Hot Jupiters in Odd Places: How Did They Get There?

Jerome de Leon, The University of Tokyo jpdeleon@astron.s.u-tokyo.ac.jp

What is a Hot Jupiter?

- Hot Jupiters are massive planets that orbit close to their parent stars
  - 0.36 M_{Juo} < mass < 11.8 M_{Juo}
  - 0.015 AU < semi-major axis < 0.1 AU
- Many have been discovered to orbit very close to their central stars (e.g., Marcy & Butler 1998; Marcy et al. 1997; Borucki et al. 2011)

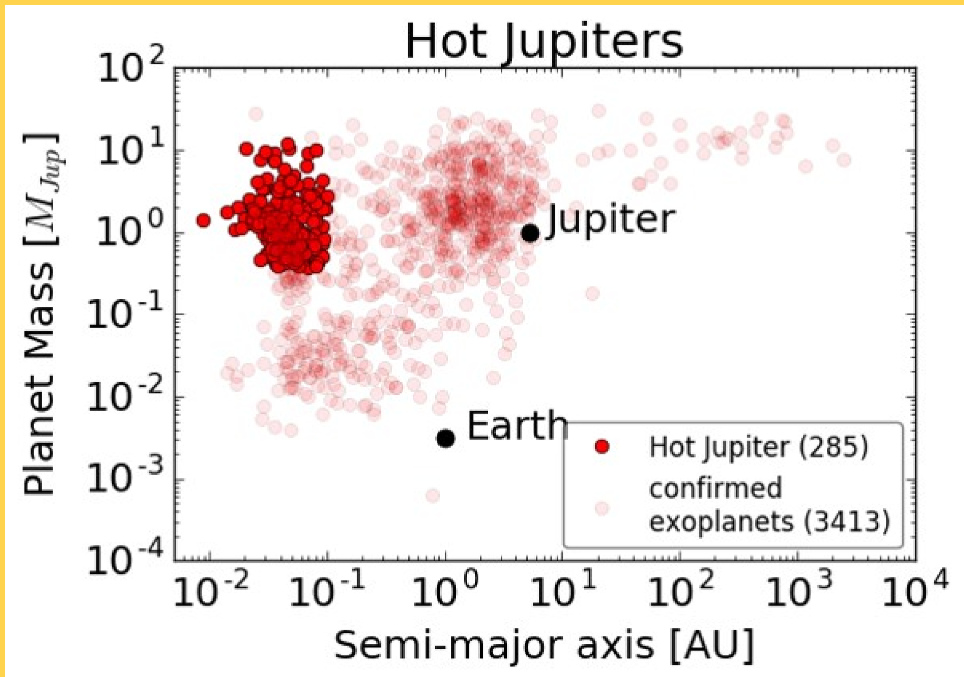


Fig. 1 Accounts for at least 10% of known exoplanets mostly discovered by transit and RV techniques.

Example: 51 Peg b

The first discovered exoplanet around a normal star, 51 Peg, hosts a gas giant with a 4-day period.

ARTICLES

A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

51 Peg b cannot be formed in-situ since there is insufficient mass at such small radii and the temperature is too high to allow the formation of rocky or icy planetesimals

