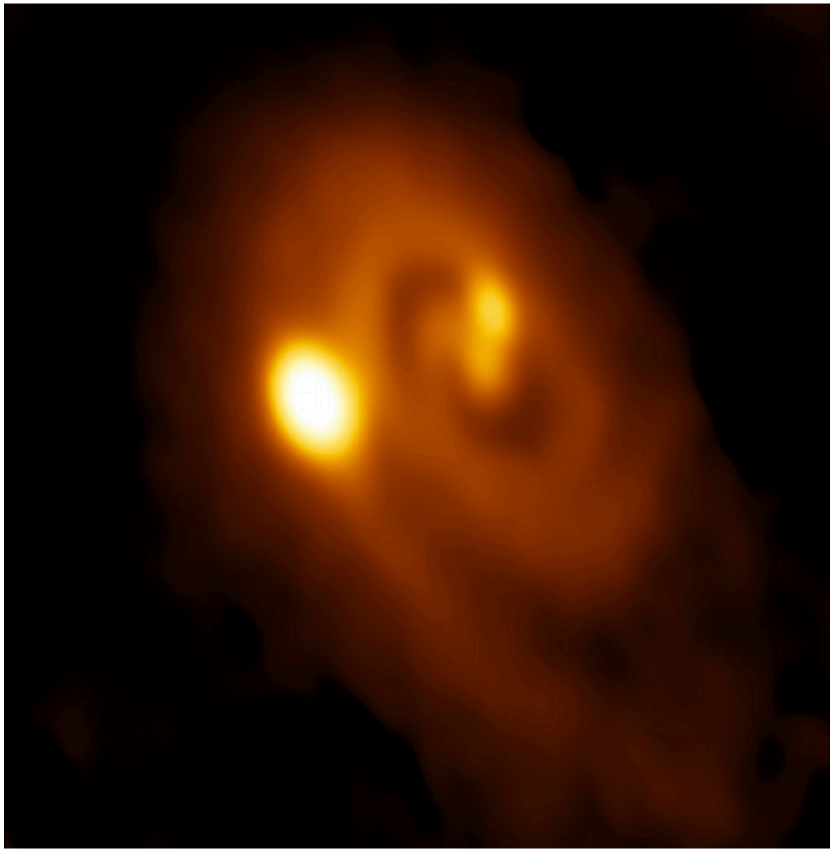
[25] Exoplanet Characterization (11/30/17)

Upcoming Items

1. Read chapters 24.1-24.3 for Tuesday
2. We will have a final exam review in the last discussion section (Friday, Dec 8) and also 6-8 PM Monday, Dec 11 (in this classroom, as before)
   Completely driven by your questions!

APOD 12/2/16



Course Evaluation is Open!

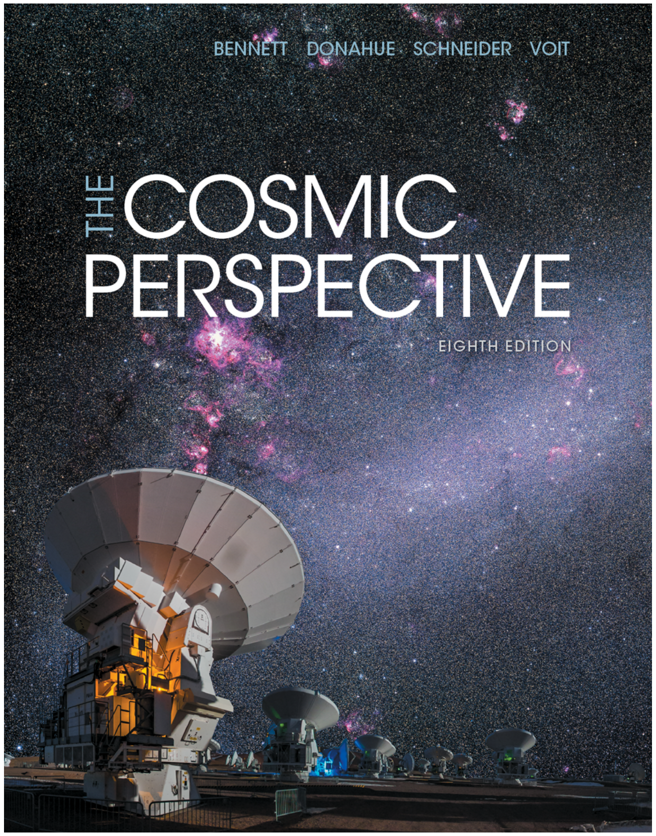
- **http://CourseEvalUM.umd.edu**
- Please complete: your honest feedback will help us improve the course
  I find your *written* feedback especially helpful
- Open from November 30 to December 12
- Thanks!

LEARNING GOALS

Ch. 13.2–13.4

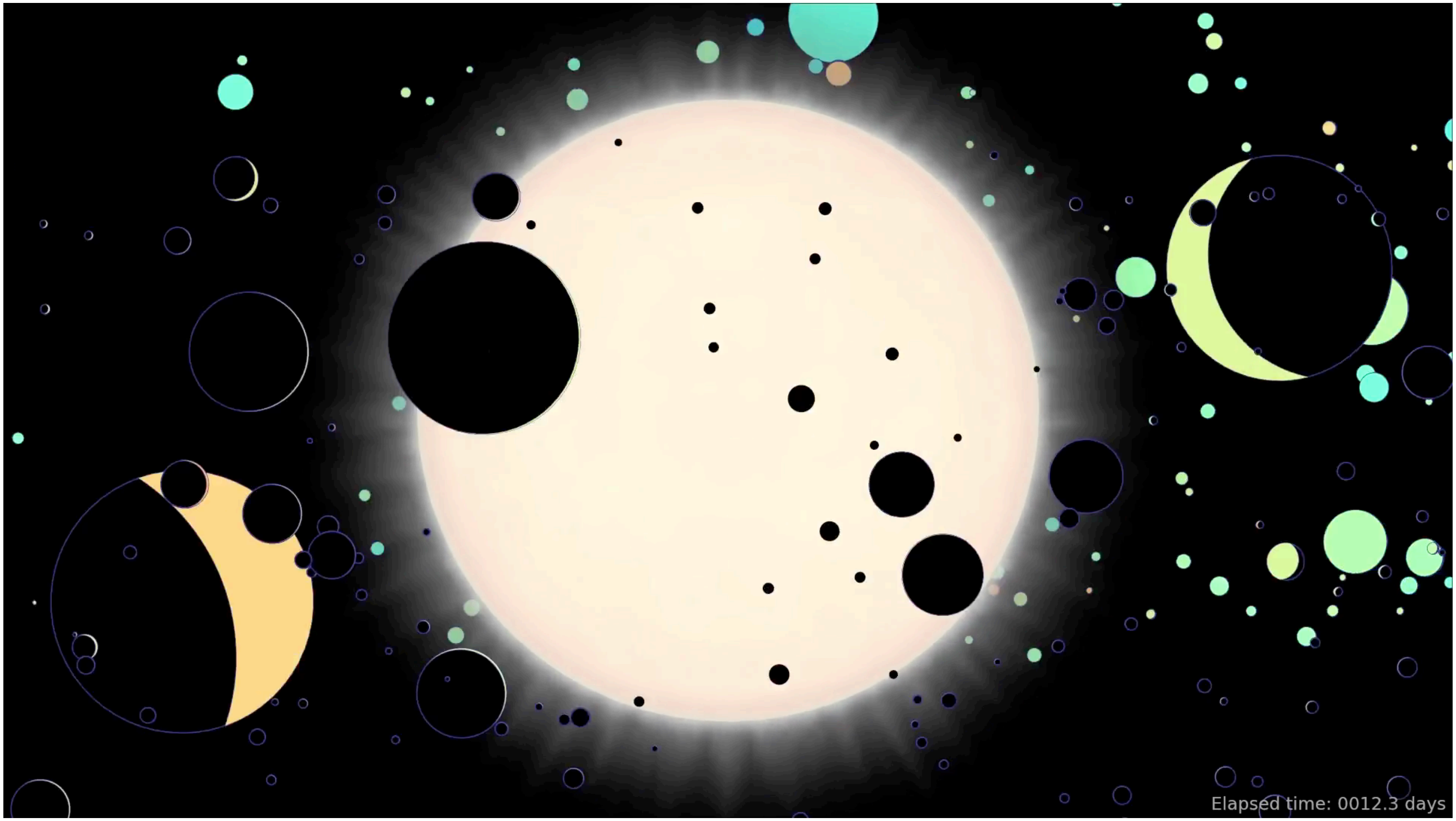
By the end of this lecture, you should be able to…

