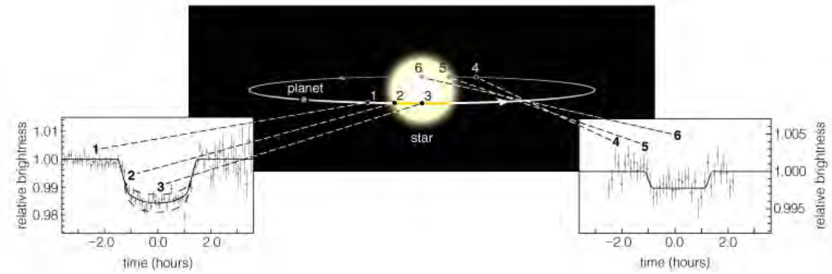
Agenda for Ast 309N, Oct. 16

- The transit method and NASA's Kepler satellite
- Feedback on 10/11 card
- Other methods: microlensing, timing, imaging
- Begin: aging of Sun-like stars (short video)
- Participation card (individual)
- Reading for this week:
  - Kaler, ch. 3; Wheeler, pp. 27 – 37

Transit Method (for exoplanets)

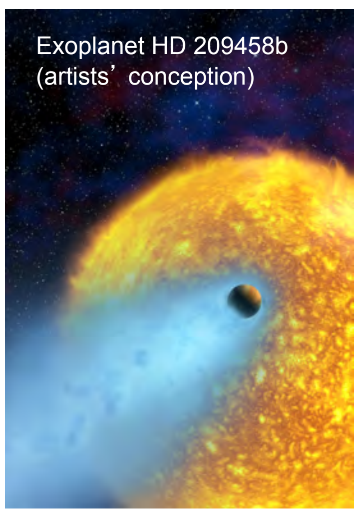


- A **transit** is when a planet crosses in front of a star
- The resulting (partial) eclipse reduces the star's apparent brightness and tells us planet's radius
- The orbital tilt is known (must be nearly edge-on); this means Doppler measurements will give you the *actual* planet mass – not just the lowest possible mass

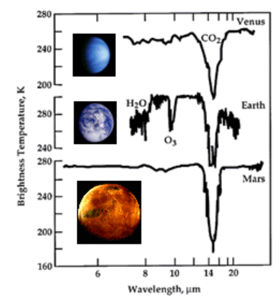
Spectroscopy of Hot Jupiters

51 Peg b was the first of a class of exoplanets called "hot Jupiters." They have masses similar to Jupiter, but are very close to their parent star, so they have short orbital periods and are heated to extremely high temperatures.

… in fact, the atmosphere of hot Jupiter HD 209458b is seen to be evaporating

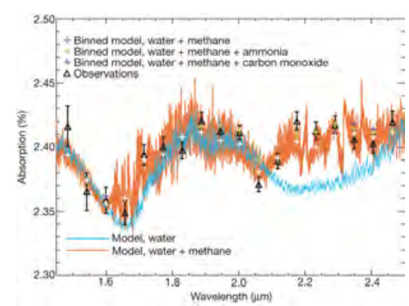


Molecules in Transiting Exoplanets



- Water (H_2O) and methane (CH_4) have been detected in the transiting planet HD 187933b; CO might be present as well.

Molecules in the atmospheres of exoplanets may even provide information on biological activity; such measurements are hard but not impossible…



What is *Kepler?*

- *Kepler,* a NASA Discovery mission, was launched on March 9, 2009.
- It uses the "transit" method of searching for extrasolar planets.
- In the first few months of operation it found several large planets (Jupiter- and Neptune-like) in small orbits.
- Its overall goal was to detect Earth-like planets around Sun-like stars; as of fall 2012 it has certainly found Earth-sized (and even smaller) planets.

TRANSITS CAN BE USED TO DETECT EARTH-SIZE PLANETS

From **TRANSIT DATA** obtain:

Duration and depth of the transits, orbital period and inclination.