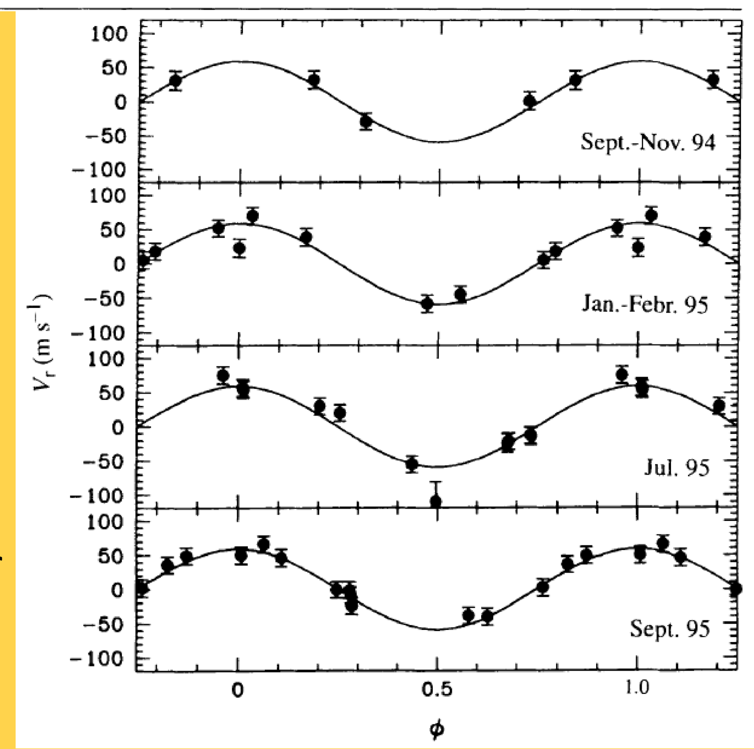
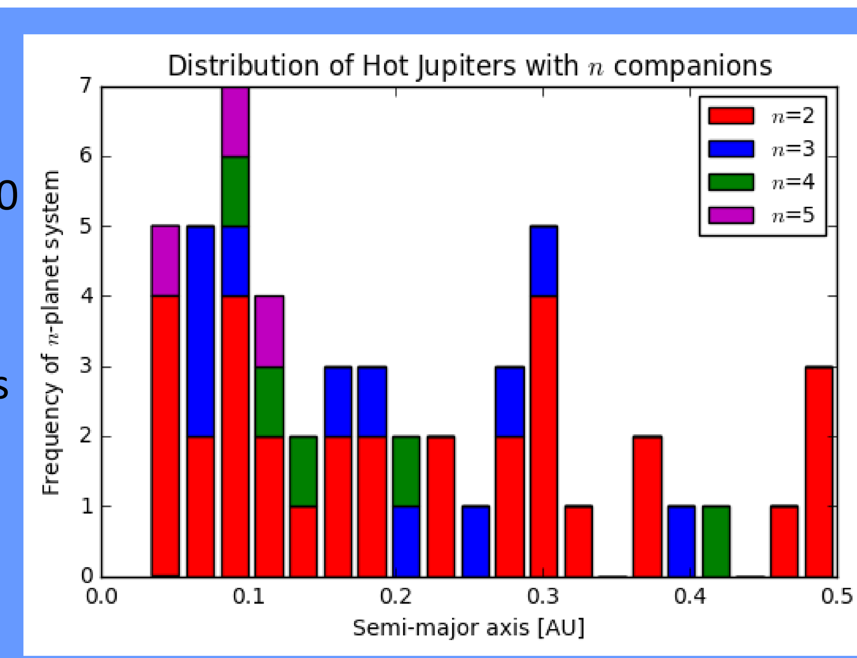
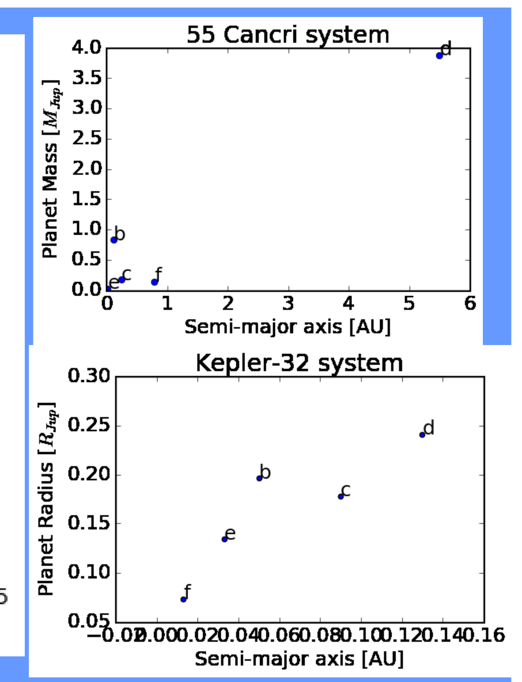