- … *describe in words the trends represented by plots and tables of exoplanet mass, radius, eccentricity, and multiplicity;*
- … *speculate about how these observed trends might change if observational biases were removed;*
- … *summarize ways in which the nebular theory can be modified to explain seemingly anomalous exoplanet populations.*



Any astro questions?

Worlds: The Kepler Candidates



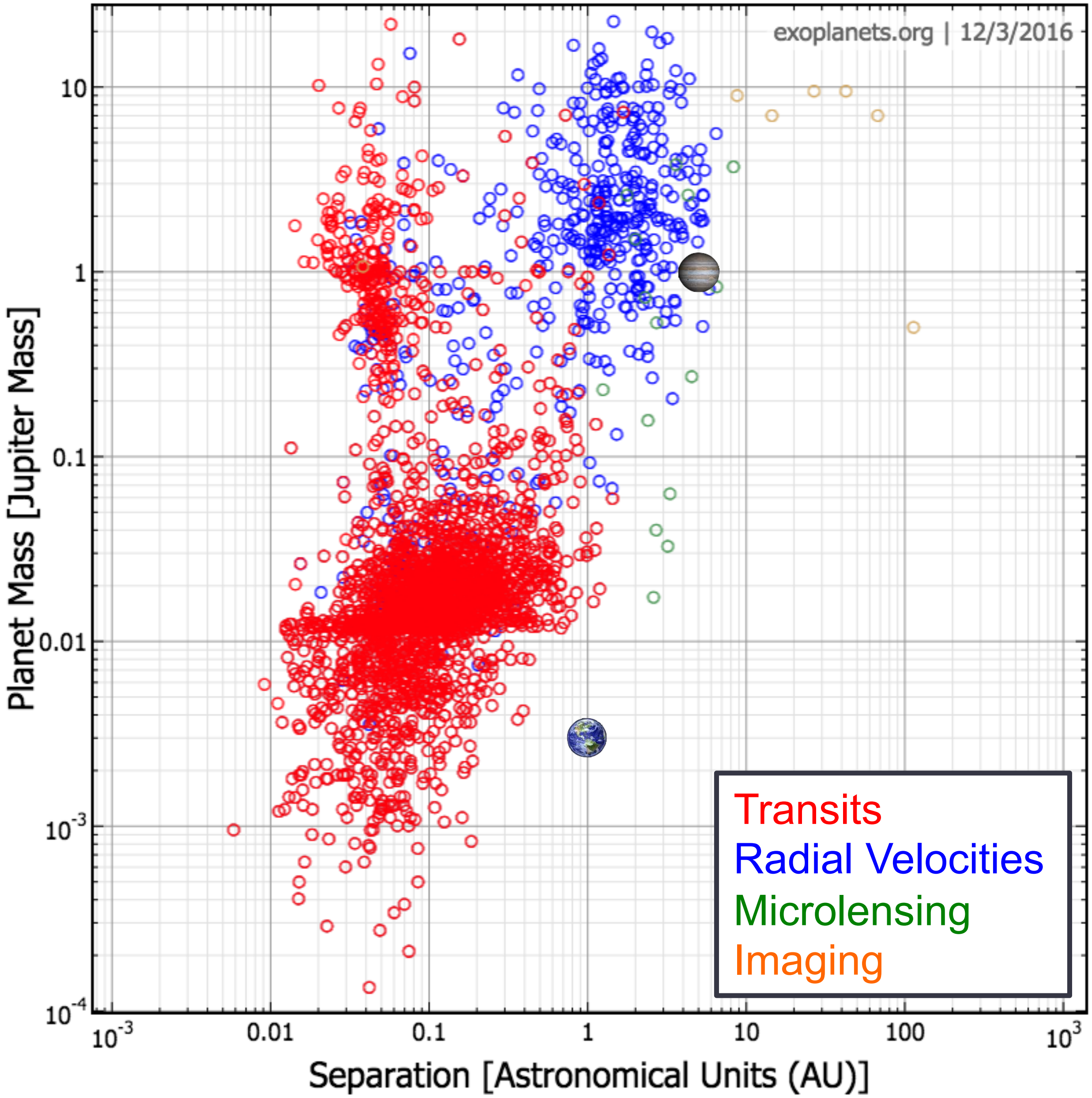
https://vimeo.com/47408739

Most of the unexpected characteristics of exoplanets can be explained by all of the following EXCEPT

