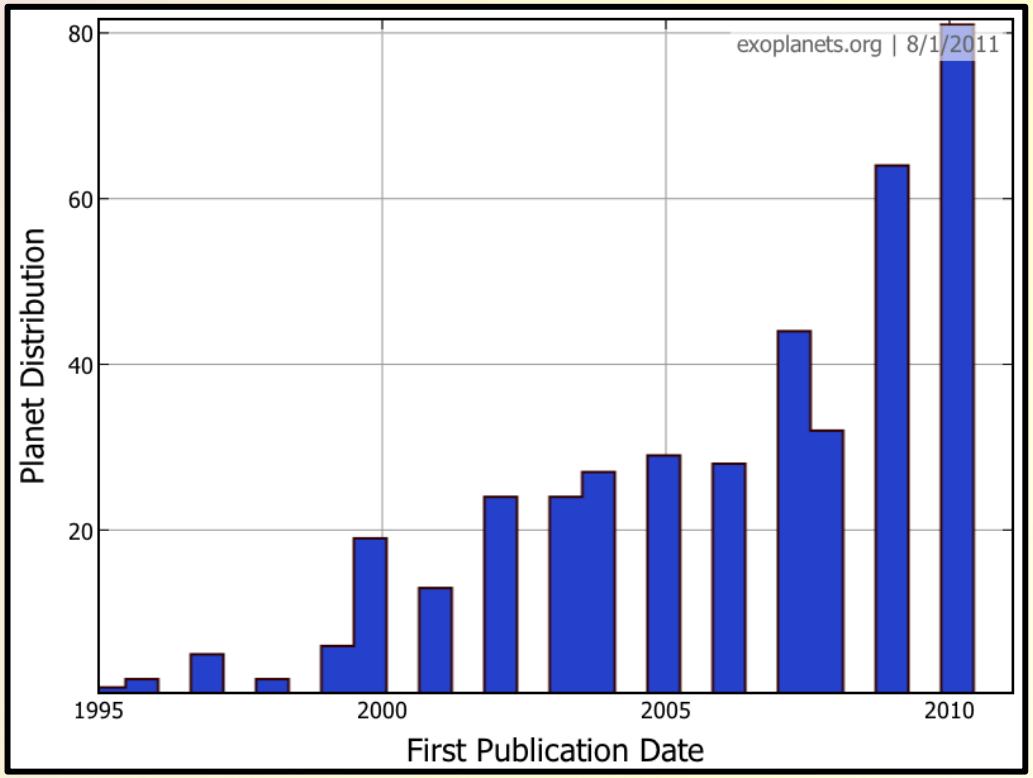
Extrasolar Planet Collisions and the Effects on the Structure of Hot Jupiters

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Advisor: Fred Adams

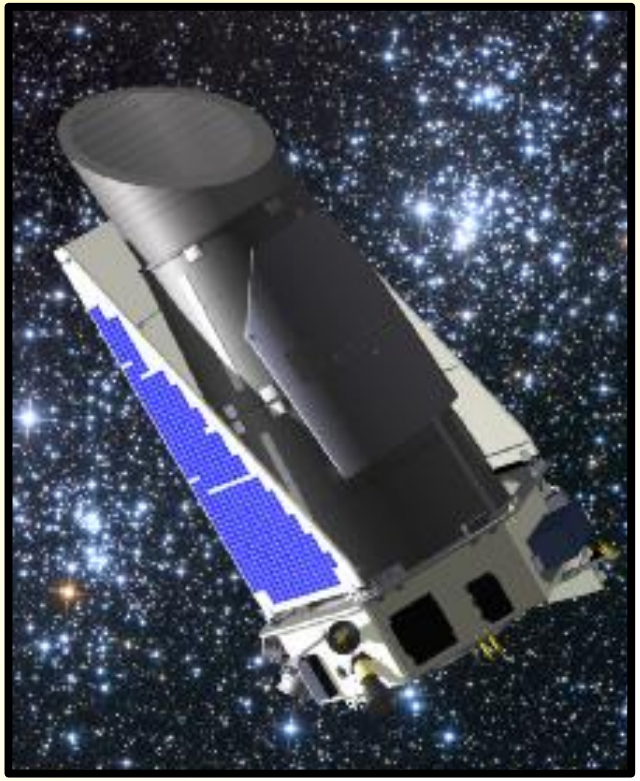
University of Michigan
2011 REU Symposium

Background: Planet Inventory

1995: first exoplanet discovered
2011: ~ **550** planets



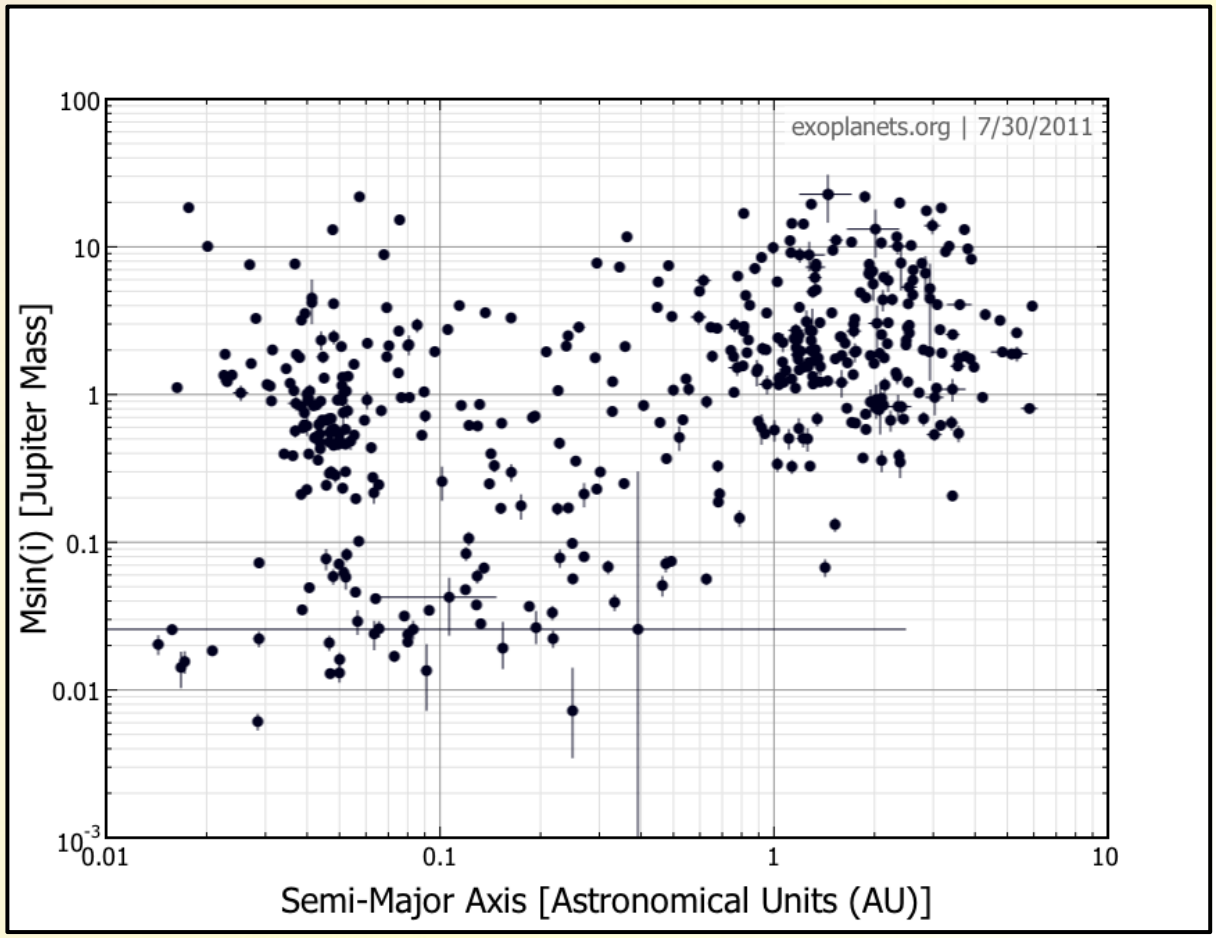
~1000 more planets
awaiting confirmation
(NASA Kepler satellite)



