tilted orbit until its path started affecting the inner planet, HAT-P-7b, producing the latter's retrograde orbit.

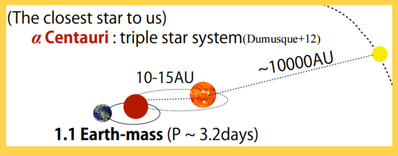
Quasi-stable Planets in Multiple-star Systems

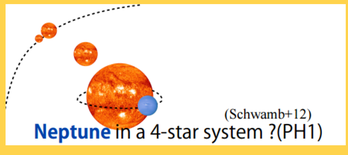
Most known planets in multi-star systems is thought impossible to form in-situ due to very strong gravity from the binary potentially disrupting the primordial protoplanetary disk, making planet formation difficult.



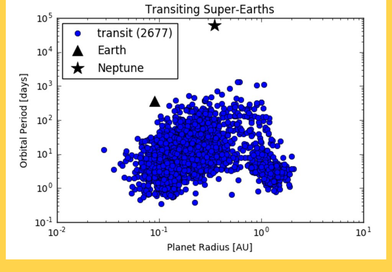


N-body numerical simulation showing the disruption of a circumbinary disk which still allowed the circumbinary planet Kepler-34(AB)b to form albeit experiencing super-catastrophic events and migration from their formation location.





16 Cygni Bb or HD 186427 b is the first eccentric Jupiter and planet in a triple star system to be discovered. Prox. Cen b in α-Cen triple star system has recently been discovered. A Neptune-sized planet is also reported to exist in a 4-star system.



Super-Earths Bonanza

Kepler found that the most common type of planet in the galaxy is something between the size of Earth and Neptune—a "super-Earth," which has no parallel in our solar system and was thought to be almost impossible to make.

Kepler's surprising finding that 60% of sun-like stars are orbited by a super-Earth .

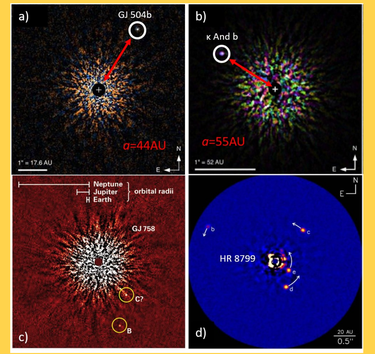
The circumstellar disks around low-mass stars can accommodate the formation of super-Earths both as a:

- failed core of a giant planet through the gas giant planet formation process, and as a
- small terrestrial-class objects through direct collisional growth of protoplanetary bodies and planetary embryos

Super-Earths are formed through a combination of a core accumulation process and planetary migration (Haghighipour 2013)

Wide-orbit Planets

Direct Imaging have found giant planets several times the mass of Jupiter, orbiting their star at more than twice the distance Neptune is from the sun—another region where theorists thought it was impossible to grow large planets.



Formation mechanisms

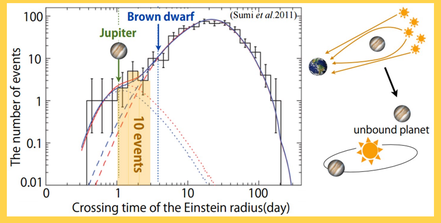
a) core accretion + planet-planet scattering

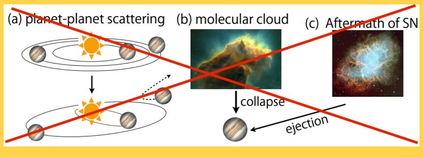
b) direct collapse of molecular cloud

Most directly imaged sub-stellar companions are brown dwarfs like GJ 504 b (Kuzuhara+13), K And b (Carson+13) and GJ 758 b (Thalmann+13). HR8799 (Marois+08) is the only multi-planetary system directly imaged hosting planets and brown dwarfs in wide (a >50 AU) orbits.

Free-floating planets

The fraction of free-floating planets discovered by microlensing technique = 1.8 times as many as Main Sequence stars in our galaxy (Sumi et al. 2011). There are several explanations how such a planet can form directly or end up free-floating.





Formation mechanisms:

a. in-situ formation?

b. Planet-planet scattering?

c. ejection from stellar flyby?

d. ejection after supernova?

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