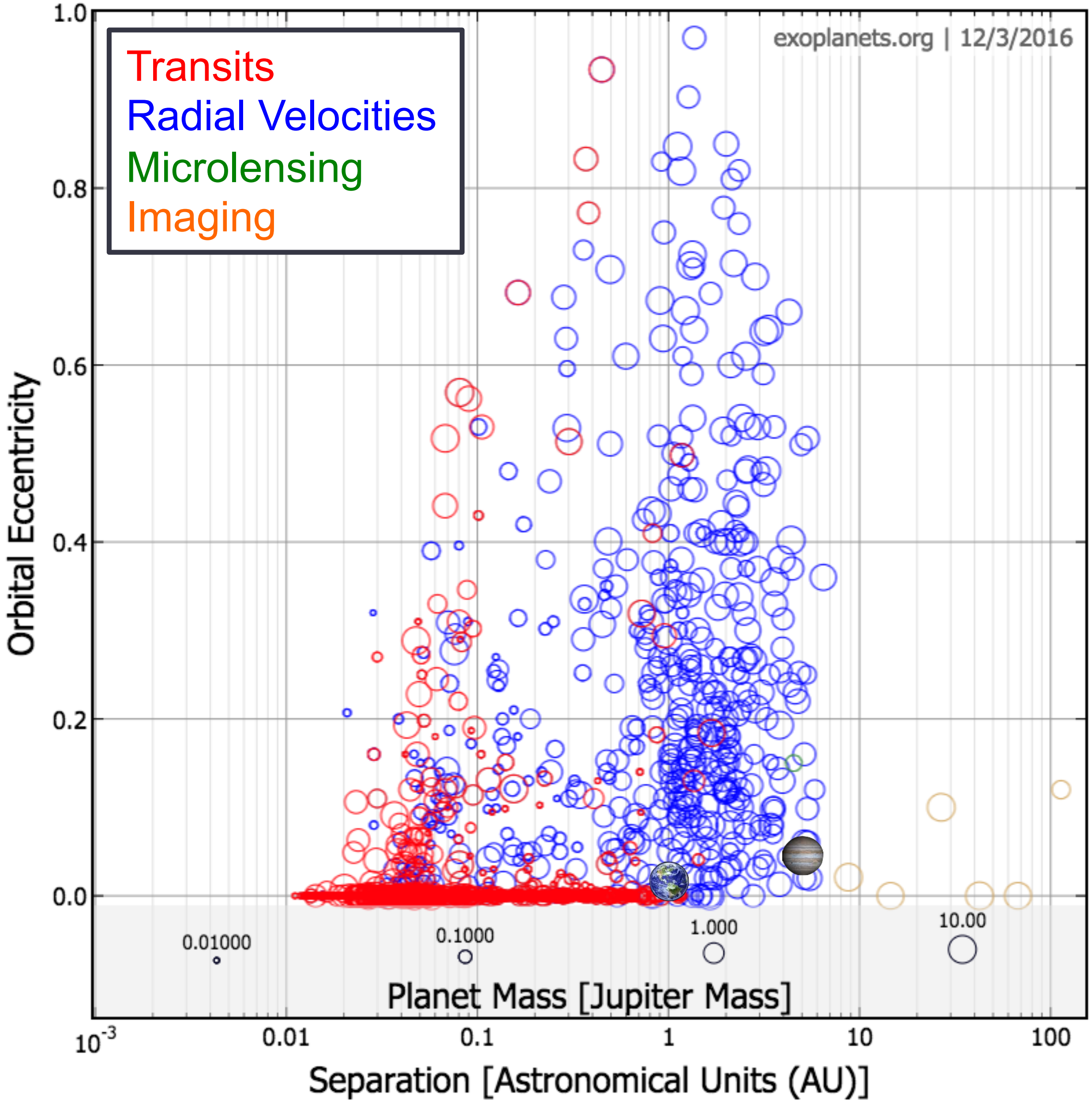
A. Close gravitational encounters between exoplanets.
B. Orbital migration of exoplanets in a gas disk.
C. Stellar and/or tidal heating of exoplanets.
D. Galactic cosmic ray heating of exoplanets.
E. Resonant interactions between exoplanets.

Exoplanet Characterization

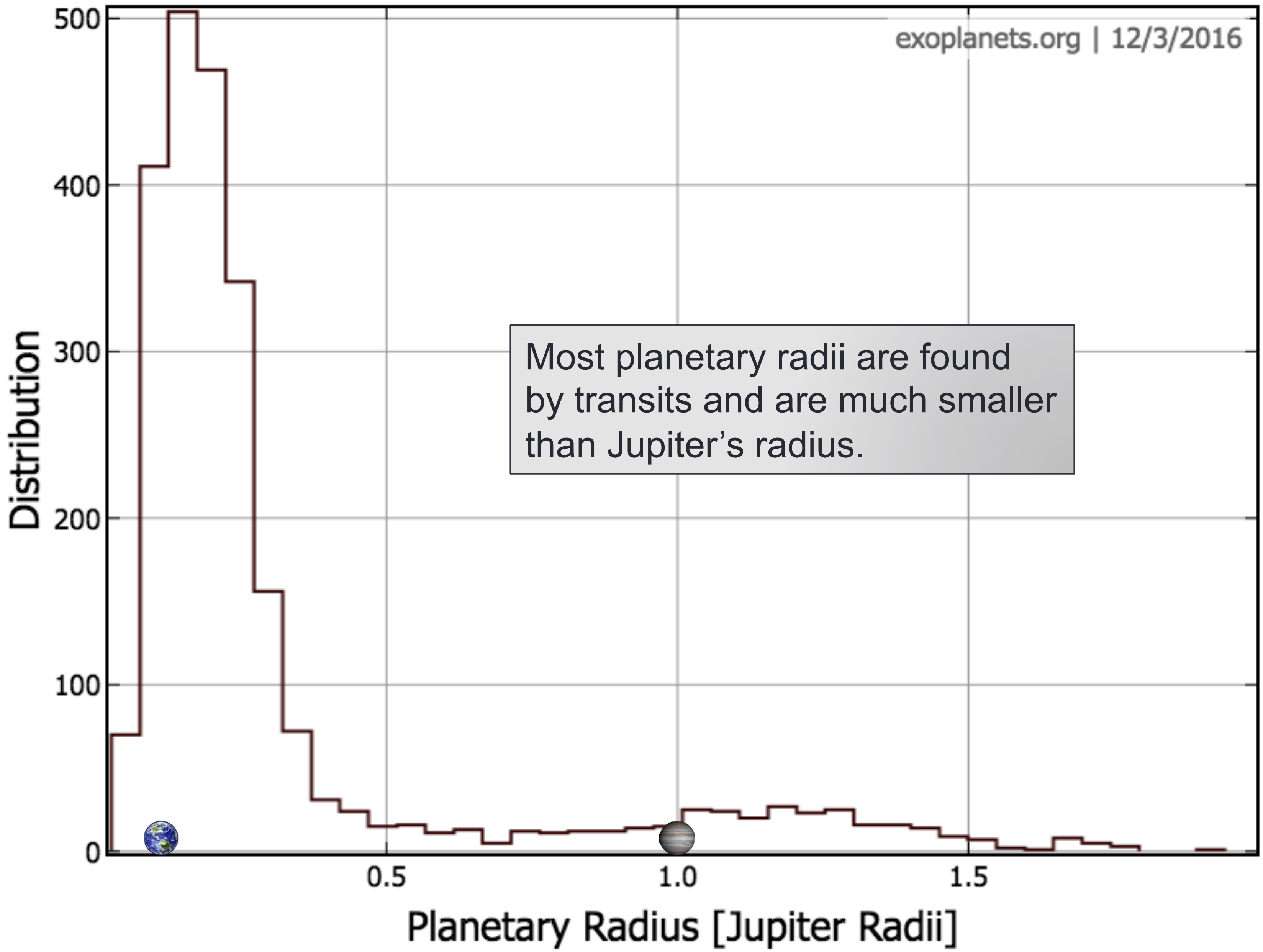
- We have found enough exoplanets that we can see clear trends, but we must remain aware of detection biases.
  - Most known exoplanets have small orbits (including “hot Jupiters”).
  - Many exoplanets have moderate to high eccentricity.
  - Transits reveal many Earth-size planets (and “super-Earths”).
  - Some exoplanets have very high or very low bulk density.
  - We are approaching planets analogous to Earth...
- Can get composition & see weather for some exoplanets.
- Multi-exoplanet systems and circumbinary planets exist.
- Modifications to the nebular theory appear to be needed.
  - Including orbital migration, planet scattering, and resonances.
- 20% of Sun-like stars have “habitable” Earth-like planets.

