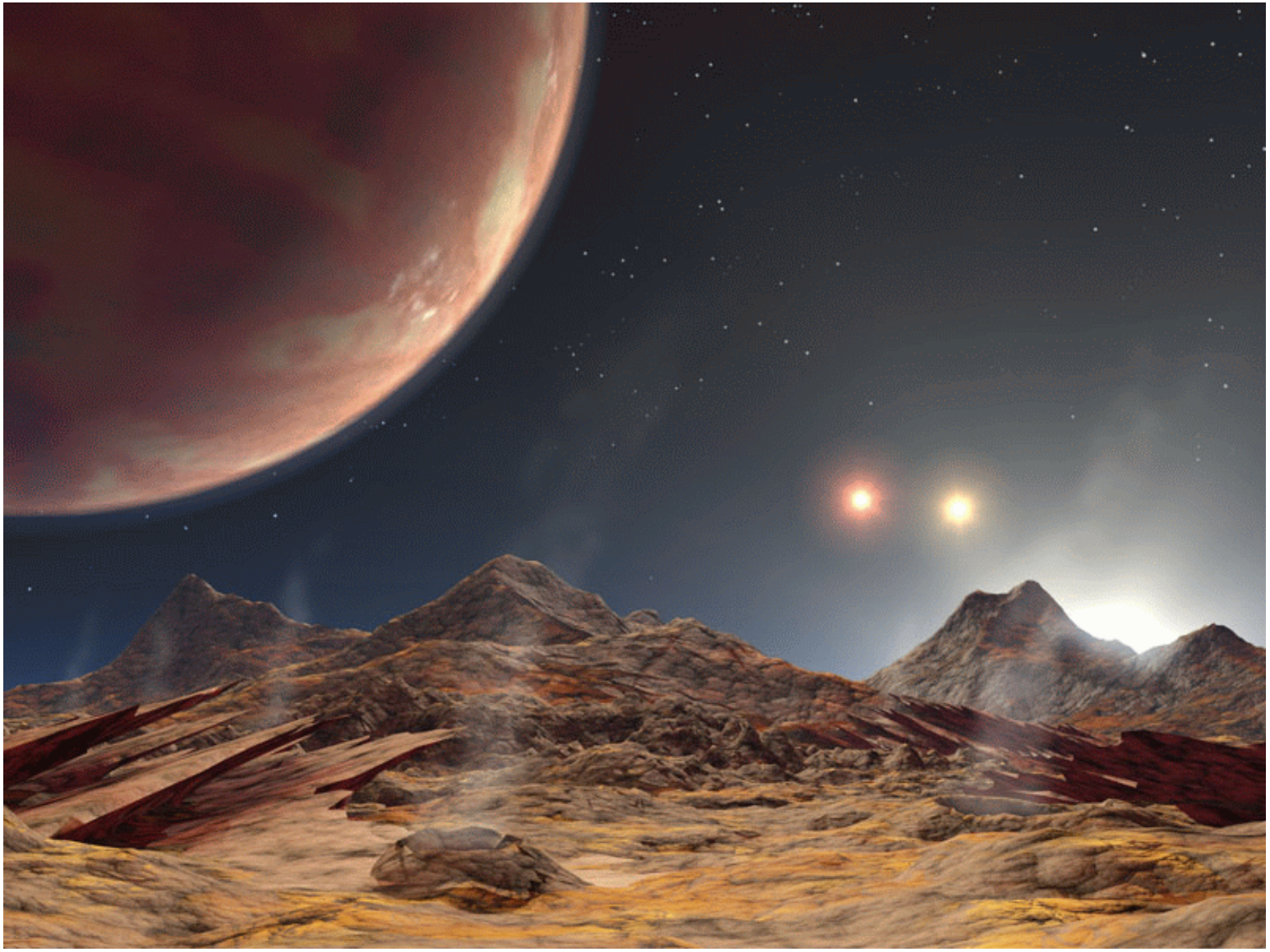


“Sometimes I think we're alone. Sometimes I think we're not. In either case, the prospect is staggering!”

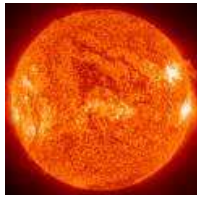
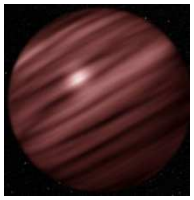
Arthur C. Clarke

What We Will Learn Today

- How do we detect planets around other stars?
- How do the different techniques work?
- Which technique(s) have been the most effective to-date?
- How will we search for Earth-like planets?