Source: NASA

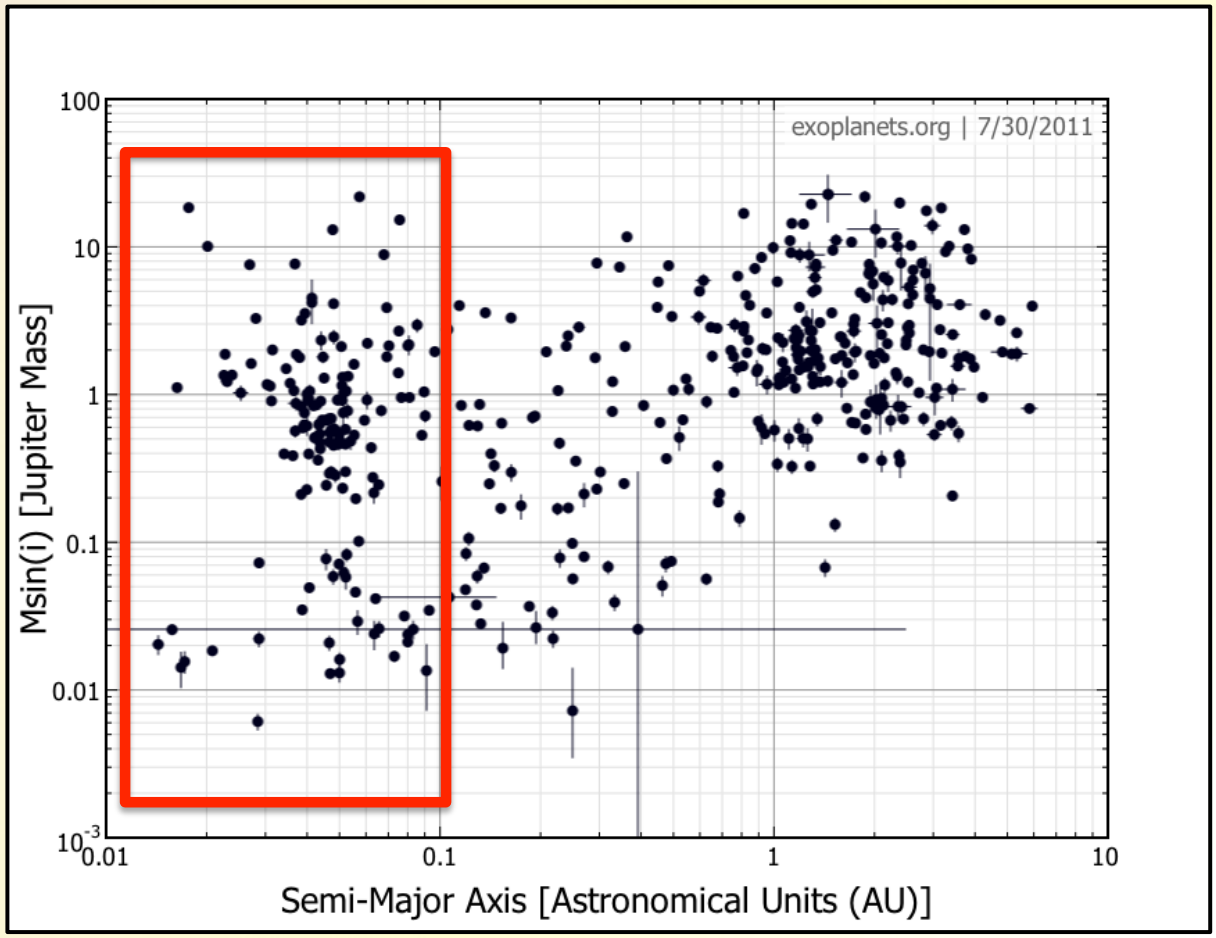
Background: Planet Inventory

Many planets with semi-major axis < 0.1 AU



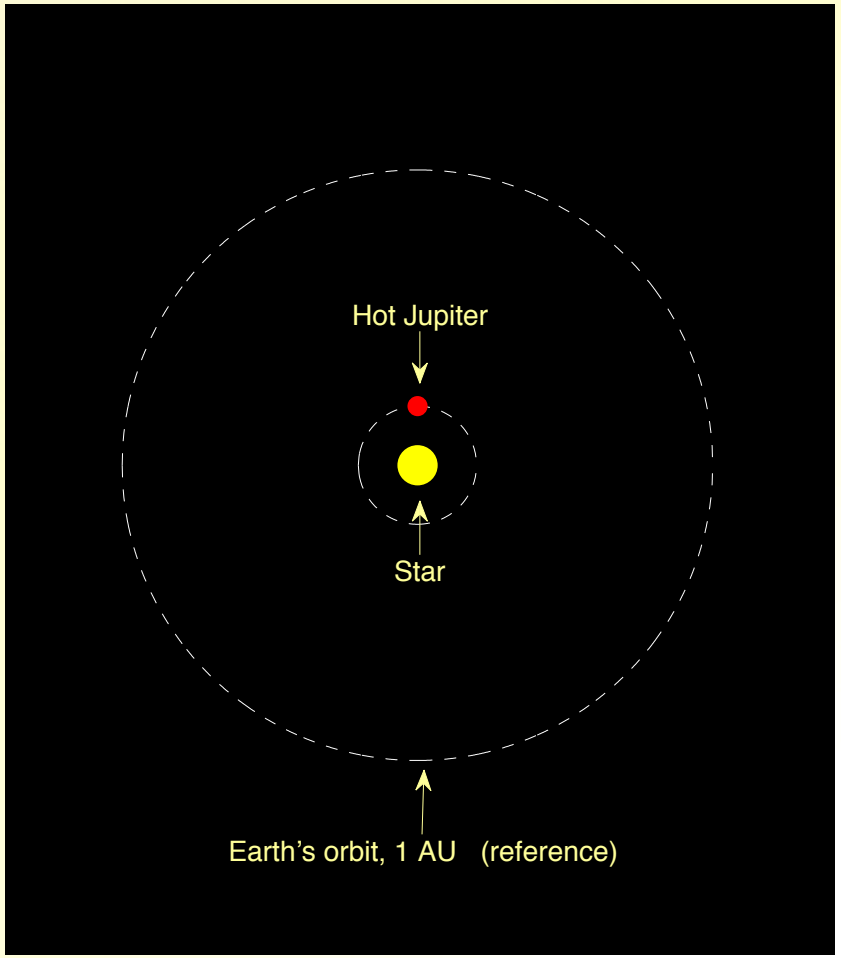
Background: Planet Inventory

Many planets with semi-major axis < 0.1 AU



Hot Jupiters

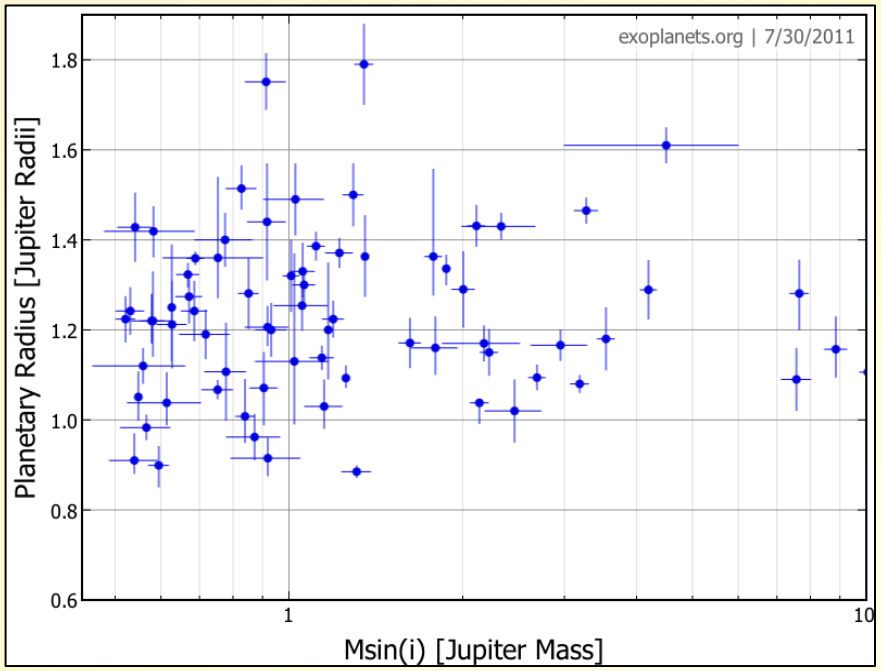
- Gas giants ~ 1 $M_{Jupiter}$
- Rocky core 10 – 100 M_{Earth}