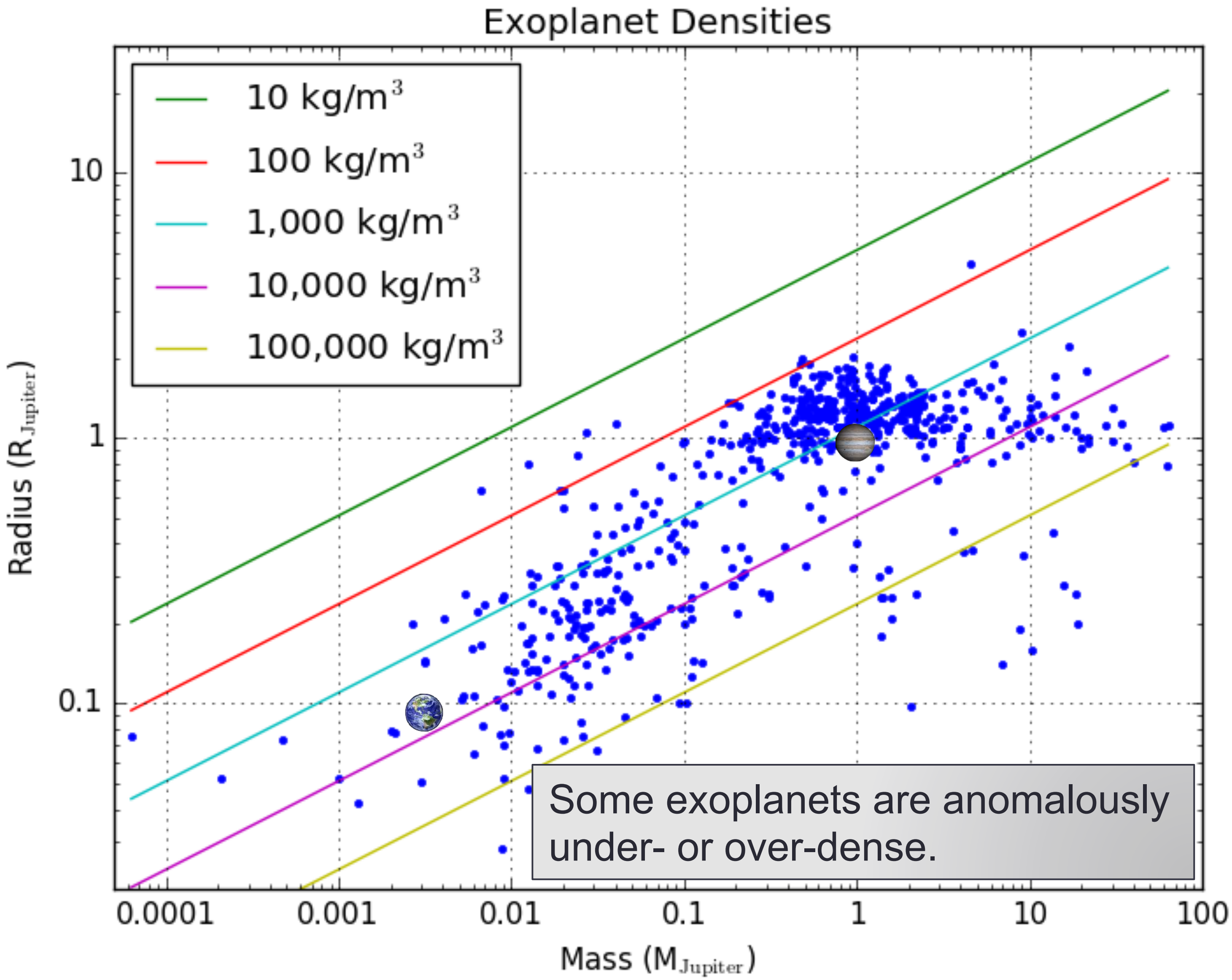


- Most detected exoplanets have orbits smaller than Jupiter's.
- Most Kepler exoplanets have less mass than Jupiter.
- Note detection biases!



- Many exoplanets have larger eccentricity than our planets.
- Are biases important here?

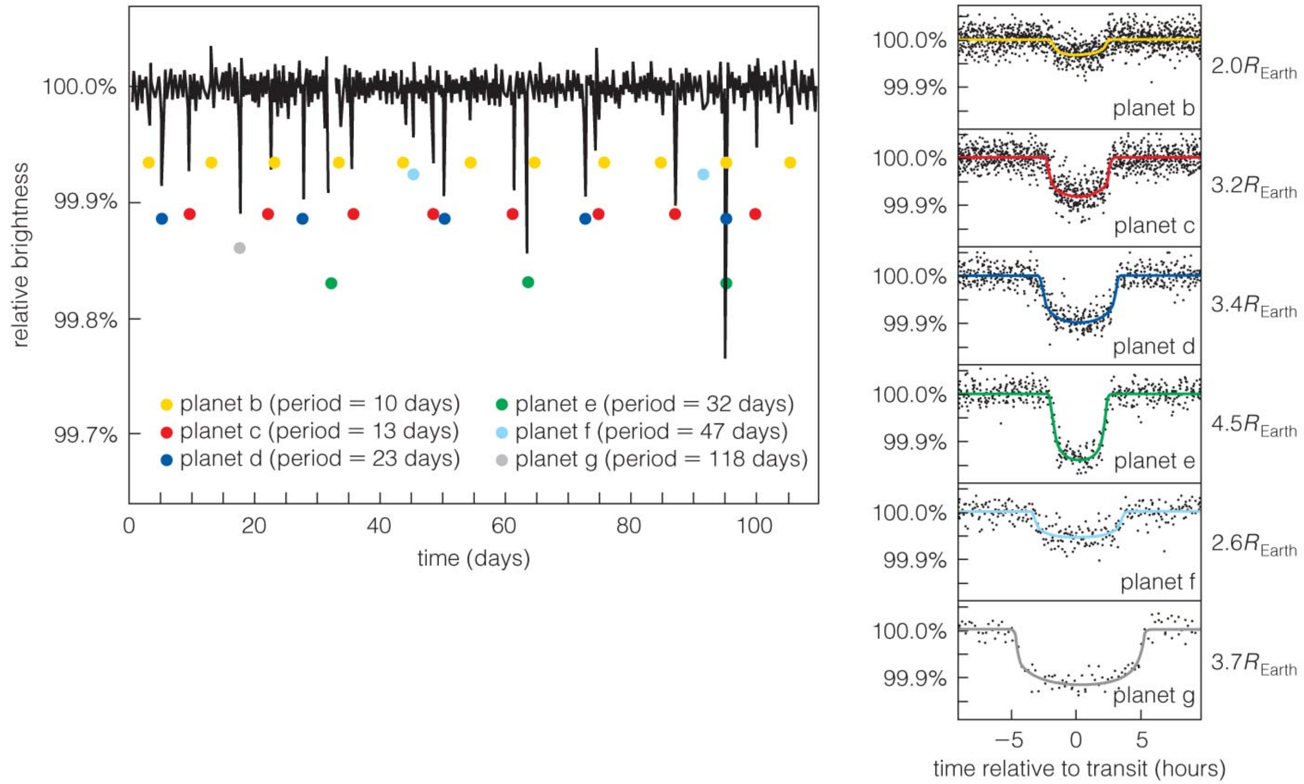

exoplanets.org | 12/3/2016
Most planetary radii are found by transits and are much smaller than Jupiter's radius.
Distribution
500
400
300
200
100
0
0.5
1.0
1.5
Planetary Radius [Jupiter Radii]



Some exoplanets are anomalously under- or over-dense.