Planets Around Other Stars

- "Extra-solar planets" or "Exoplanets"
- The Copernican revolution raised the question of whether planets orbit other stars
- But, what is a planet?
  - The IAU only defined a planet in our Solar System
  - We do not have a current definition of a planet in general!
- Stars
  - Fuse Hydrogen in their core during their Main Sequence phase
  - At least 80 M_{Jup}
- Brown Dwarfs
  - Fuse Deuterium or Lithium in their core
  - At least 13 M_{Jup}
- Planets
  - Below ~ 13 M_{Jup}
  - Orbit a star

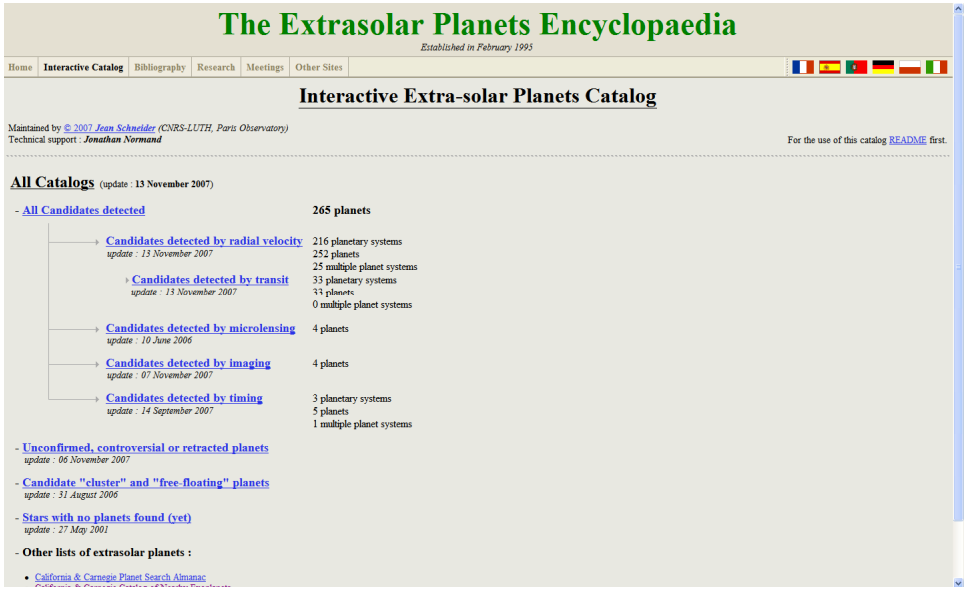
Detecting Exoplanets is Hard

- If we lived on a planet around a nearby star, say about 10 light years away
  - Only 11 known stars are within 10 ly from the Sun
  - The Sun would be visible to the naked eye as a star
  - Earth would be
    - 0.00003 arcsec in size
      - 0.5 mm pencil tip held over 2000 miles away!
    - 0.3 arcsec away from the Sun
      - 0.5 mm pencil tip held over 2 miles away
    - Less than a billionth as bright as the Sun
  - Jupiter would be
    - 0.0003 arcsec in size
      - 0.5 mm pencil tip held over 200 miles away!
    - 1.5 arcsec away from the Sun
    - About a billionth as bright as the Sun
- Planets are very hard to see next to their bright stars

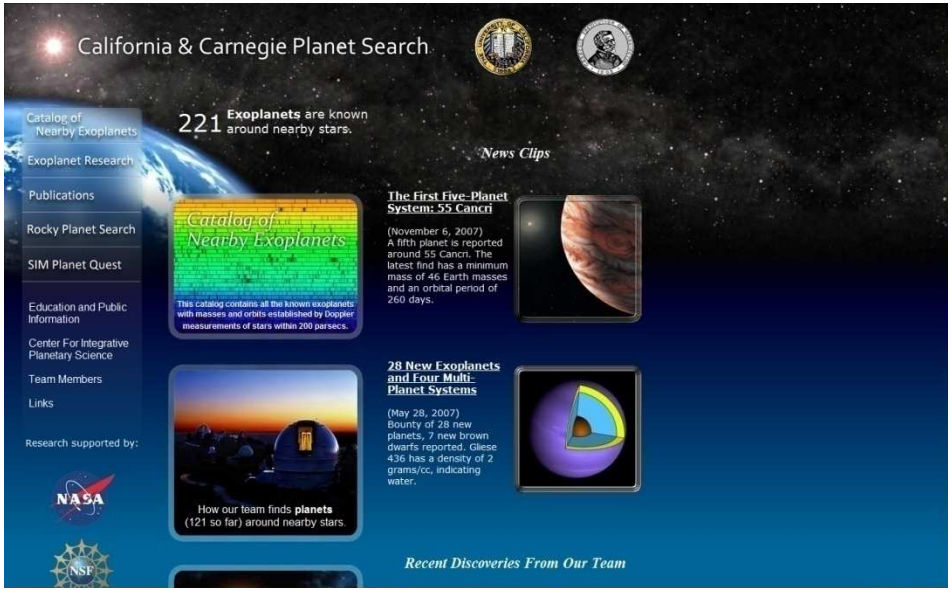
Discovery of an Exoplanet

- Announcement of exoplanet discovery
  - October 6, 1995
  - Michel Mayor and Didier Queloz
  - Independently confirmed soon after by Geoffrey Marcy & Paul Butler
- Star: 51 Pegasi
  - 50 light years away
- Since then, over 200 planets have been discovered

