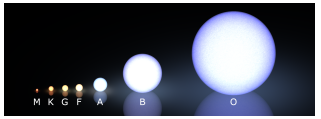
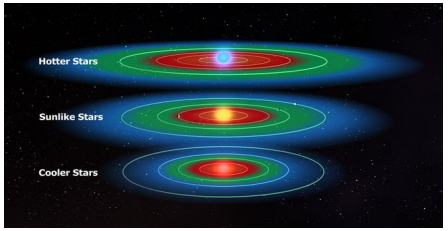
Summary

- Stars are very far away
- Stars come in a variation of colors, sizes and brightnesses

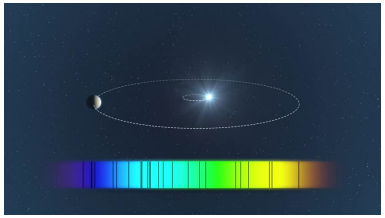


- "Earth-like" means a rocky planet in the habitable zone



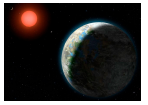
Summary

- We can't see planets directly
- We look for planet's effects on stars
  - Planet's gravity pulls the star a little bit
  - Very difficult to measure the star's change in position
  - Easier to measure the change in the star's speed
    - Doppler method

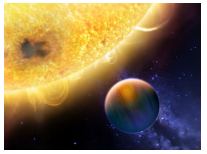


Discoveries with Doppler Method

- 529 planets
- A few potentially habitable planets rocky planets
  - Somewhat controversial



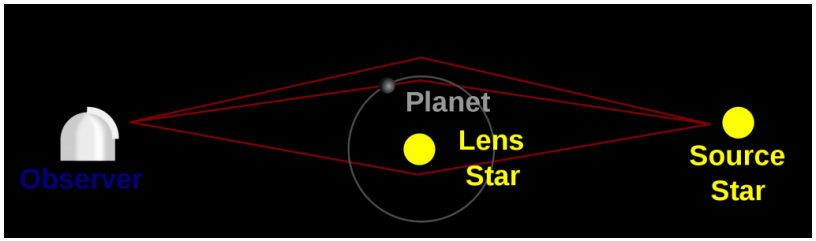
- But mostly large, hot gas giant planets
  - Biggest change in star's speed from big planets close to star



Other Ways a Planet Effects Starlight?

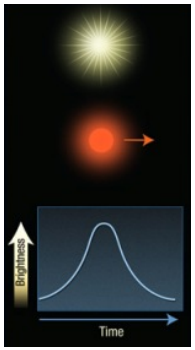
Other Ways a Planet Effects Starlight?

- Gravity bends light



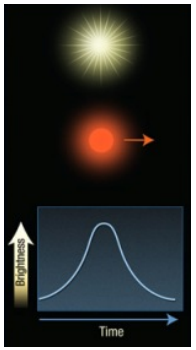
Gravitational Microlensing

- Gravity bends light
- If a star passes in front of a distant star it will focus the light like a lens



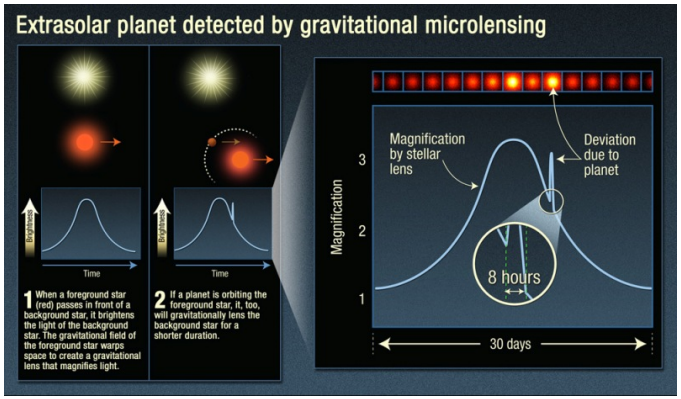
Gravitational Lensing

- Gravity bends light
- If a star passes in front of a distant star it will focus the light like a lens