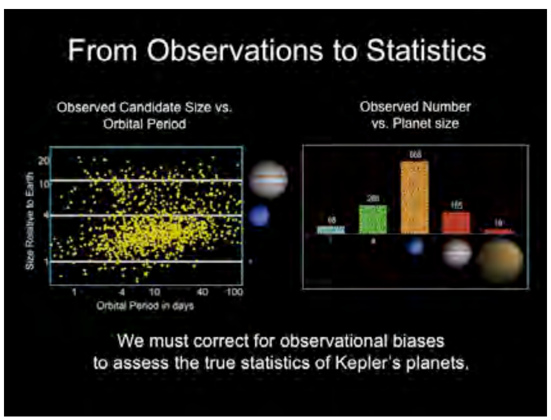
Derive planet sizes and orbital radii (combined with stellar information)

From **ENSEMBLE of PLANETARY SYSTEMS** obtain:

Estimates frequency of planet formation for inner planets.

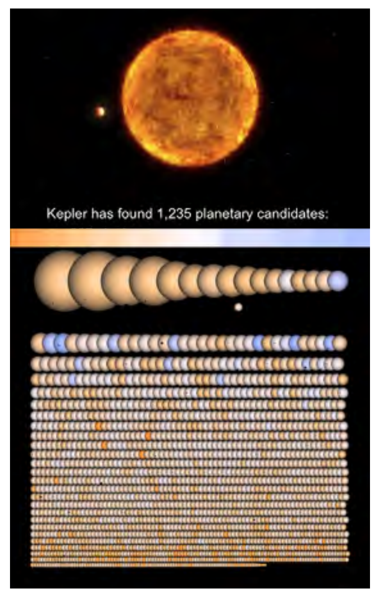
Requires thousands of stars because will see transits only for orbits that are fairly precisely aligned

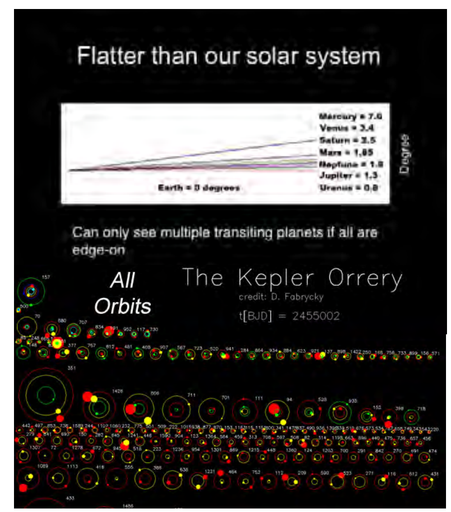
Presentation by W. Borucki, Principal Investigator, May 2011



This means that conclusions about frequencies of large vs. small planets must take the "bias" of the transit method into account.

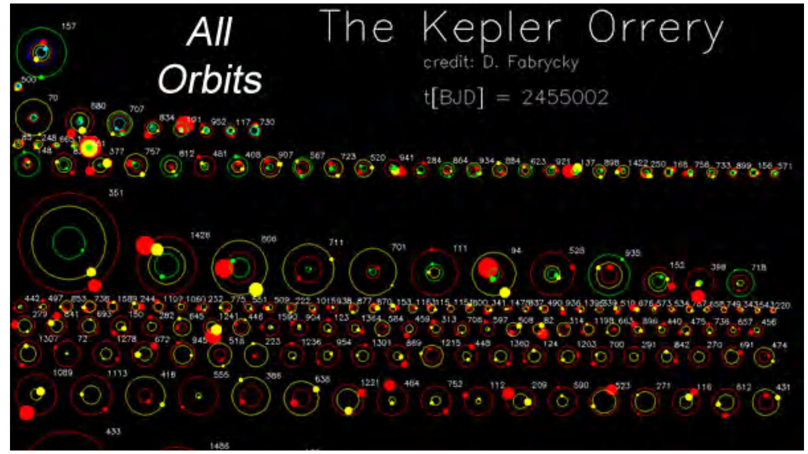
Presentation by D. Latham, Kepler Team, May 2011





Follow-up to Kepler Detections

- Kepler finds apparent transits (drop-outs in light curves); these are designated "candidates" or "Kepler Objects of Interest" – e.g. KOI 22.
- Some turn out to be binary star systems.
- If the dips turn out to be due to an exoplanet, you get a measure of the ***radius*** ("size") of the planet
- To get a mass for the planet you need to go back to using the *Doppler method*. Then you know the orbit's inclination angle, so you have the actual ***mass***.
- With mass and radius, you can compute the planet's overall ***density***, which implies its composition.