http://exoplanet.eu



http://exoplanets.org



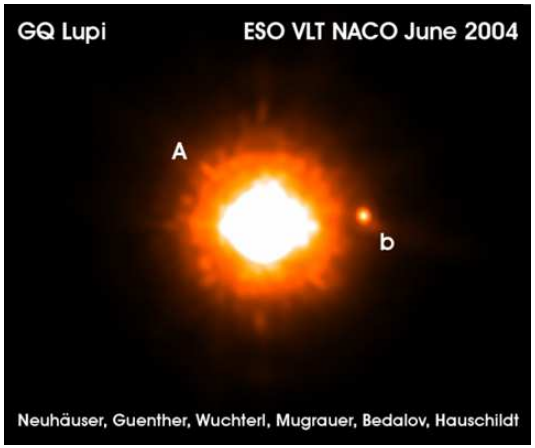
Exoplanet Detection Techniques

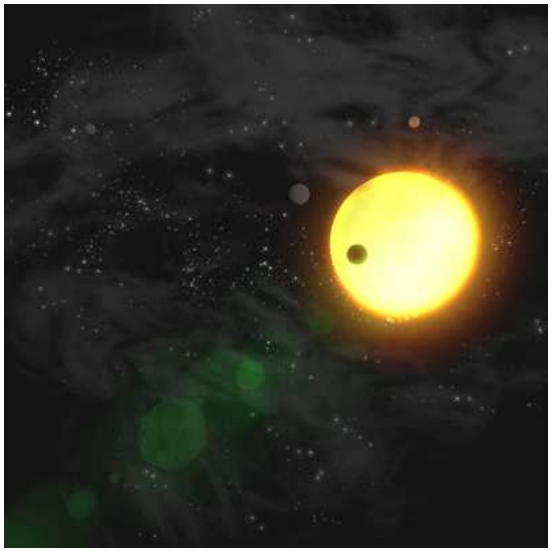
Indirect methods:

- Radial Velocity
- Transits
- Astrometry
- Pulsar Timing
- Microlensing

Direct methods:

- Direct imaging





The Clue: Planets Make Stars Wobble

- Center of Mass
  - The Earth goes around the Sun
  - The Moon goes around the Earth

Not quite!

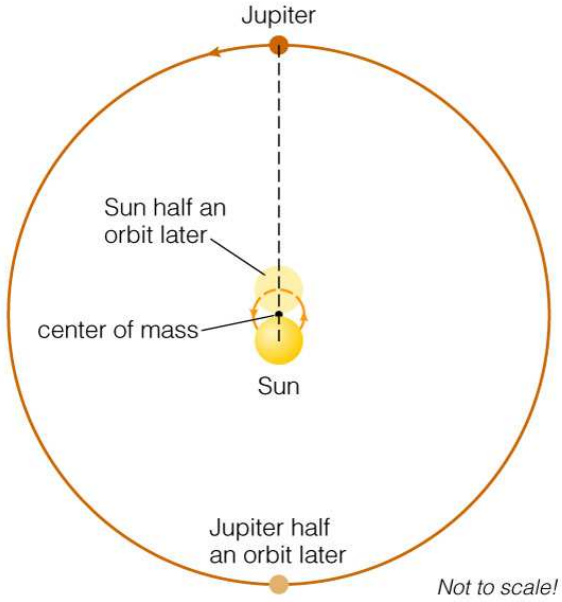


Fig 13.1

- Most methods infer the presence of planets by detecting stellar wobble

This can be detected! →

Earth around Sun: 30 km/s

Jupiter around Sun: 13 km/s

Sun, due to Earth: 0.1 m/s

Sun, due to Jupiter: 13 m/s

The Clue: Planets Make Stars Wobble

- Center of Mass
  - The Earth goes around the Sun
  - The Moon goes around the Earth

Not quite!