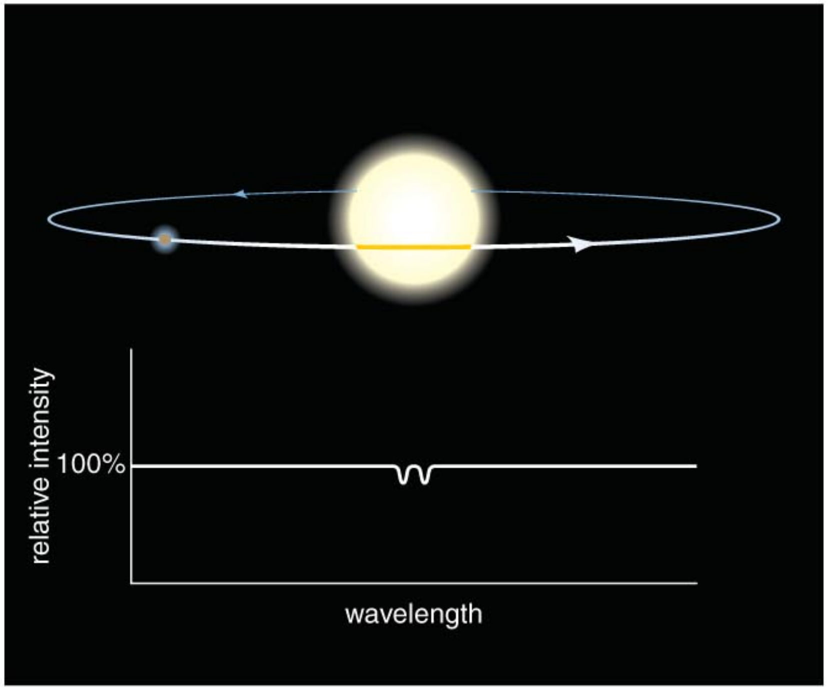
The Kepler-11 system

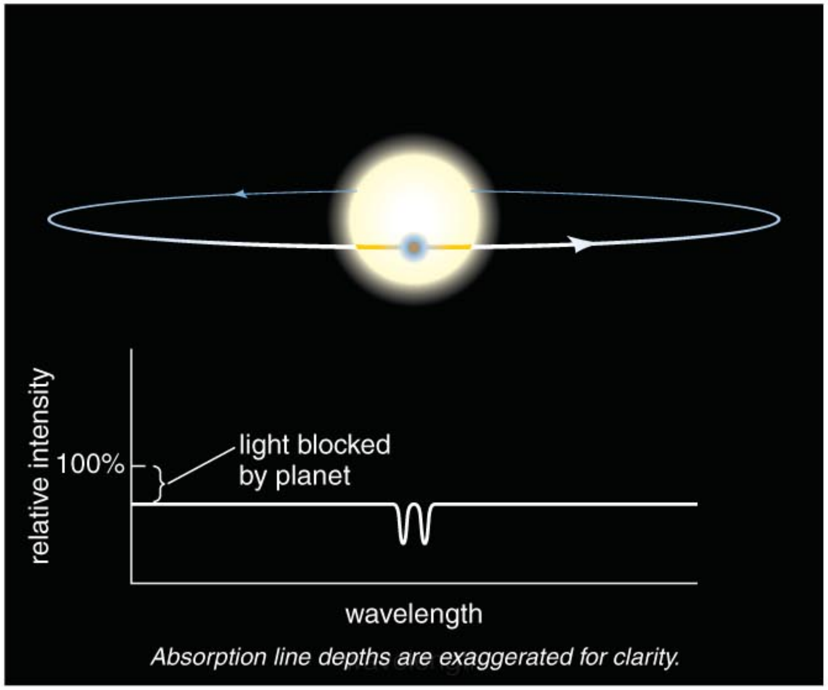
About 25% of exosystems detected have multiple planets.



- The periods and sizes of Kepler-11's 6 known planets can be determined using transit data.