- Period < 10 days
- First type of exoplanet discovered (easy to find)

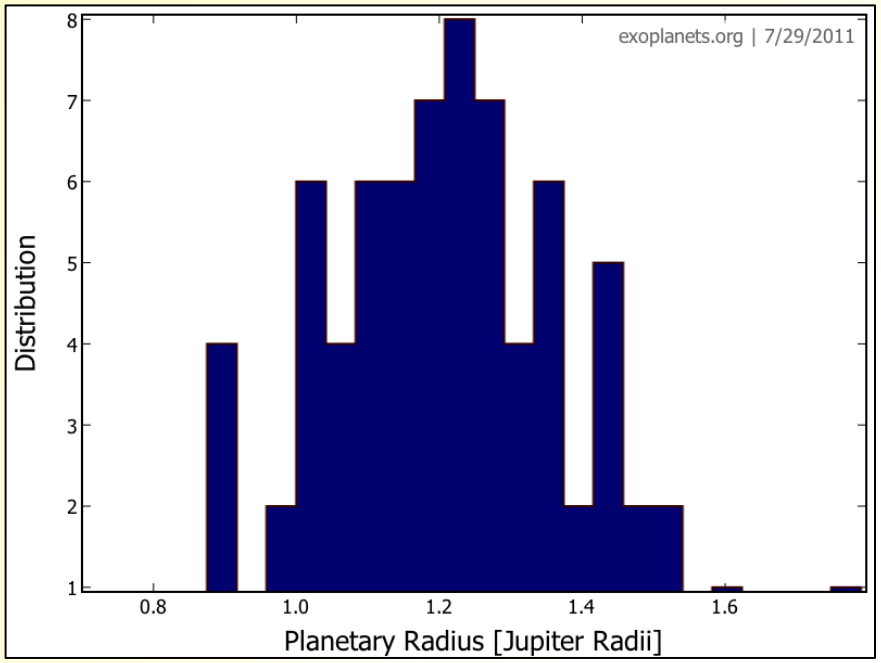


Observations vs. Theory

- Observed hot Jupiters exhibit a range of radii
- Many are **larger** than predicted, while some are **smaller**
- Large planets are explained **by unknown heat sources**
- Small planets attributed to **heavy cores**