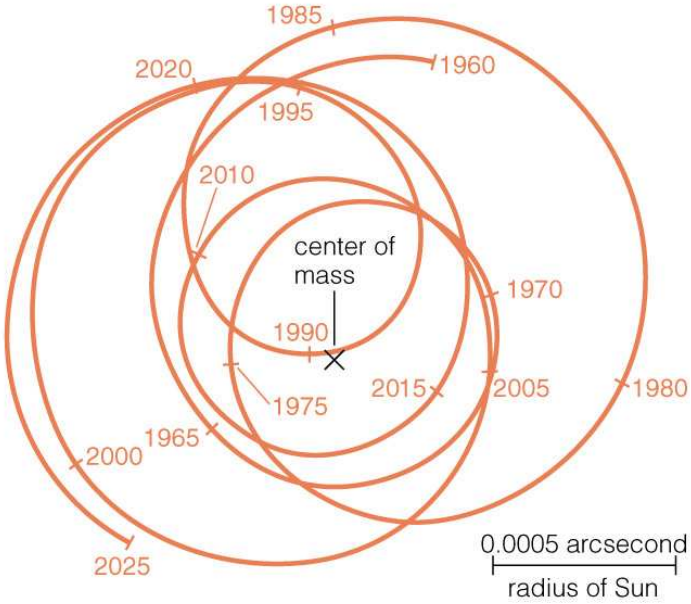


Fig 13.2

- Most methods infer the presence of planets by detecting stellar wobble

This can be detected! →

Earth around Sun: 30 km/s

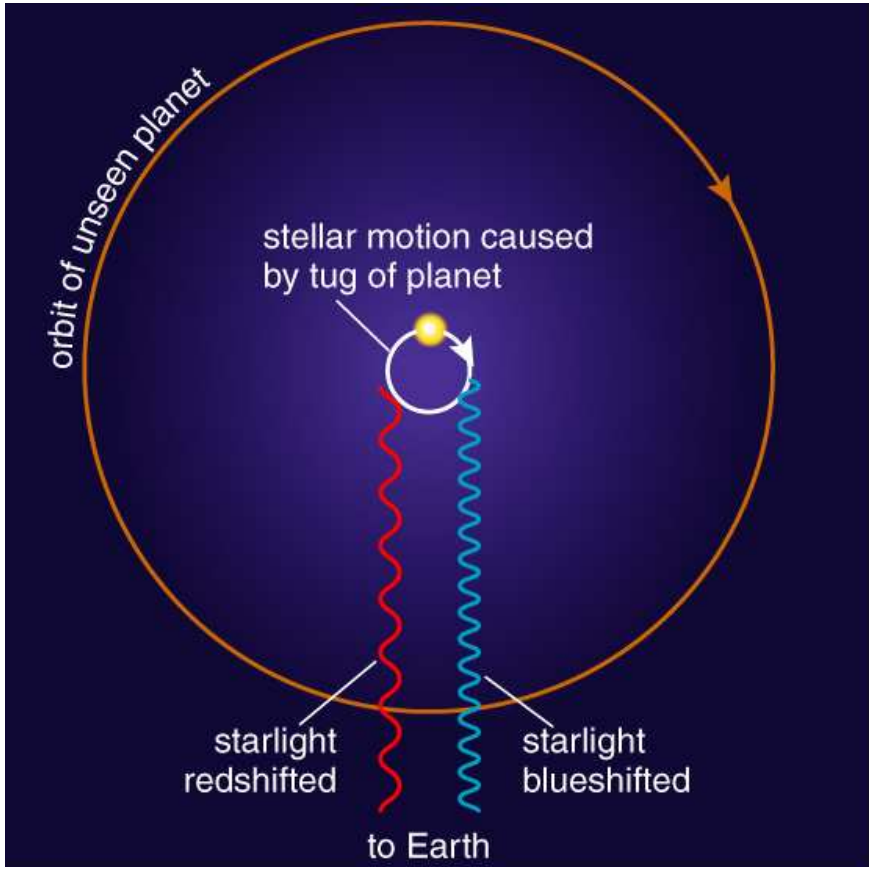
Jupiter around Sun: 13 km/s

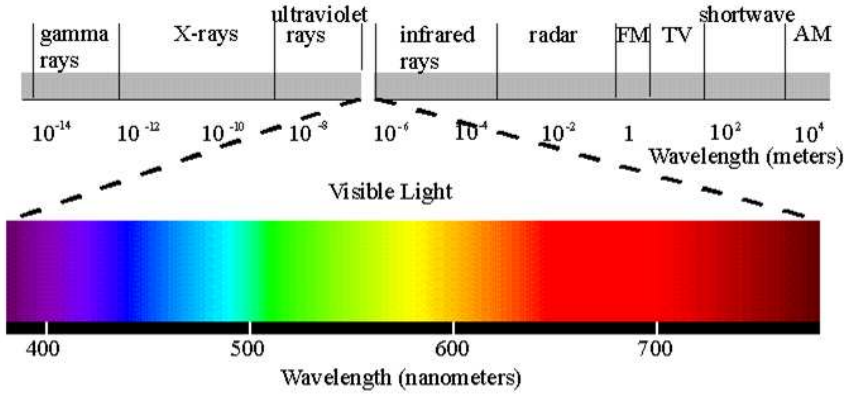
Sun, due to Earth: 0.1 m/s

Sun, due to Jupiter: 13 m/s

Radial Velocity: The Doppler Effect

- Measure the star's velocity toward or away from Earth





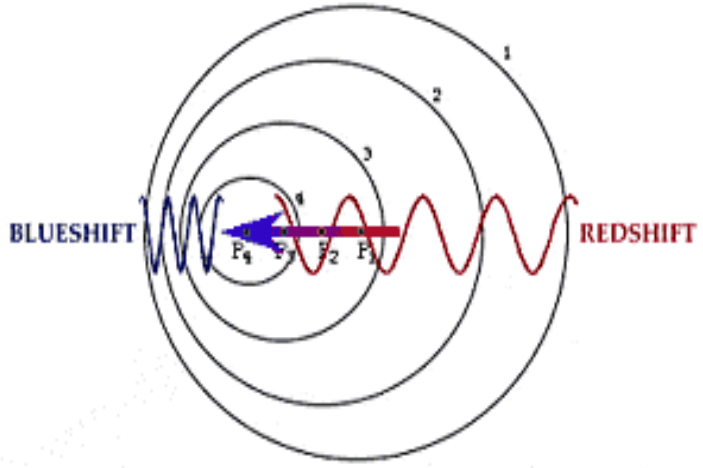
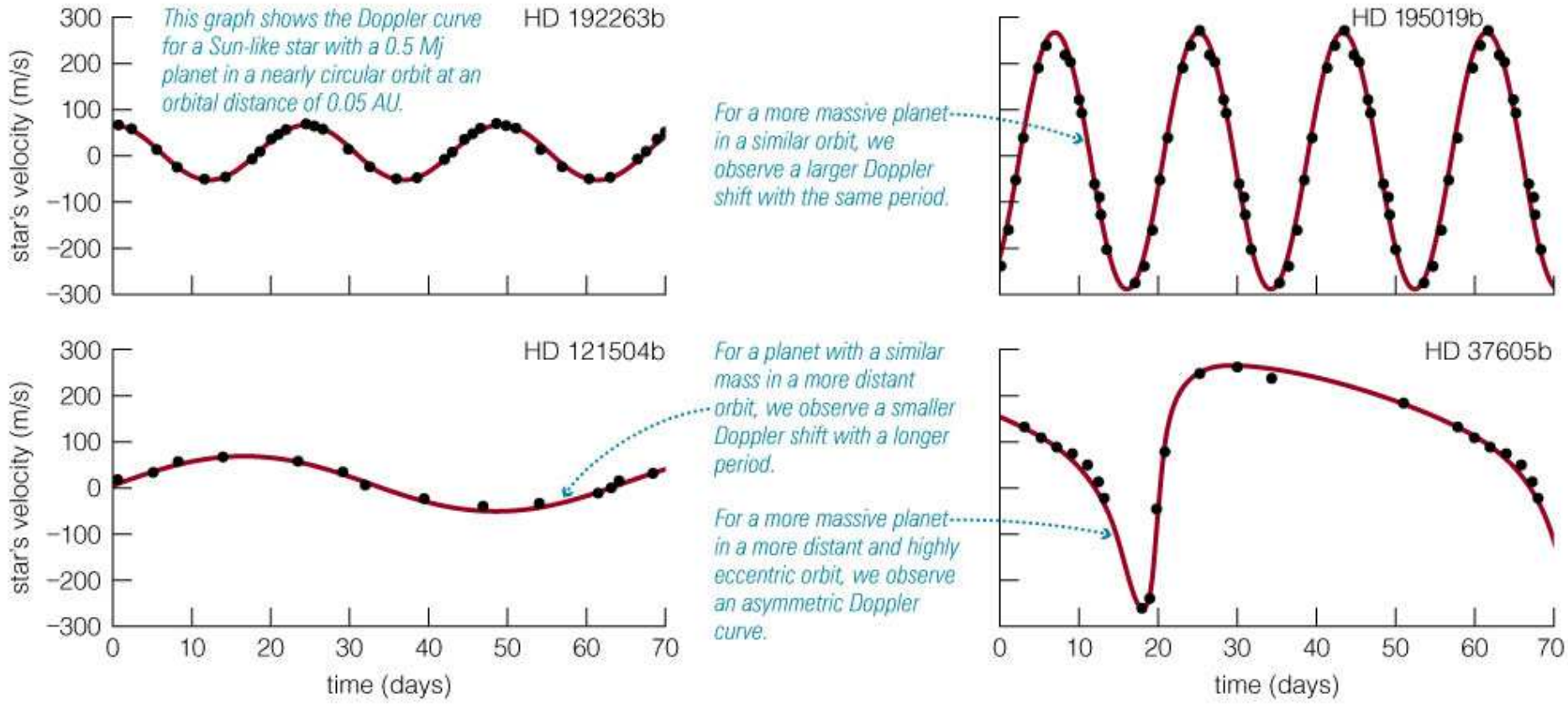


Fig 13.3 a

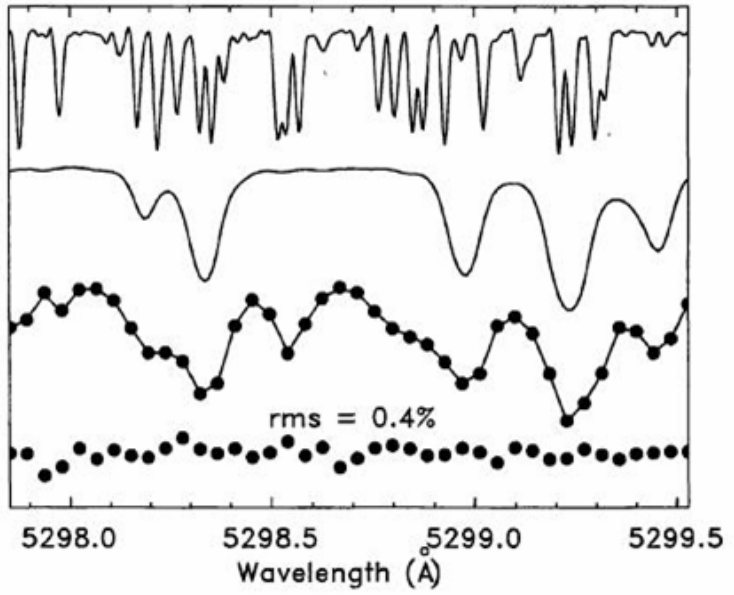
Stellar RV Leads to Planet Info



© 2006 Pearson Education, Inc., publishing as Addison Wesley

Radial Velocity: Summary

- Spectroscopy is used to measure Doppler shifts
- Most productive method so far
  - 95% of all planets detected
- All are giant planets, down to about Neptune's masses
- Needs a fairly inclined system
- Requires a very fine-tuned process to detect planets
  - Specialized field (3 m/s precision)
  - Dedicated long-term surveys
- Can only obtain minimum companion mass
  - How many "planets" are actually stellar companions?