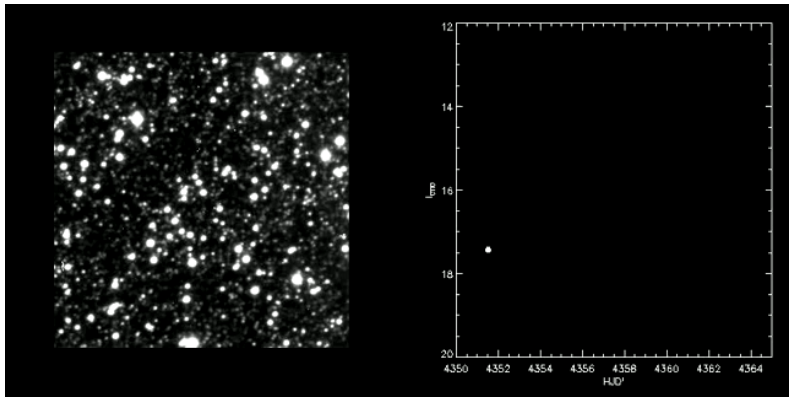


Gravitational Microlensing

- If a planet is aligned just right, it also bends the light creating an extra spike



A Real Microlensing Event

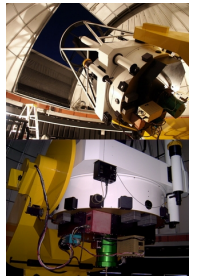


Different from the Doppler Method

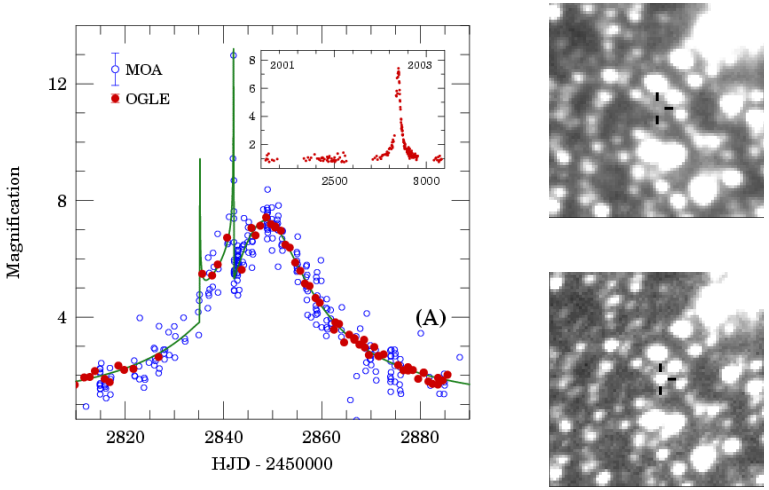
- Gravitational Microlensing does not watch the planet orbit the star
- The lensing happens only when the star and planet together happen to pass exactly in front of a more distant star
  - So it happens only once per planet
- All we can measure this way is the mass of the planet
- Microlensing is rare, so it is difficult to measure how common planets are this way

Finding Microlensing Events

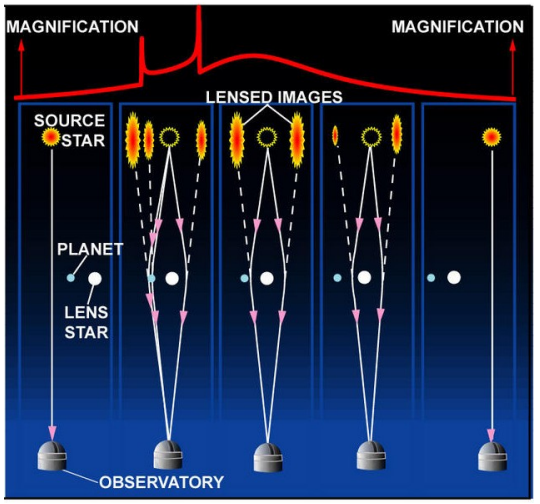
- Use a dedicated telescopes looking at very crowded star fields
  - First planets found by the OGLE project (Andrzej Udalski), based in Poland, using a telescope in Chile



The First Microlensing Planet

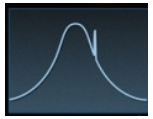


Why the Brightness Has 2 Spikes



Microlensing Results

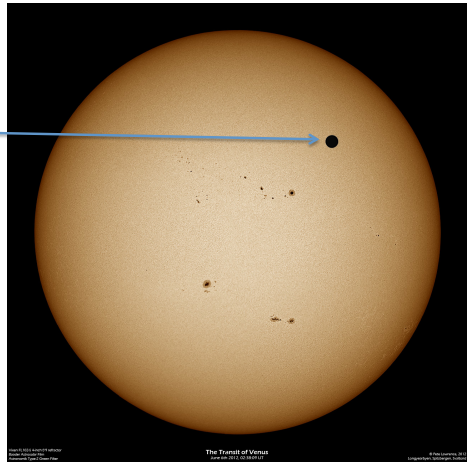
- There are now 5 major microlensing teams watching the sky
- 36 confirmed planets have been discovered, with an assortment of masses
  - A few may be as small as the Earth
  - We know how far they are from their star in a few cases
  - But we only see them once then they're gone



Other Ways a Planet Effects Starlight?