$$\rho = 0.16 - 26 \ \ g/cm^3$$





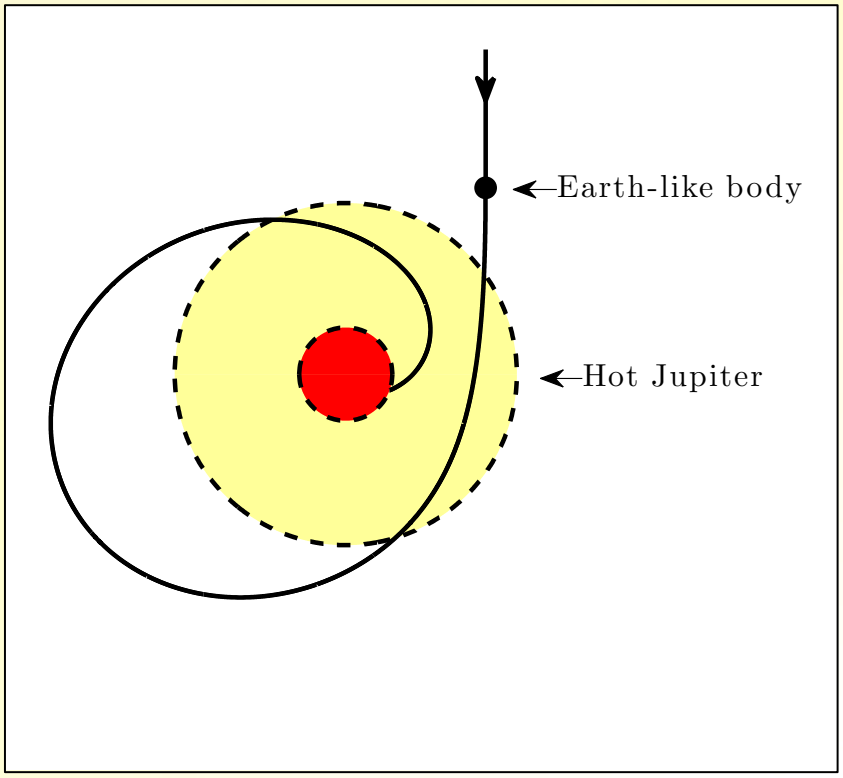
Possible Heat Sources

To explain the full distribution of anomalous radii, probably need a combination of heat sources

- Stellar radiation (high UV flux)
- Magnetic fields (ohmic heating)
- **Collisions with Earth-like planets?**

Collisions as heat sources

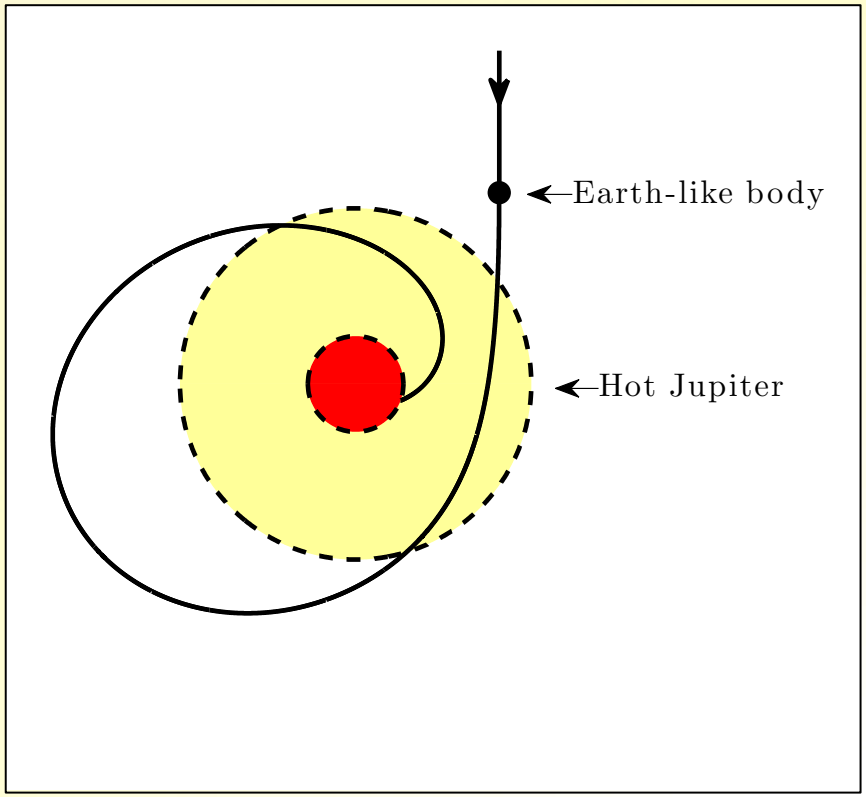
- Small rocky bodies can collide with Jovian planets and heat the atmospheres
- Energy deposited **deep** in the interior could provide a planet with a **long-term heat source**



Collisions as core accretion

- Heavy cores are inferred for the anomalously small Hot Jupiters

- Incoming deposits of rock could help explain **core accumulation**



hot Jupiter structure

Orbit calculations require a **density profile**

Assume the pressure and density follow a **polytropic** relation, $P = K\rho^{1+1/n}$

Equilibrium and continuity of mass

$$\rightarrow \frac{dP}{dr} = \frac{-Gm(r)\rho(r)}{r^2}$$

$$\frac{dm}{dr} = 4\pi r^2 \rho(r)$$

hot Jupiter structure

Define the dimensionless variables

$$\xi \equiv \frac{r}{R}, \quad f^n(\xi) \equiv \frac{\rho(r)}{\rho_c}, \quad \mu(\xi) \equiv \frac{m(r)}{4\pi R^3 \rho_c}, \quad R = \sqrt{\frac{\Gamma K}{(\Gamma - 1) 4\pi \rho_c^{2-\Gamma}}}$$

Substitute into the differential equations

$$\rightarrow \text{ Lane} - \text{Emden equation}$$

$$\frac{1}{\xi^2}\frac{df}{d\xi}\left(\xi^2 \frac{df}{d\xi}\right) + f^n = 0, \quad \frac{d\mu}{d\xi} = \xi^2 f^n$$

boundary conditions:

$$f(\xi_c) = 1, \quad \left.\frac{df}{d\xi}\right|_{\xi=\xi_c} = 0, \quad \mu(\xi_c) = \frac{1}{3}\xi_c^3$$

hot Jupiter structure

At the planet surface, $\rho = 0$

Dimensionless radius and mass:

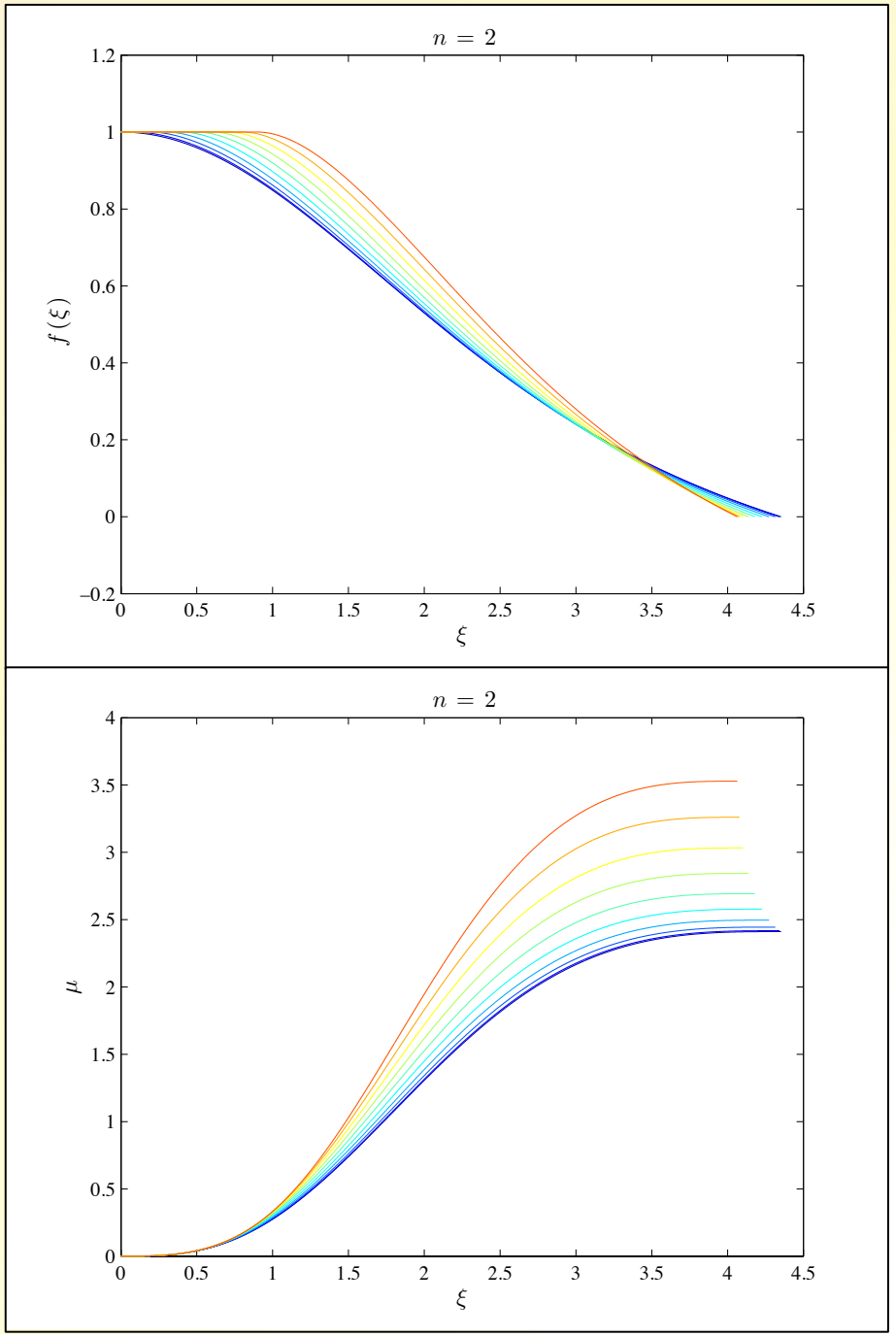
$$\xi_0,\ \mu_0$$

ξ_0 is the first zero of $f(\xi)$,

$$\mu_0 \equiv \mu(\xi_0)$$

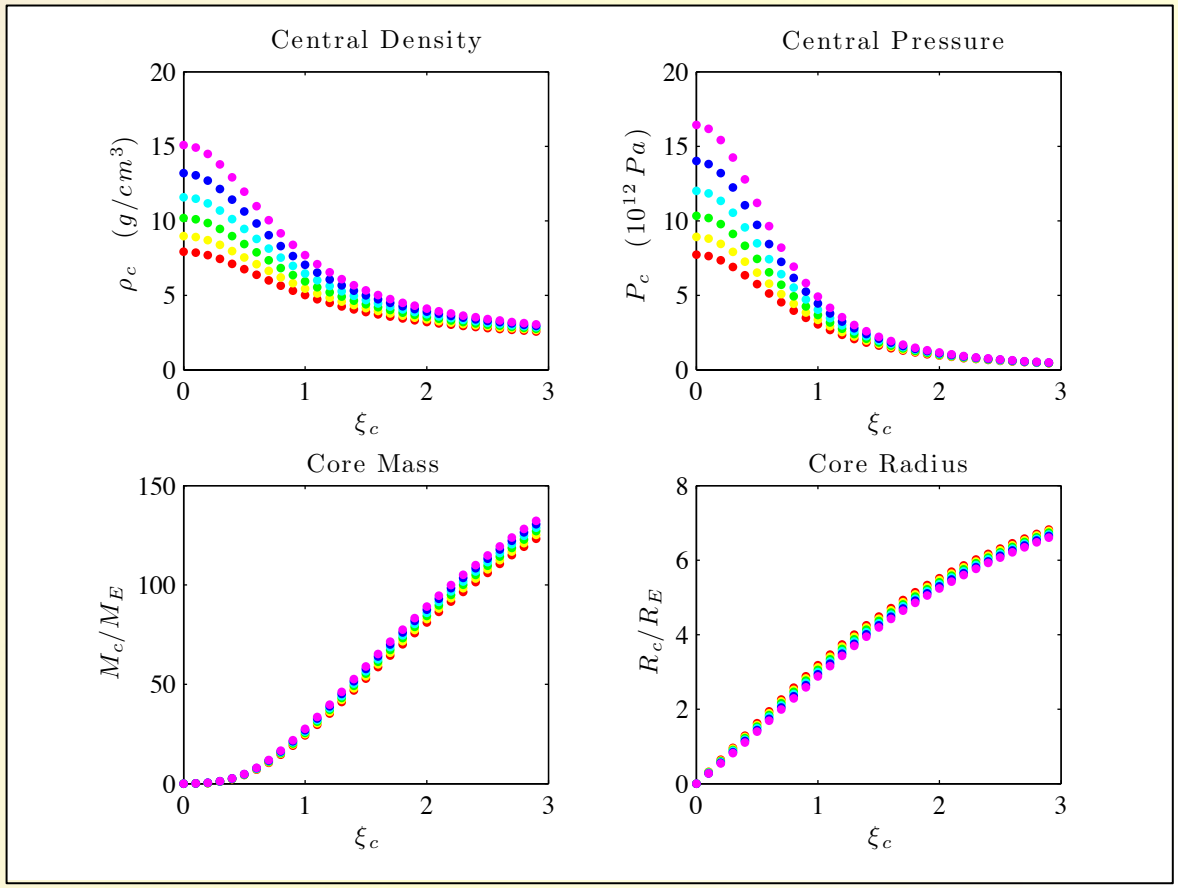
Physical radius and mass:

$$R_J = R\xi_0,\ M_J = 4\pi R^3 \rho_c \mu_0$$



hot Jupiter structure

Polytropic index and (dimensionless) core radius, along with physical radius and mass determine the central density, core mass, and other physical quantities



Orbital Dynamics

1-body problem

Equation of motion:

$$\ddot{r} = \frac{-Gm(r)}{r^2}\hat{\boldsymbol{r}} - \frac{1}{M_P}\rho(r)v^2\hat{\boldsymbol{v}}$$

non-dimensionalize

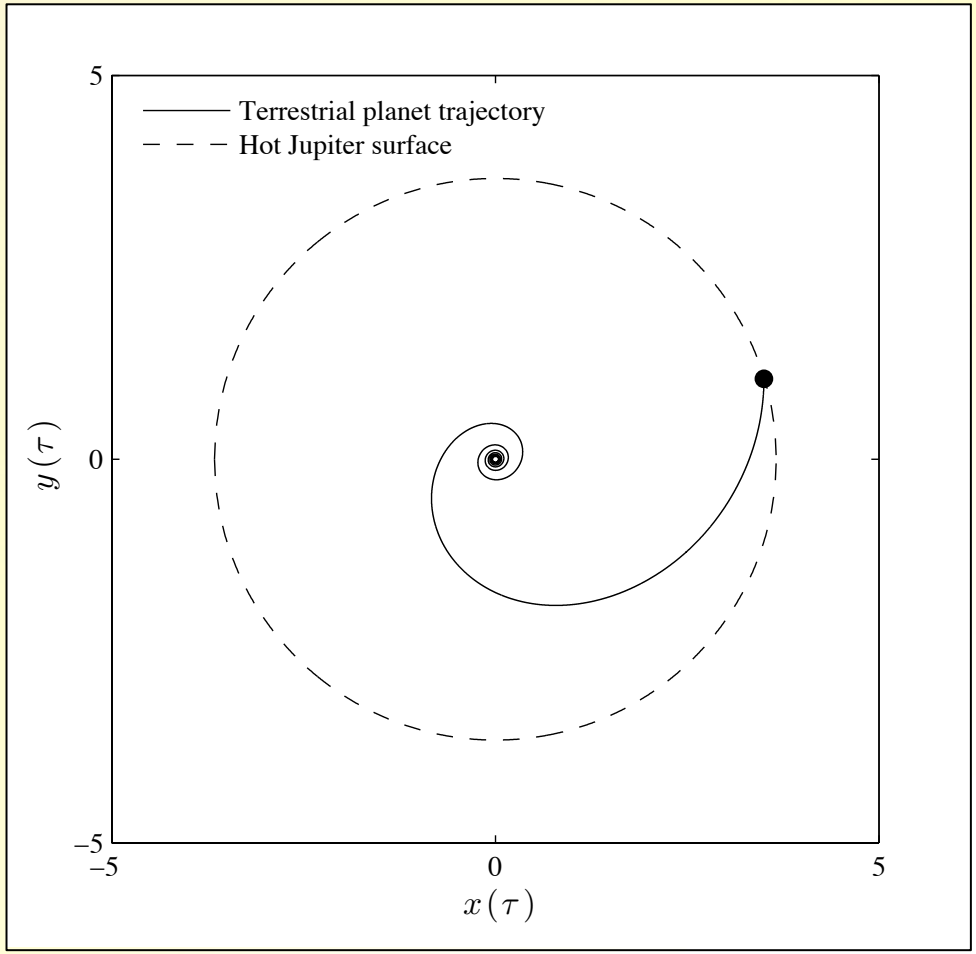
$$\rightarrow \ddot{\boldsymbol{\xi}} = \frac{-\mu(\xi)}{\xi^2}\hat{\boldsymbol{\xi}} - \alpha f^n \dot{\xi}^2 \hat{\dot{\boldsymbol{\xi}}}$$