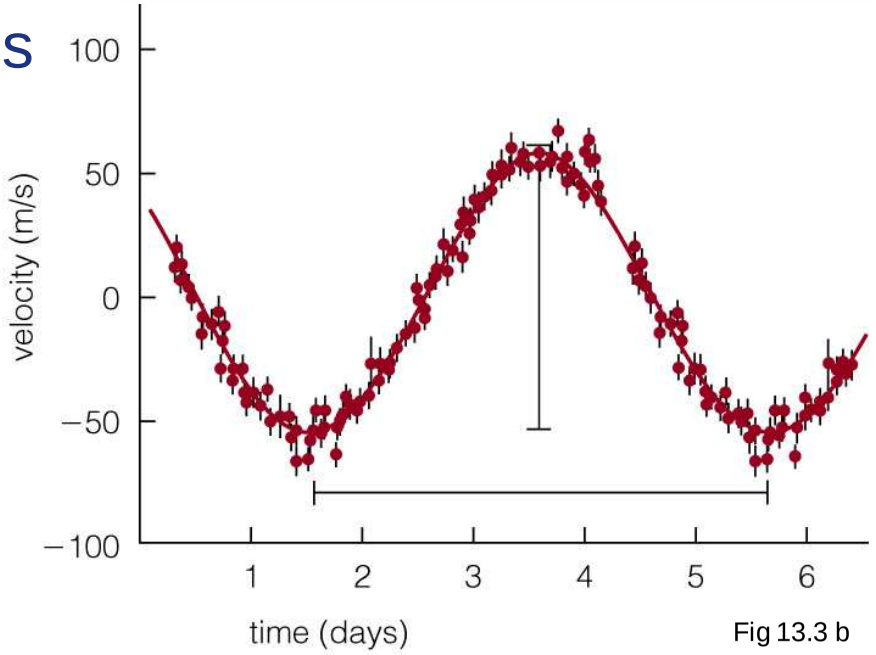
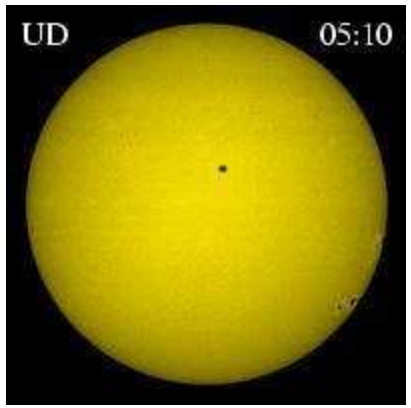


Fig 13.3 b

Transits

- Remember any Mercury or Venus transit events?
- Photometry is used to measure change in stellar brightness as the planet passes in front



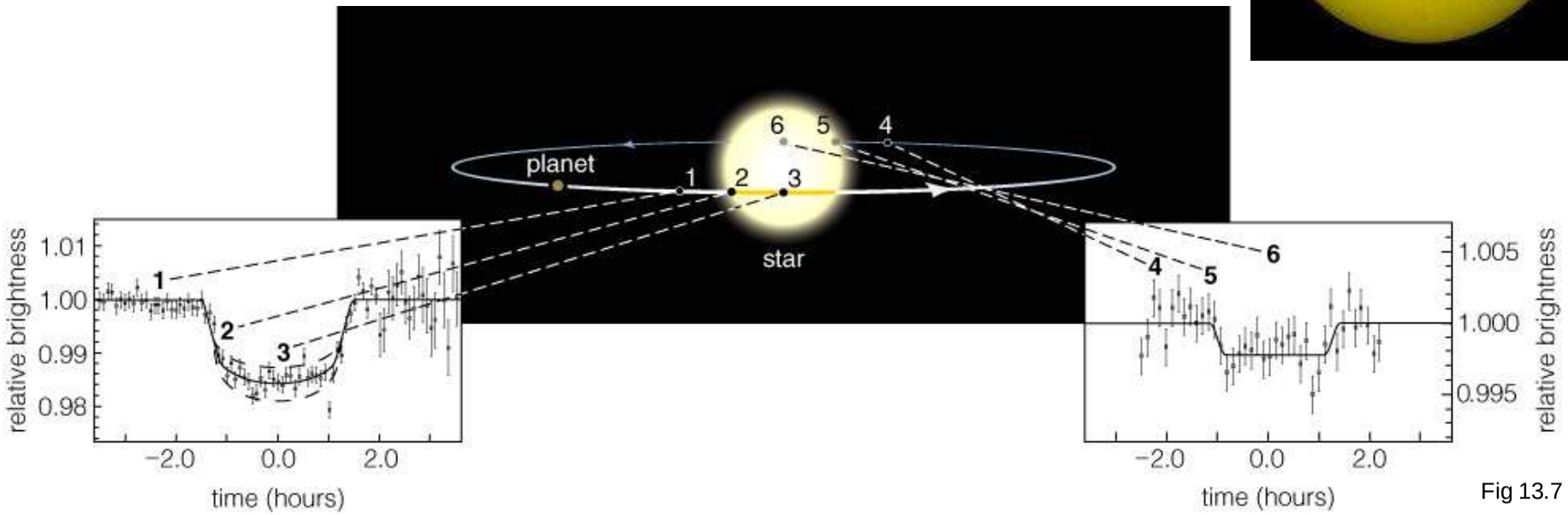


Fig 13.7

Transits: Pluses & Minuses

- Advantages
  - Can get lots of information
    - Radii
    - Inclination
    - Eccentricity
  - Can probe planetary atmospheres!
- Disadvantages
  - Favors close-in planets, or very inclined orbits
  - Hard to do, specialists required
  - Systems detected can be far, follow-up observations difficult
- Future
  - NASA's Kepler Mission
  - Launch: February 2009
  - Will detect Earth-sized planets!