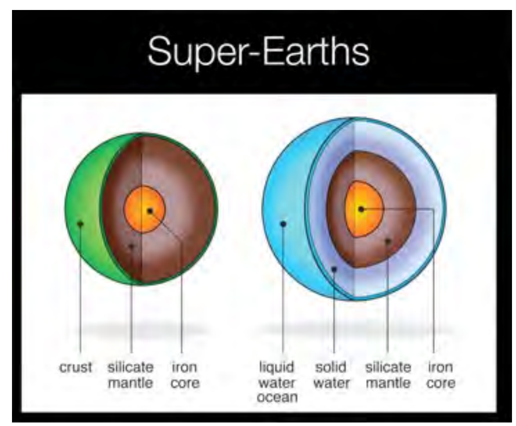


The "Kepler Orrery" can be found and downloaded from the Kepler or Planetquest websites, or viewed on YouTube.

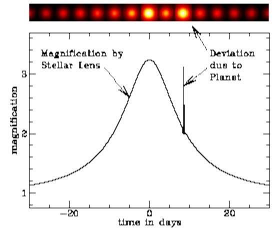
Recent Kepler Results

- *Many* multiple-planet systems
- Planets in binary star systems; even multi-planet systems around binary stars!
- Planets with radii smaller than Earth's
- Small planets are, in fact, common – the bigger ones were found first only because *they're easier to see*
- Planets have a *range* of average densities, as calculated by combining measurements of the radius (from transits) with that of mass (from Doppler method)
- Average density gives hints about the composition but may not be sufficient to uniquely establish the internal structure.

Some Models for (Large) Terrestrial Planets



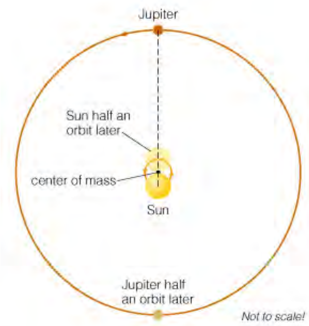
"Microlensing" Method of Planet Detection



There is another method which uses the light curve – changes in brightness as a function of time – but not the brightness of the star the planet is orbiting! This method is based on the prediction from Einstein's theory of gravity, General Relativity, that the presence of matter will bend the path of a ray of light. When looking towards a background star, if another star moves nearly in front of it, we see a brightening effect, as if a magnifying glass were being passed in front of it. If the foreground star has a planet, we see its effect as well.

Exoplanets: Timing Method

- First seen in pulsars
- The star is displaced along the line of sight as it orbits the center of mass of the system
- This causes a delay in the arrival time of the pulses due to the extra distance the light must travel
- The first claimed detection, A. Lyne in 1991, was bogus. The period was exactly 1 year; he was seeing the effect of Earth's orbit!

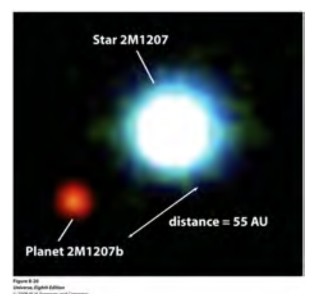


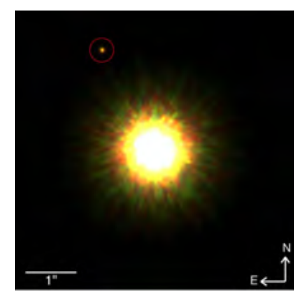
Exoplanets: Timing Method

- Soon afterwards, however, Andrew Wolszczan found definite evidence of multiple, low-mass objects orbiting the pulsar B1257+12.
  - he found two planets of about 4 Earth masses each, in orbits with *a* = 0.37 and 0.47 A.U.
  - proof of their reality? You can see them "tug" on each other, affecting their orbits
- Pulsar B1620-26 in the globular cluster M4 appears to have a ≈ 10 Jupiter mass object orbiting it; this is a binary pulsar in which a disk was formed due to mass transfer.