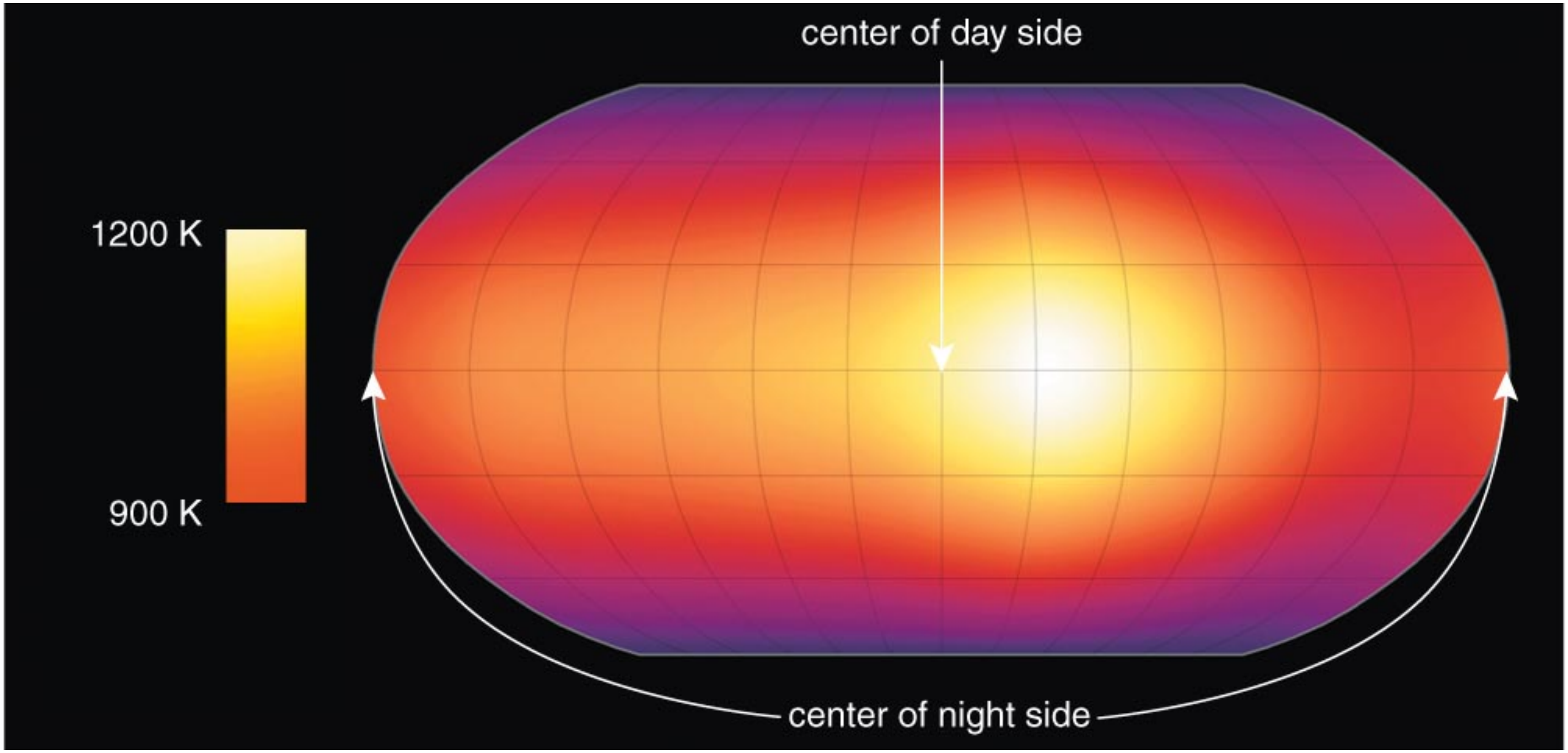
Spectrum During Transit



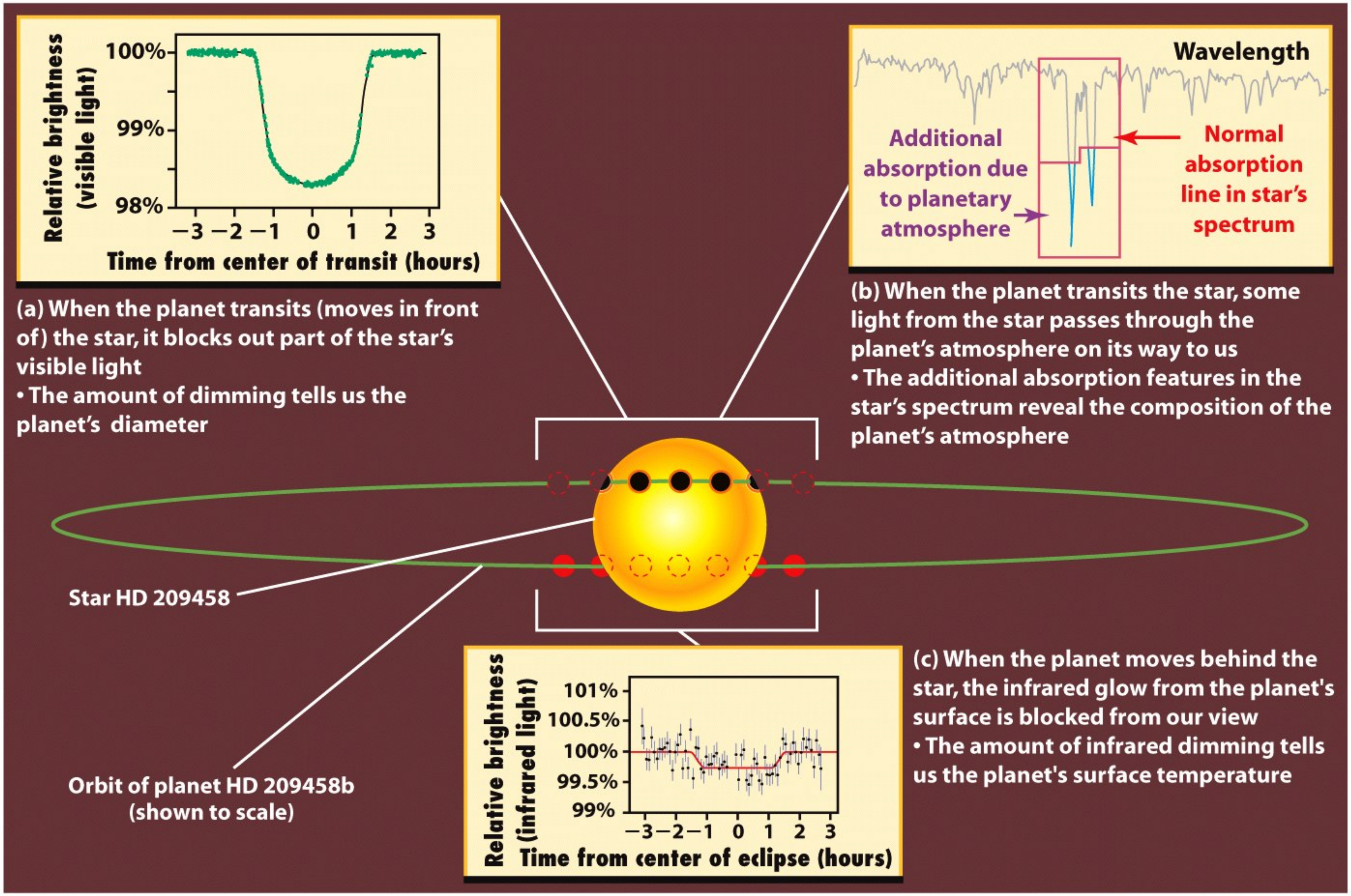


- Change in spectrum during a transit tells us about the composition of planet’s atmosphere.

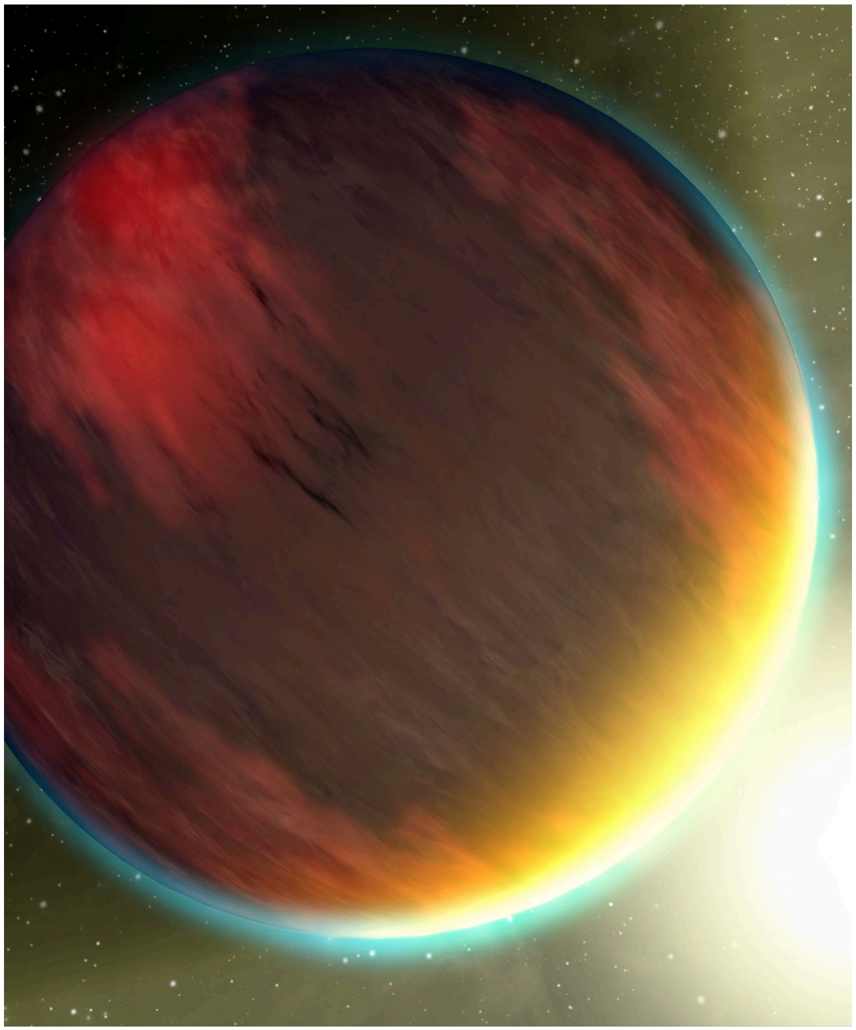
Surface Temperature Map



- Measuring the change in infrared brightness during an eclipse enables us to map a planet's surface temperature.


Relative brightness (visible light)
100%
99%
98%
−3 −2 −1 0 1 2 3
Time from center of transit (hours)
(a) When the planet transits (moves in front of) the star, it blocks out part of the star's visible light
• The amount of dimming tells us the planet's diameter
Wavelength
Additional absorption due to planetary atmosphere
Normal absorption line in star's spectrum
(b) When the planet transits the star, some light from the star passes through the planet's atmosphere on its way to us
• The additional absorption features in the star's spectrum reveal the composition of the planet's atmosphere
Star HD 209458
Orbit of planet HD 209458b (shown to scale)
Relative brightness (infrared light)
101%
100.5%
100%
99.5%
99%
−3 −2 −1 0 1 2 3
Time from center of eclipse (hours)
(c) When the planet moves behind the star, the infrared glow from the planet's surface is blocked from our view
• The amount of infrared dimming tells us the planet's surface temperature

HD 209458 (in Pegasus)



- First transiting exoplanet (also first direct detection).
- $M = 0.71\ \mathrm{M_{Jup}}$, $R = 1.38\ \mathrm{R_{jup}}$ ➔ very low density (about ⅓ the density of water).
- Orbits at 0.047 AU ➔ surface temp. 1130 K!
- Spectrum shows H, C, O, and Na (sodium) being evaporated from planet by starlight! Maybe H_2O too?