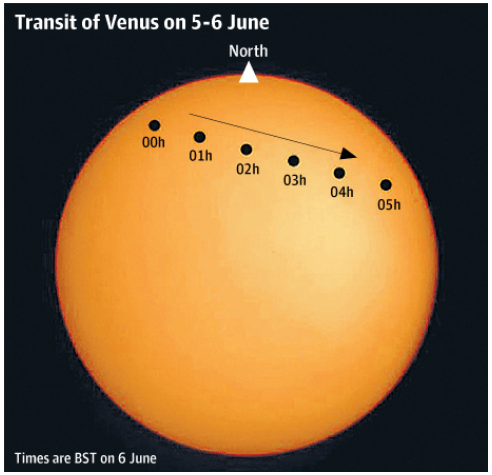
Planetary Transits

- We see Venus and Mercury go in front of the Sun
- Called a *transit*
  - Transit of Venus



Transit of Venus

- Took about 8 hours

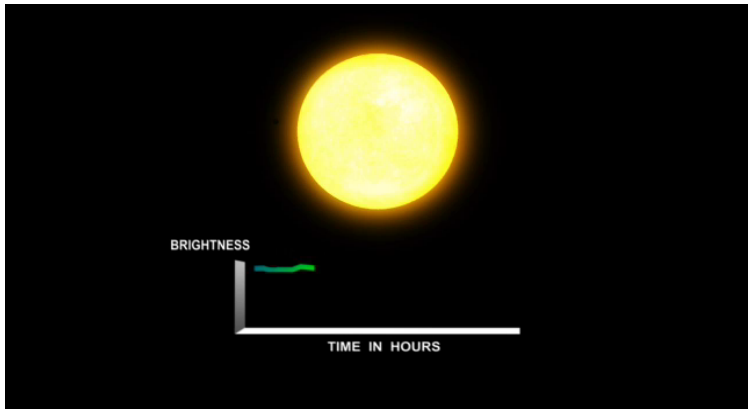


Transiting Exoplanets

- Don't see the disk of the star
  - All we have is the amount of starlight, not an image of the star

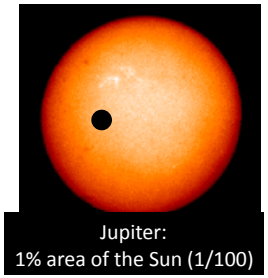
Other Ways a Planet Effects Starlight?

- Measure the brightness of the star as the planet blocks the light

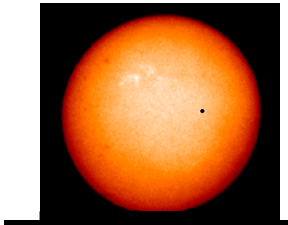


How Much Light Gets Blocked?

- Depends on how much of the area of the star is blocked by the area of the planet
  - Depends on the square of these radii



Jupiter:
1% area of the Sun (1/100)



Earth or Venus
0.01% area of the Sun (1/10,000)

The Planet Needs to Actually Go In Front of the Star

- The orbit must be aligned so that we're viewing it edge on

How Often is a Planet Aligned?

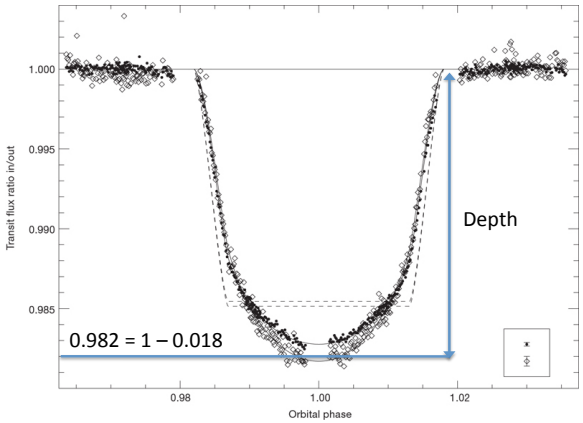
- The orbit must be aligned so that we're viewing it edge on
- If we assume the orbits are randomly aligned, planets closer to their stars are more likely to be aligned
  - 10% for hot Jupiters
  - ½% for Earth-like orbits

How Easy is the Transit Signal to See?