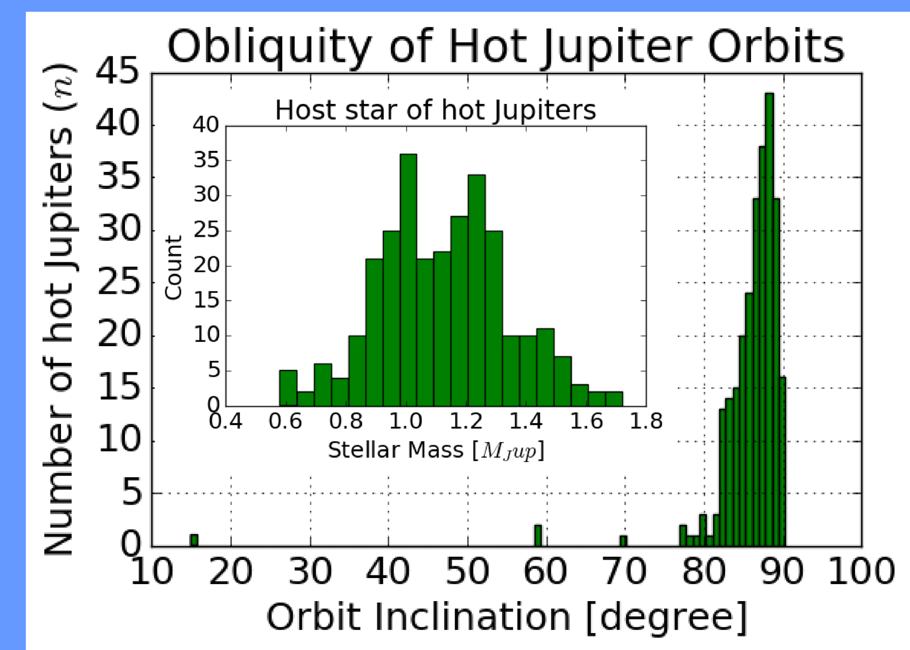
Fig. 2. Orbital motion of 51 Peg at 4 different epochs (Mayor & Queloz et al. 1995)

Known Properties of Hot Jupiters

- There is an excess of objects that have orbital period, P < 10 days and masses similar to that of Jupiter
- The objects rarely have companion planets on nearby orbits
  - Example: 55 Cancri (2 separated hot-Jupiters; 3 others)
  - Counter-example: Kepler-32 (2 nearby hot-Jupiters)
- Many 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
  - Example: HAT-P-7







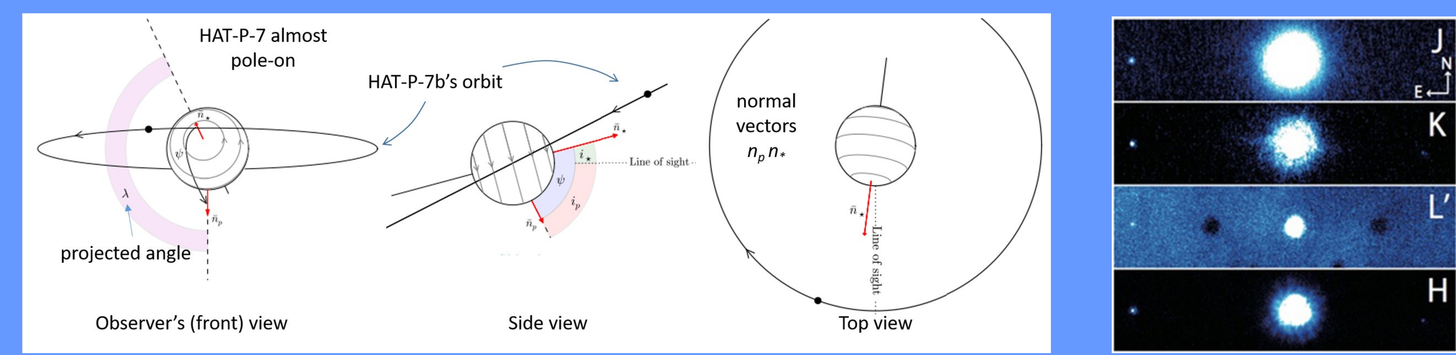


Fig. 3 Sketch of HAT-P-7b's and its host star's 3D orbital parameters showing spin-orbit misalignment. A second star has been detected shown left in the near-IR image captured by the 8-m Subaru telescope.