Surprising Characteristics

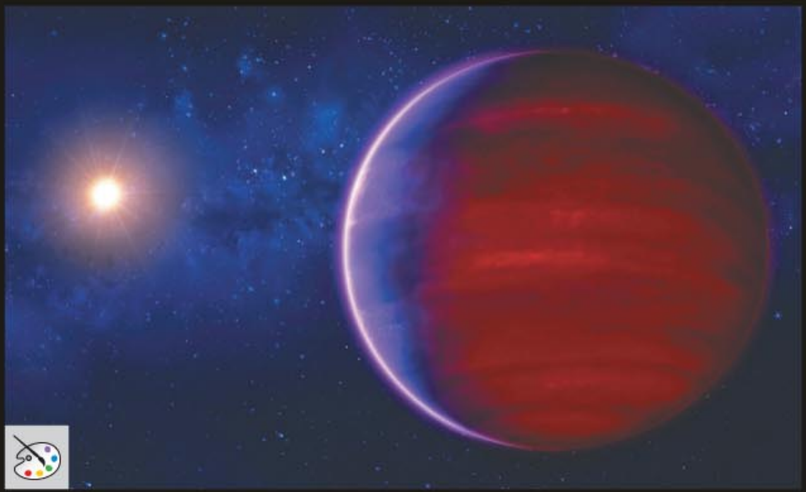
- Some extrasolar planets have highly elliptical orbits.
- Some massive planets, called *hot Jupiters,* orbit very close to their stars.
- Some massive planets have very low bulk densities (less than 200 kg/m^3): *inflated Jupiters*.
- Group question: how can we account for these surprises?

http://en.wikipedia.org/wiki/List_of_exoplanet_extremes

Hot Jupiters

Jupiter

Composed primarily of hydrogen and helium
5 AU from the Sun
Orbit takes 12 Earth years
Cloud top temperatures ≈ 130 K
Clouds of various hydrogen compounds
Radius = 1 Jupiter radius
Mass = 1 Jupiter mass
Average density = 1.33 g/cm^3
Moons, rings, magnetosphere



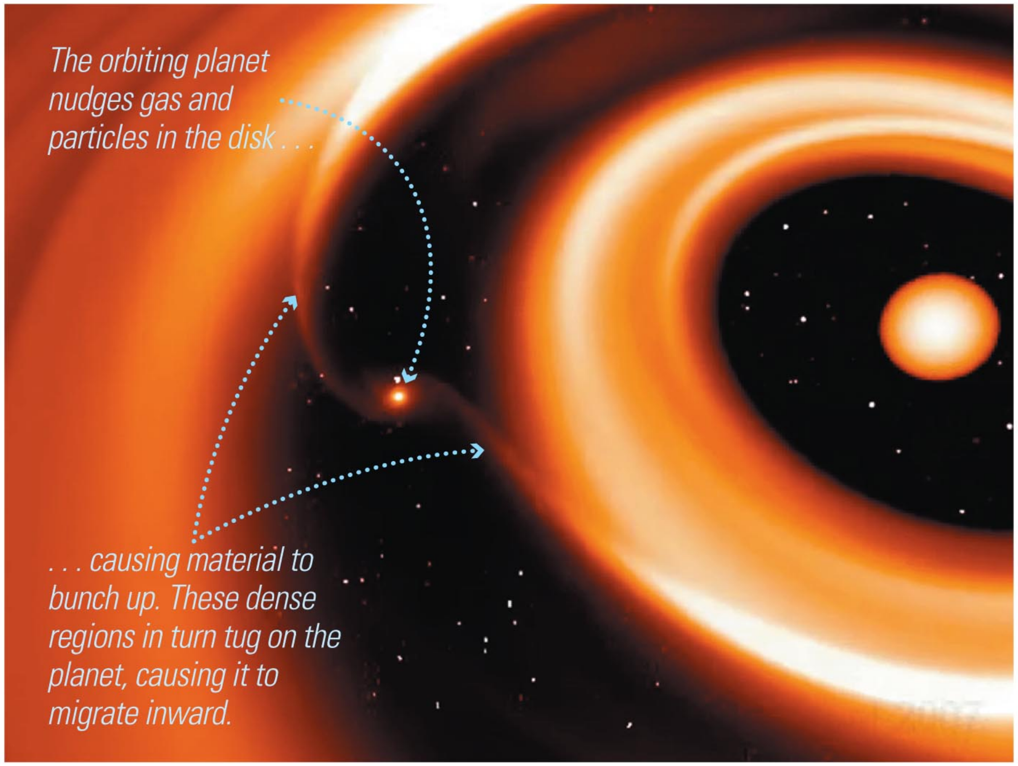
Hot Jupiters orbiting other stars

Composed primarily of hydrogen and helium
As close as 0.03 AU to their stars
Orbit as short as 1.2 Earth days
Cloud top temperatures up to 1300 K
Clouds of "rock dust"
Radius up to 1.3 Jupiter radii
Mass from 0.2 to 2 Jupiter masses
Average density as low as 0.2 g/cm^3
Moons, rings, magnetospheres: unknown

Revisiting the Nebular Theory

- Nebular theory predicts massive Jupiter-like planets should not form inside the frost line (at << 5 AU).
- The discovery of hot Jupiters has forced a reexamination of the nebular theory.
- *Planetary migration* or gravitational encounters may explain hot Jupiters as well as eccentric Jupiters.
- Stellar and/or tidal heating and other mechanisms can explain “inflated Jupiters” while gravitational compression explains super-dense Jupiters.

Planetary Migration



- A young planet's motion can create waves in a planet-forming disk.
- Models show that matter in these waves can tug on a planet, causing it to migrate inward.
- But what halts migration?

Orbital migration of the planetary companion of 51 Pegasi to its present location

Nature 380, 606-607, 1996.