where

$$\dot{\xi} = \frac{d\xi}{d\tau}, \quad \tau = \sqrt{4\pi G\rho_c}\, t,$$

$$\alpha \equiv \frac{\xi_0^2}{4\mu_0}\frac{M_J}{M_P}\frac{R_P^2}{R_J^2}$$

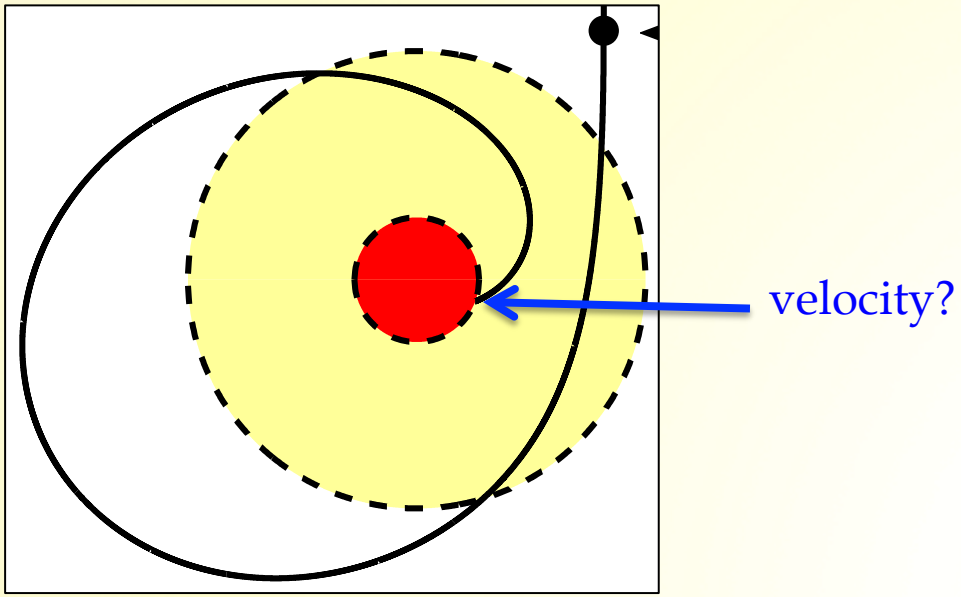
↑ Friction coefficient



Heat Distribution

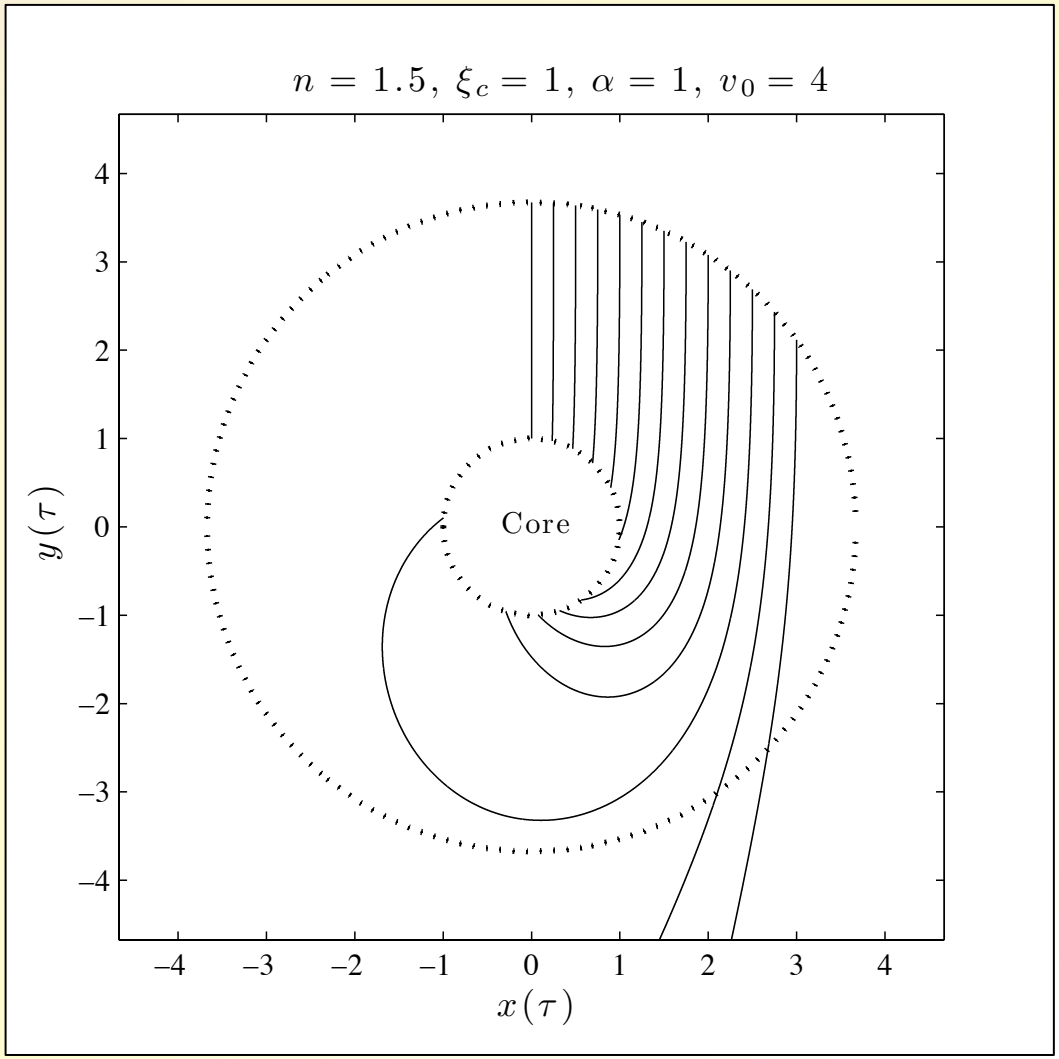
Monitor the kinetic energy **throughout** the trajectory

- Energy dissipated in the outer atmosphere will radiate away too quickly
- Want the velocity of the terrestrial planet as it reaches the core
- High velocities imply large amounts of heat deposited, homogenous cores



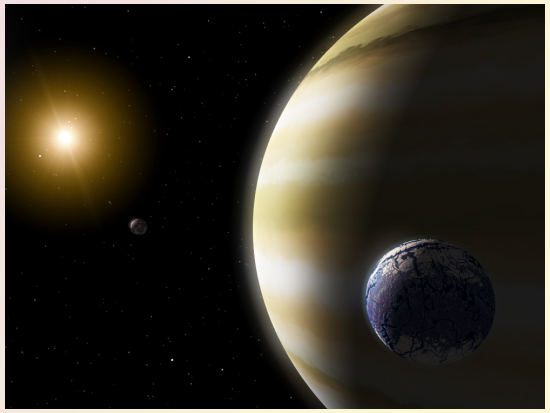
Free Parameters

- Impact parameter
- Initial velocity
- Planet mass
- Core radius
- Polytropic index



Need a thorough survey of this parameter space

Results



- Cross-section for capture is large
- Most of the energy is dissipated in the outer atmosphere
- Core velocities 10 – 50 km/s

Planets greater than 10 M_{Earth} are most likely to produce significant structural changes