- From Earth it is not too difficult to measure a 1% (Jupiter-size-planet) transit 
- HD 209458 b: First transiting planet detected in 1999 separately by David Charbonneau and George Henry,
  - after this planet was detected (by Geoff Marcy and Paul Butler) using the Doppler method

The Light Curve of HD 209458 b

- Using an Earth Telescope
- About 1.8%, larger than Jupiter



How do we Find Transiting Exoplanets

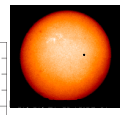
- If every star has a planet
  - only 10% of them will transit if they are hot jupiters
  - Only ½% of them will transit if they are in Earth-like orbits
- So look at lots of stars
  - Collection of robot telescopes

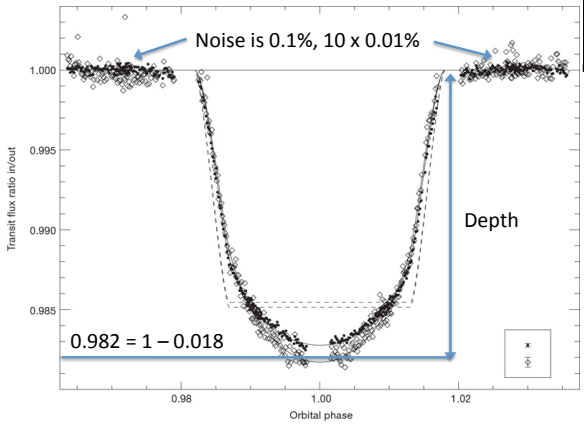
Transits Found With Earth Telescopes

- 227 confirmed transiting planets
- Almost all large in small orbits
  - We can only see large transits from Earth
  - One planet about 2.5 times size of Earth
- Several multiple-robot-telescope projects underway

Deep, 1% Transits From Earth are Easy

- But 0.01% (Earth-size planet) is a very different story



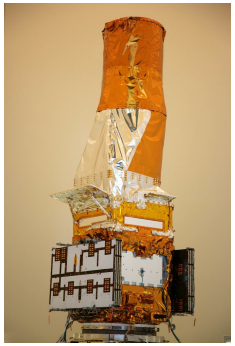


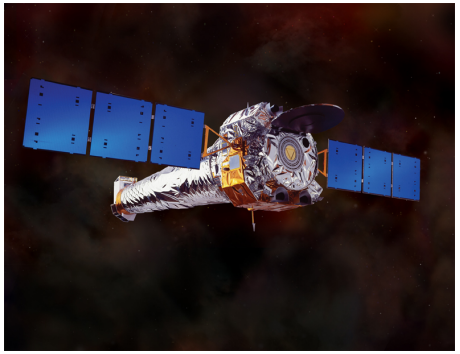
Earth is a Bad Place to Look for Transits

- Noise sources
  - Atmosphere
  - Temperature variations (day-night cycle)
- Length of observation is wrong
  - Earth-orbit transit is 13 hours
    - But night is about that long or shorter
- So go to Space!

First Transit Search From Space

- CoRot (Convection Rotation and Transits)
  - Designed to both detect transiting planets and measure properties of stars



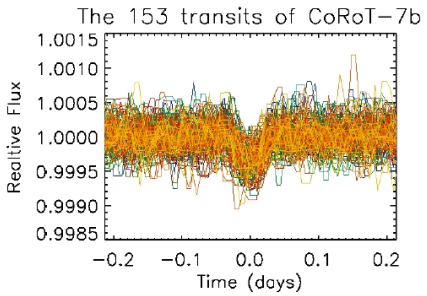


CoRot

- Small (27 cm), wide field telescope
- Launched in 2006, into a low Earth orbit
  - Looks at stars for a few weeks at a time
  - Still suffers from a day-night cycle
- Originally intended as a 2.5-year mission
  - Lasted 6 years, until November 2012

CoRot discoveries

- 28 confirmed planets
  - Several hundred candidates
  - Still mostly large in small orbits
- Smallest planet: CoRot-7b
  - 1.5 time Earth radius
  - 0.8 day period
    - Hot!!