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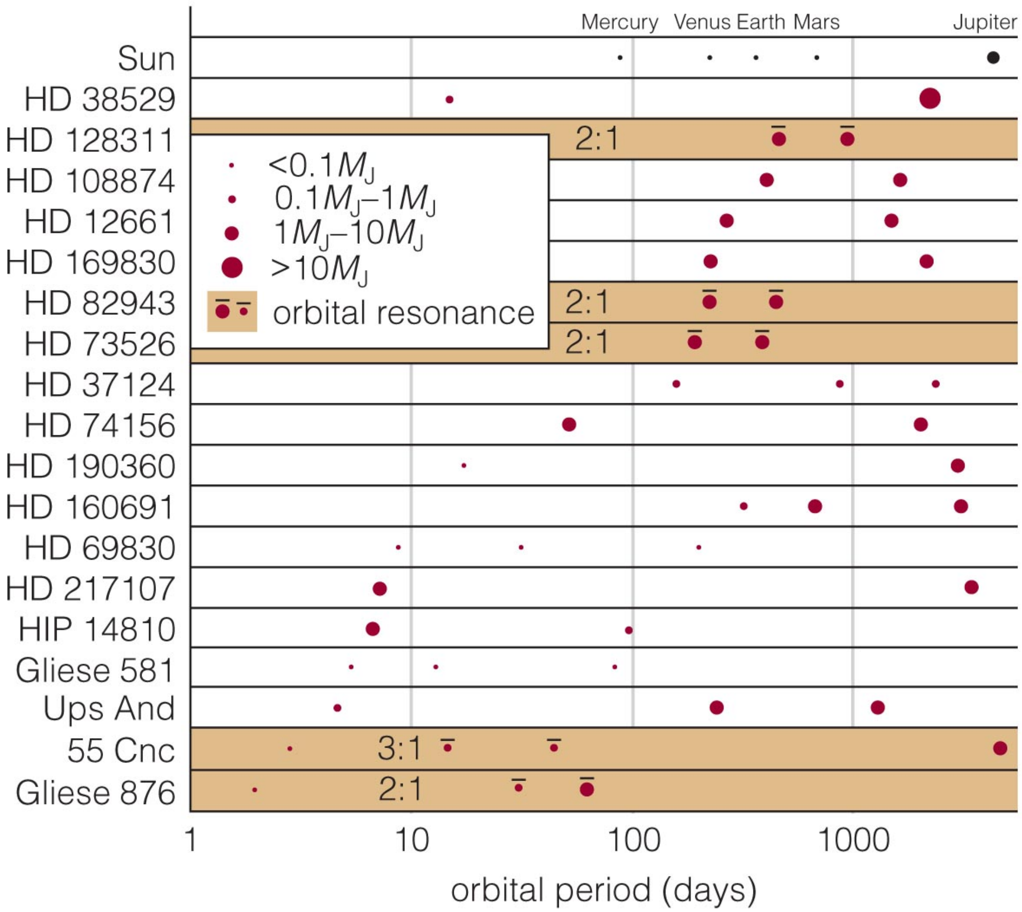
THE recent discovery[1] and confirmation[2] of a possible planetary companion orbiting the solar-type star 51 Pegasi represent a breakthrough in the search for extrasolar planetary systems. Analysis of systematic variations in the velocity of the star indicate that the mass of the companion is approximately that of Jupiter, and that it is travelling in a nearly circular orbit at a distance from the star of 0.05 AU (about seven stellar radii). Here we show that, if the companion is indeed a gas-giant planet, it is extremely unlikely to have formed at its present location. We suggest instead that the planet probably formed by gradual accretion of solids and capture of gas at a much larger distance from the star (~5 AU), and that it subsequently migrated inwards through interactions with the remnants of the circumstellar disk. The planet's migration may have stopped in its present orbit as a result of tidal interactions with the star, or through truncation of the inner circumstellar disk by the stellar magnetosphere.

Gravitational Encounters

- Close gravitational encounters between two massive planets can eject one while flinging the other into a highly elliptical orbit.
  - Orbits with sufficiently small perihelia can be circularized by tidal forces ➔ hot Jupiters. You'll explore this in the homework
- Multiple close encounters with smaller planetesimals can also cause migration (inward or outward).

Orbital Resonances



- Resonances between planets can also cause their orbits to become more elliptical.

Modifying the Nebular Theory

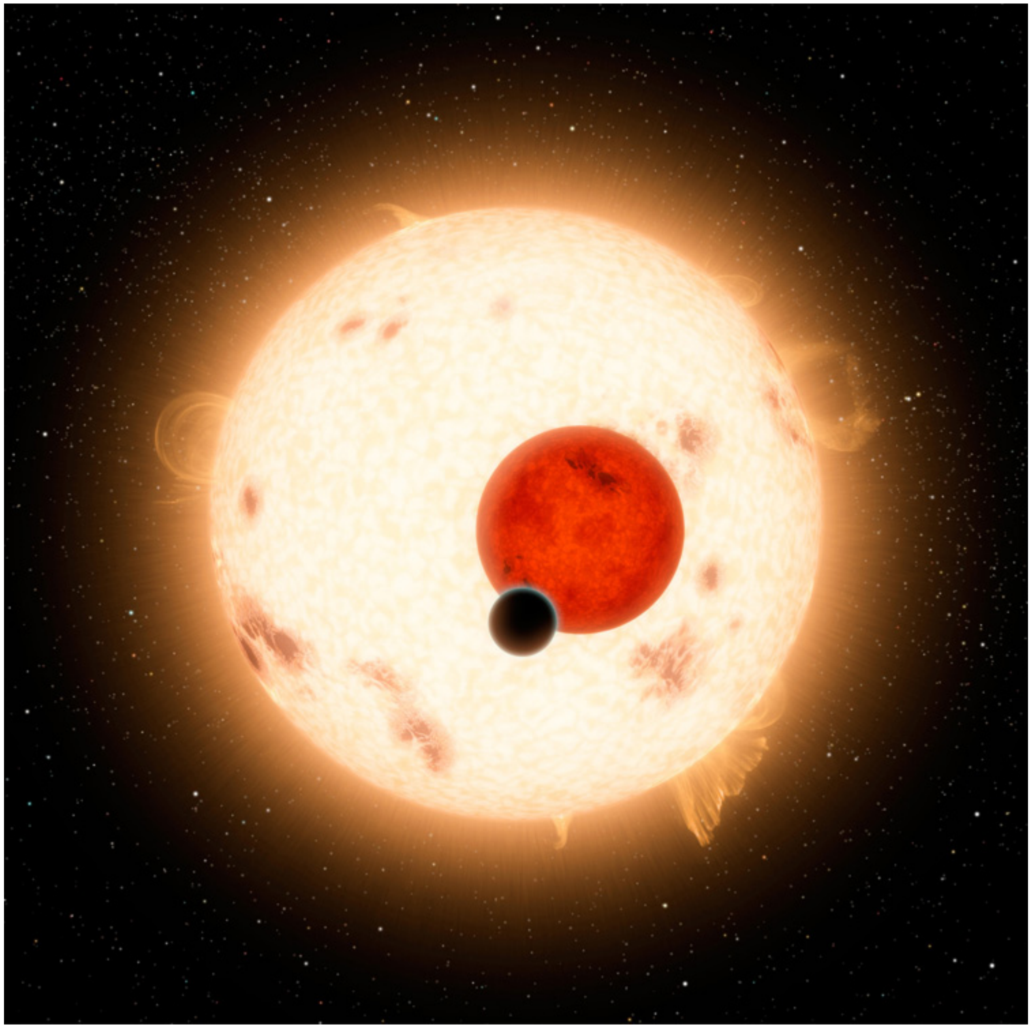
- Observations of exoplanets have shown that the nebular theory is incomplete.
- Effects like planetary migration & gravitational encounters are likely more important than previously thought.

The Maximum Packing Hypothesis

- Multiplanet systems seem to be on the edge of dynamical stability: they are “maximally packed” in the sense that adding a planet between the known planets would make the system unstable.
  - Same is true in our solar system!
- In fact, some exoplanets have been discovered based on *predictions* that a dynamical opening should be filled.
  - Rory Barnes & collaborators.

Circumbinary Planets

- Nearly half of stars in the Milky Way are in binary or multiple star systems.
- Occasionally, binary stars host planets, too!



Artist impression of Kepler-16 system.

The Habitable Zone

- A planet is said to be in the "habitable zone" if liquid water could plausibly exist somewhere on the surface under normal conditions, i.e., if the effective temperatures bracket 273 K (the melting point of water).
- For our solar system, the habitable zone lies between the orbits of Venus and Mars.

  How useful is the concept of the habitable zone?