Direct Imaging of Exoplanets

This low-mass object is circling a brown dwarf …

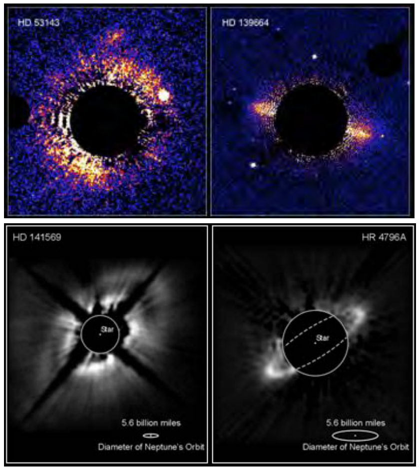




But this one orbits a Sun-like star. Image from a Sep. 15, 2008 press release, taken with adaptive optics on Gemini N telescope.

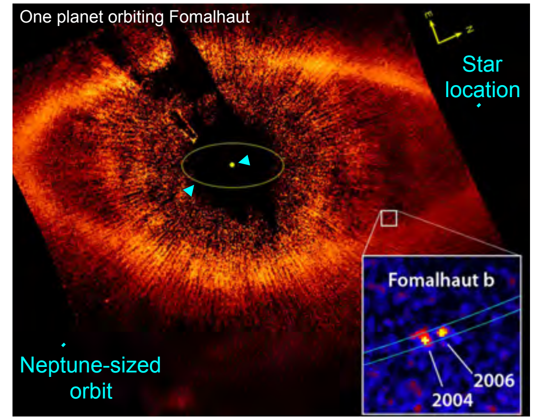
Disks around Other Stars

- Optical and infrared images show that other stars, especially young stars, have circumstellar disks.
- "Gaps" in their disks may be places where planets are forming by accretion.



The First Images of Exoplanets

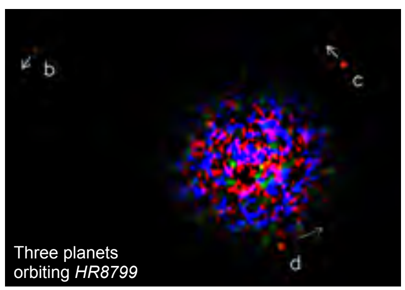
- New images show planets orbiting bright young nearby stars
- Although more than 350 planets are known to orbit other stars, none could be imaged until now



Hubble Space Telescope visible image of the star Fomalhaut (whose light was blocked), with a dust belt similar to the Kuiper belt. Inset: *Images taken ~2 years apart show a planet moving around the star.*

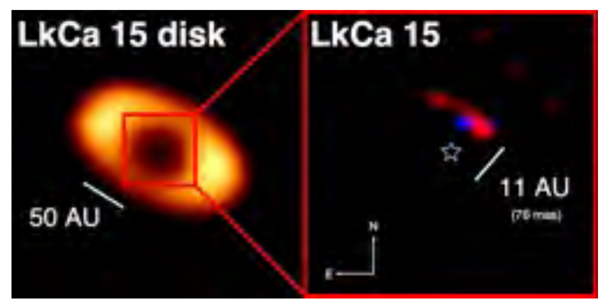
Glowing Young Planets

- This star has three orbiting planets - the first imaged *planetary system*!
- Planets are much fainter than their parent star, so are difficult to image
- How are these pictures possible?
  - Advanced observing techniques used to block the star's light
  - Observations were repeated, confirming planetary motion
  - The planets are young and hot, and therefore are brighter (in the infrared) than they would be from reflected starlight alone



Keck Observatory infrared image of star HR8799 and three orbiting planets with orbital directions indicated by arrows. The light from the star was subtracted, but a lot of 'noise' remains (colored blobs at the center).

Young Planet in a Circumstellar Disk



- The young star Lick Calcium 15 is surrounded by a disk.
- A "gap" has developed in the disk, suggesting that a planet has formed and is collecting material from a ring at that radius.
- The planet has now been seen using advanced imaging techniques.
- Image taken by Adam Kraus, joining UT's Astronomy Dept in 2013