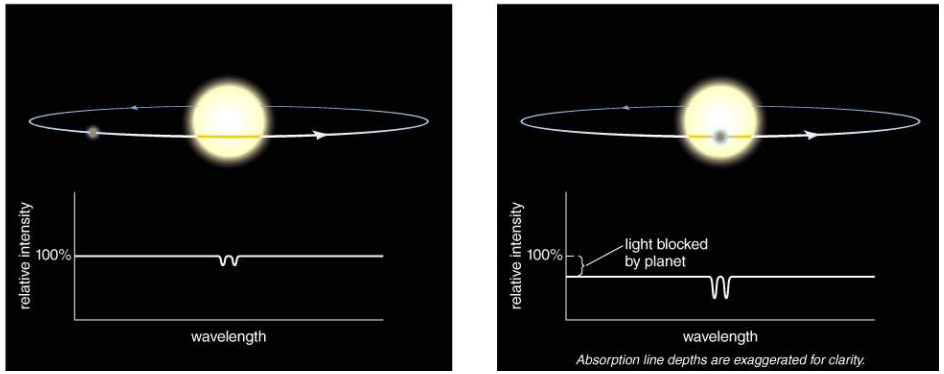
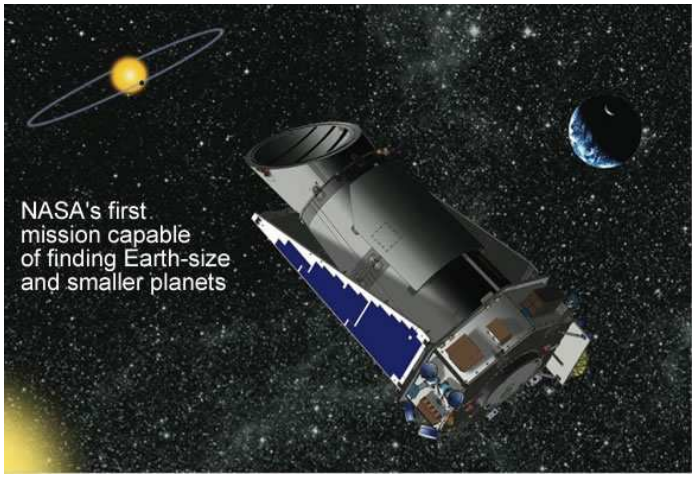
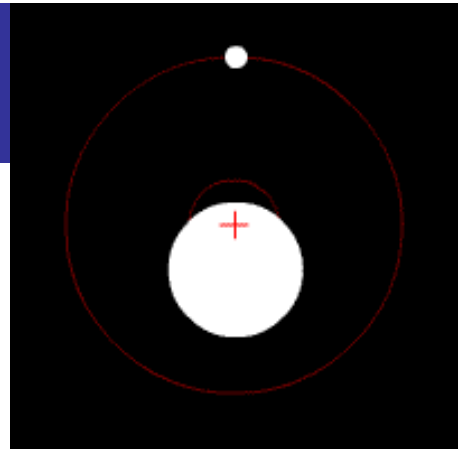