Origin of Hot Jupiters

- Hot Jupiters must form further out from their host stars, i.e., beyond the snow line, and either:
  - migrate embedded in a primordial disk or
  - migrate via dynamical interactions (e.g., Lin et al. 1996; Lubow & Ida 2010; Triaud et al. 2010)

Types of Dynamical Interactions

- planet-planet scattering (e.g., Wu & Murray 2003),
- Kozai mechanism (e.g., Kozai 1962),
  - 15% of hot Jupiters undergo migration via the Kozai mechanism, instead favoring planet-planet scattering (Dawson et al. (2013a,b)
- secular chaos (e.g., Nagasawa & Ida 2011; Wu & Lithwick 2011)

Fig. 4. Migrating gas giants gravitationally perturb smaller, rocky planets from their orbits sometimes ejecting them out of the system entirely.

Types of Planetary Migration

Type I: spiral density wave is formed

Type II: a gap is formed between the disk and a high mass planet

gap is the result of the tidal torques from the planet becoming stronger than the viscous torques of the disk

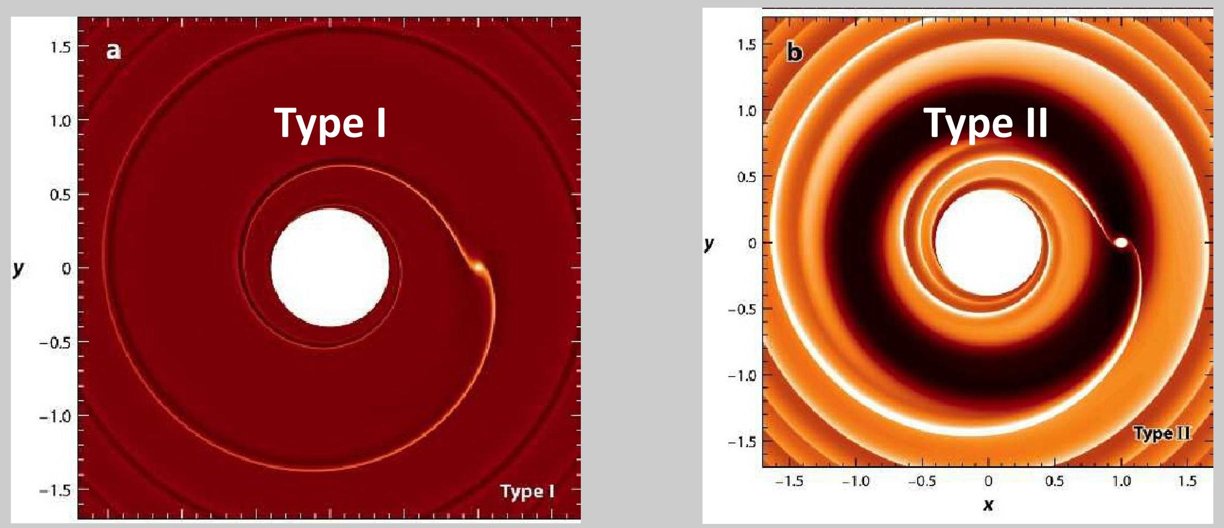


Fig. 5. Two types of migration (Haghighipour 2013)

Open Problem

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

Migration Stopping Mechanisms

Hot Jupiters stop migrating inward when they reach a barrier due to:

- the star's **magnetic field** → traps the planet in orbital resonance with the magnetospheric truncation radius (Eisner et al. 2005)
- a **gap** between the star and the inner edge of its dusty disk →traps the planet in orbital resonance with the dust sublimation radius (e.g., Kuchner & Lecar 2002)
- the parent star's **gravitational forces** →circularizes and stabilizes the planet's orbit (Ford & Rasio 2006; Wu et al. 2007; Guillochon et al. 2011; Arras et al. 2011; Matsumura et al. 2010; Lai 2011)

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