- Determine the minimum mass for orbiting planets to survive the descent

  small planets will break up in the atmosphere, large planets will lose mass

- Develop energy transport models

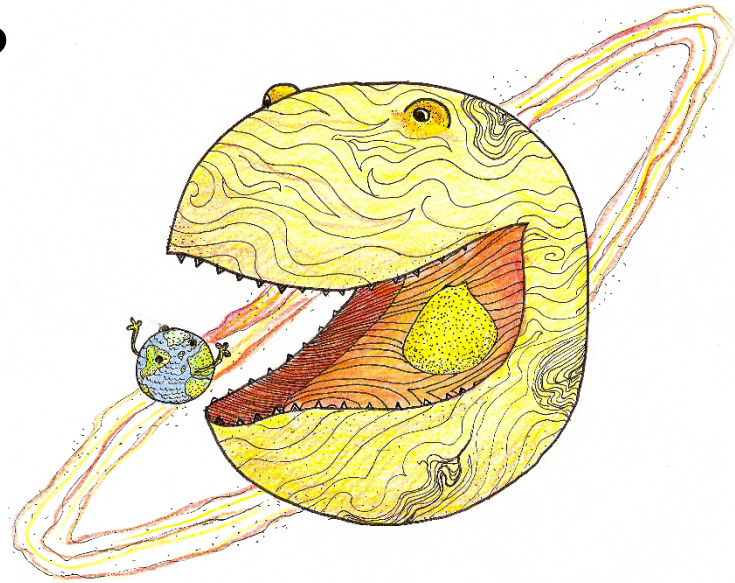
  how is this heat radiated, and how long does it take?

Acknowledgements

This research has made use of the Exoplanet Orbit Database
and the Exoplanet Data Explorer at exoplanets.org

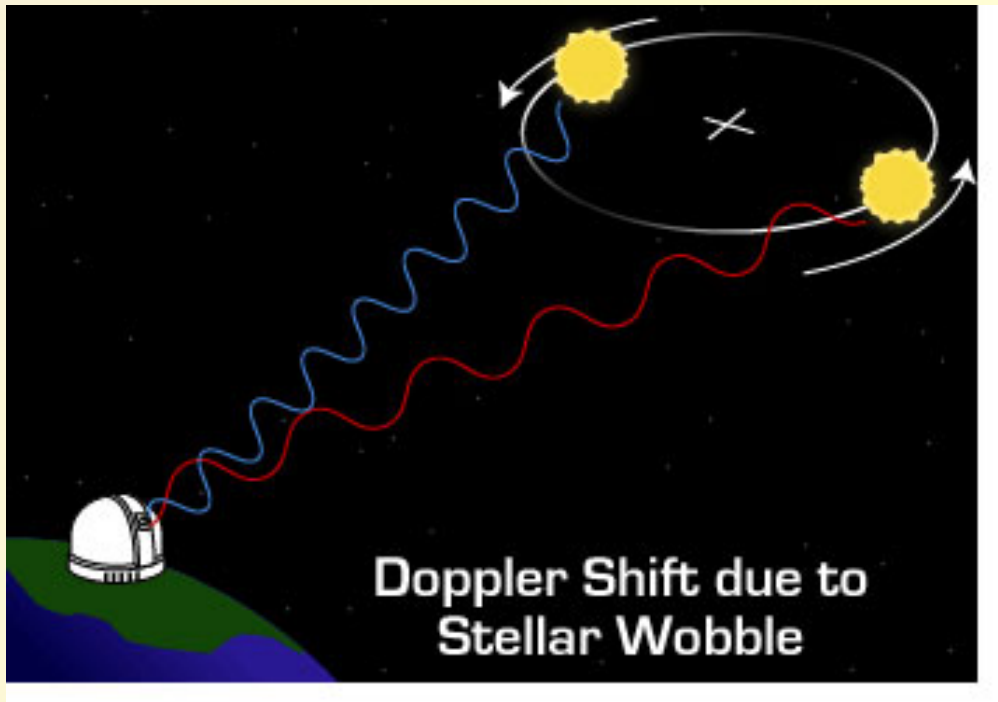
Many thanks to Fred Adams for supervising this project

Thank you
Questions?



Exoplanet detection:
Radial velocity (RV) method

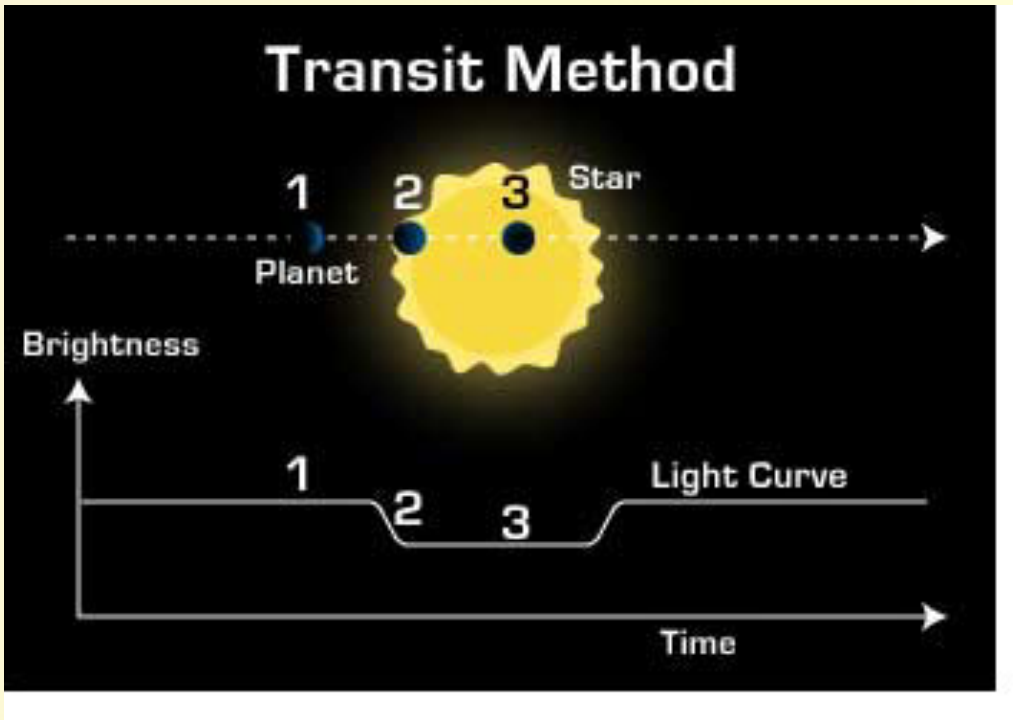
Measure Doppler shift, obtain planet mass



http://planetquest.jpl.nasa.gov/science/finding_planets.cfm

Exoplanet detection:
Transit method

Measure decrease in stellar intensity, obtain planet radius



http://planetquest.jpl.nasa.gov/science/finding_planets.cfm