Go Deeper Into Space

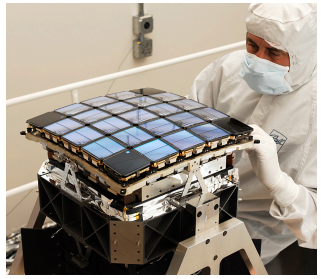
- A space telescope specifically designed to find Earth-size transiting planets in Earth-like orbits
  - Get away from the Earth
    - Into orbit around the Sun
    - Look at the same stars for many years
  - Use a larger telescope
    - Collecting more light reduces the noise
    - Use a wide field to capture many many stars at the same time

Kepler History

- First proposed: 1983
  - Bill Borucki
- "It Won't Work": 1983 – 1995
  - Not accurate enough, too much noise
- Lab tests show it will work: 1995
- Convincing more people: 1995 – 2001
- Selected!! 2001
- Begin construction: 2002
- Hire lots of people: 2002 – 2008
- Launch: 2009

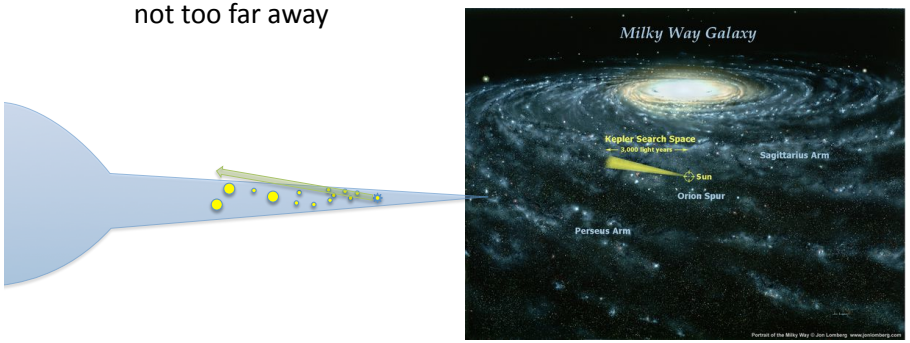
Kepler's Strategy

- Watch 160,000 to 170,000 stars (almost) nonstop for 3.5 years
  - 0.5% of 160,000 = 800 stars
    - But we don't know which ones
  - Need a wide field of view
    - 0.95 meter Schmidt camera
    - 100 square degrees of the sky (!)
    - 96 million pixels on 21 modules
  - Need fantastic stability
    - In space, orbiting the Sun
      - Earth orbit is too noisy

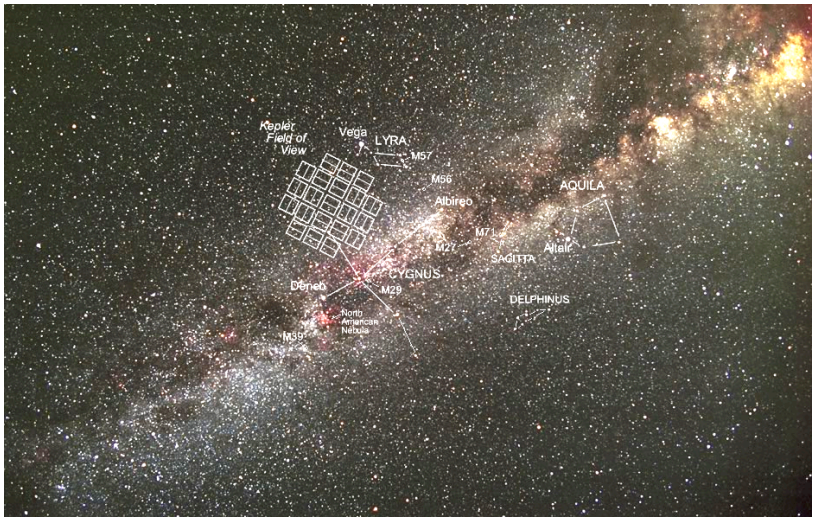


Where to Look?

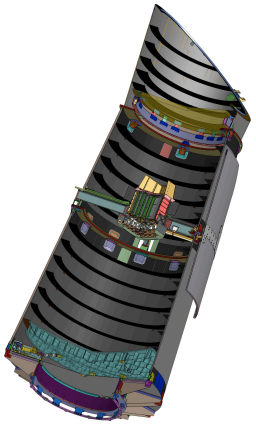
- Want lots of Sun-like stars
  - But only know the color of stars
  - Nearby yellow dwarf (Sun-like) stars look the same as distant yellow giant (not Sun-like) stars
- Solution: look a little above the Milky Way so most stars are not too far away



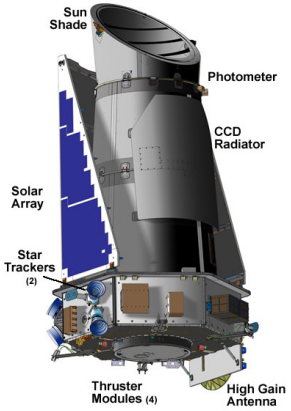
Where to Look?



Kepler's Design



Telescope (Photometer)



Telescope and Spacecraft

Wrapped and Ready to Go!