Fig 13.8

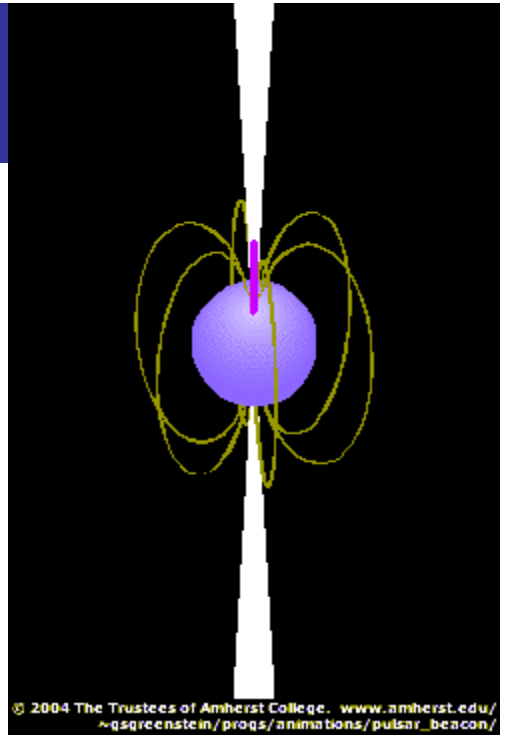


Astrometry



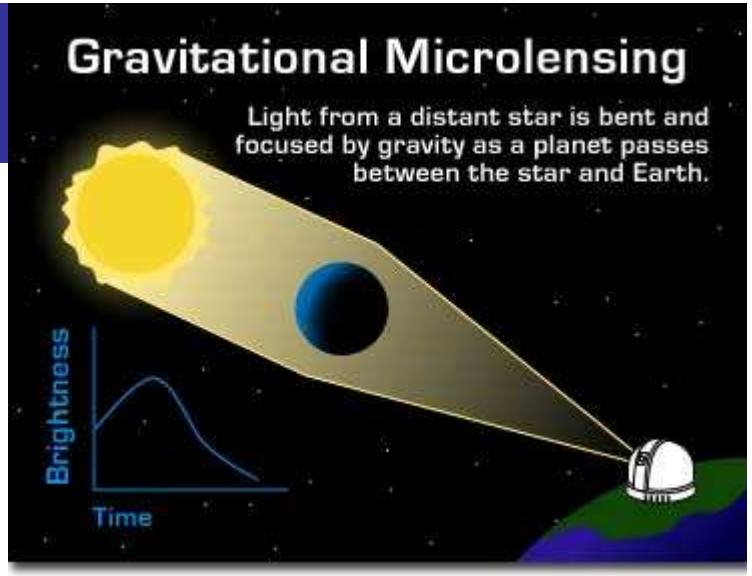
- Precise location of stars
- Detect star's wobble in plane of sky
- Advantages:
  - Works for all inclinations
  - Can get all orbital parameters, including inclination and masses!
- Disadvantages:
  - Incredibly hard to do: space-based interferometry
  - Works well only for nearby systems
- Future
  - NASA SIM Planet Quest mission?
  - Few ***micro***-arcsecond resolution!
  - Can detect nearby Earths

Pulsar Timing

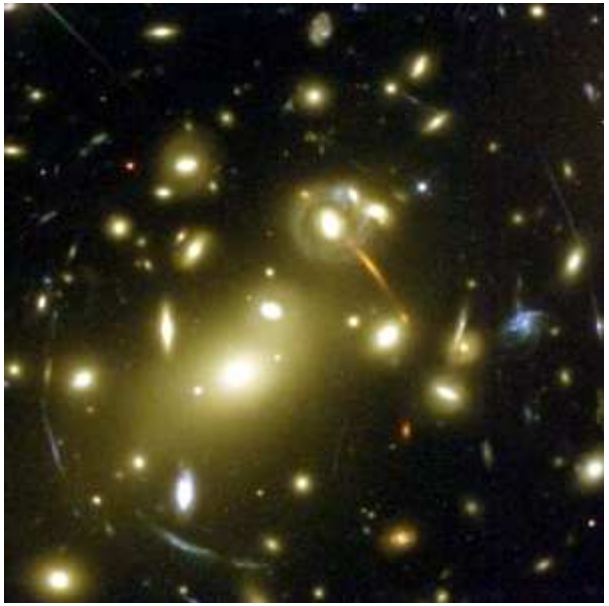


- Pulsars are truly incredible objects
  - Formerly heavyweight, now dead stars
  - Atoms crushed by gravitational force!
  - Size of a city, mass of the Sun!
  - One teaspoonful weighs a billion tons!
  - Very strong magnets 10^{14} G, Earth's is ½!
- Beacons into space
- Best clocks in the universe
- Planets detected by small variations in timing
- First planets found outside solar system (1994)
- Planets formed after star died!

Microlensing

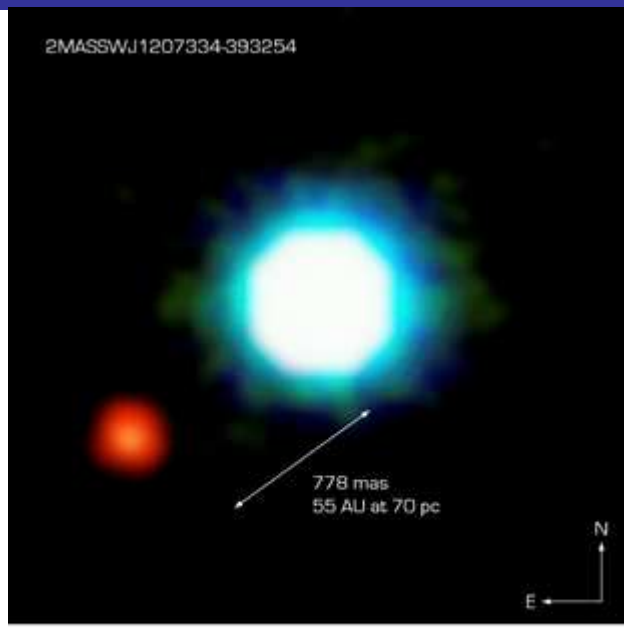


- Gravity bends light
  - Made Einstein famous
- Advantage
  - Can detect Earth-mass planets
- Disadvantages
  - Requires a rare chance alignment
  - Not repeatable
  - Detected planets are typically very far
    - Follow-up observations difficult
- Only a few found so far



Direct Imaging

- Very hard to do
- Four found so far
- Works best for young, hot, massive planets around wimpy stars
- Lucky finds versus an organized search



The Brown Dwarf 2M1207 and its Planetary Companion (VLT/NACO)

ESO PR Photo 14a/05 (30 April 2005) ©ESO