



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

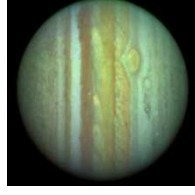
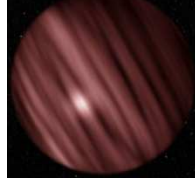
Arthur C. Clarke

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 $80 M_{\text{Jup}}$
- Brown Dwarfs
 - Fuse Deuterium or Lithium in their core
 - At least $13 M_{\text{Jup}}$
- Planets
 - Below $\sim 13 M_{\text{Jup}}$
 - 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://exoplanets.org>

The Extrasolar Planets Encyclopaedia
Established in February 1993

Maintained by © 2007 Jean Schneider, CNRS-LUTH, Paris Observatory
Technical support : Jonathan Norwood

For the use of this catalog [READ THE FILE](#)

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Interactive Extra-solar Planets Catalog

All Catalogs (update: 13 November 2007)

- **All Candidates detected**
 - 265 planets
 - 216 planetary systems
 - 255 planets
 - 13 multiple planet systems
 - 33 planetary systems
 - 11 planets
 - 0 multiple planet systems
- **Candidates detected by radial velocity**
 - update: 13 November 2007
 - > Candidates detected by transit
 - update: 13 November 2007
- **Candidates detected by microlensing**
 - update: 10 June 2006
 - 4 planets
- **Candidates detected by imaging**
 - update: 07 November 2007
 - 4 planets
- **Candidates detected by timing**
 - update: 14 September 2007
 - 3 planetary systems
 - 1 planet
 - 1 multiple planet systems

- **Unconfirmed, controversial or retracted planets**
update: 06 November 2007

- **Candidate "cluster" and "free-floating" planets**
update: 31 August 2006

- **Stars with no planets found (yet)**
update: 27 May 2001

- **Other lists of extrasolar planets :**

- California & Carnegie Planet Search, Abasco

California & Carnegie Planet Search

221 Exoplanets are known
117 around nearby stars.

Catalog of Nearby Exoplanets
This catalog contains all known exoplanets with radial velocity and/or transit measurements of stars within 200 parsecs.

The First Five-Planet System: 55 Cancri
(November 6, 2007)
A fifth planet is reported around 55 Cancri, the nearest multi-planet system. The new planet has a minimum mass of 46 Earth masses and an orbital period of 260 days.

20 New Exoplanets Discovered in Multi-Planet Systems
(Nov. 29, 2007)
A bounty of 28 new planets, 7 new brown dwarfs reported. Gas giants are about 2 grams ice, indicating water.

How Our Team Finds Planets
(121 100 days around nearby stars)

Recent Discoveries From Our Team

Research supported by: NASA, NSF

Team Members: Links

Education and Public Information: Center for Integrative Planetary Science

Publications: Rocky Planet Search, SIM Planet Quest

Exoplanet Research: Catalog of Nearby Exoplanets

News Clips

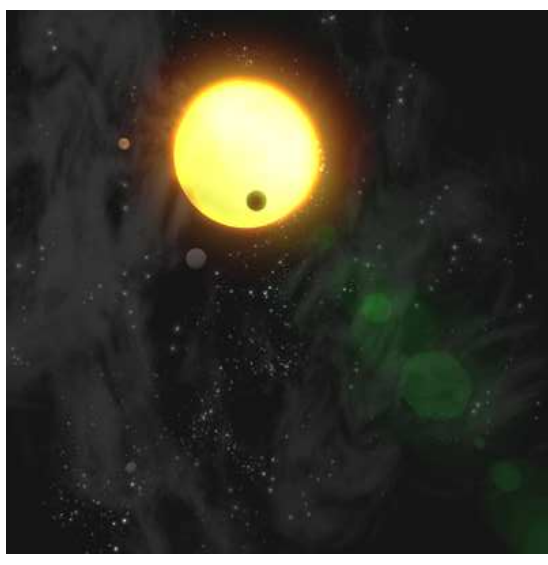
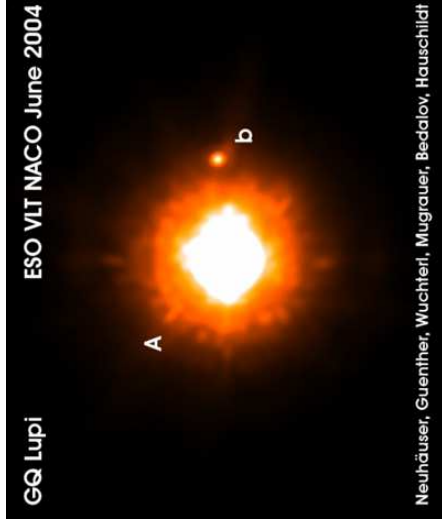
Exoplanet Detection Techniques

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 $\propto$ around the Earth

Not quite!

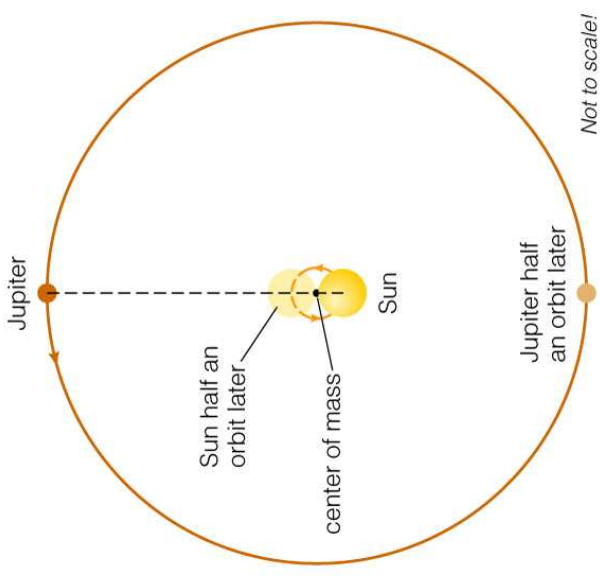
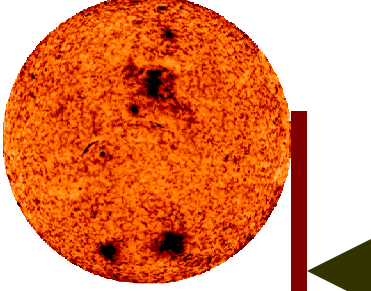


Fig 13.1

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

Earth around Sun: 30 km/s

Jupiter around Sun: 13 km/s

Sun, due to Earth: 0.1 m/s

This can be detected! $\longrightarrow$ Sun, due to Jupiter: 13 m/s

The Clue: Planets Make Stars Wobble

- Center of Mass
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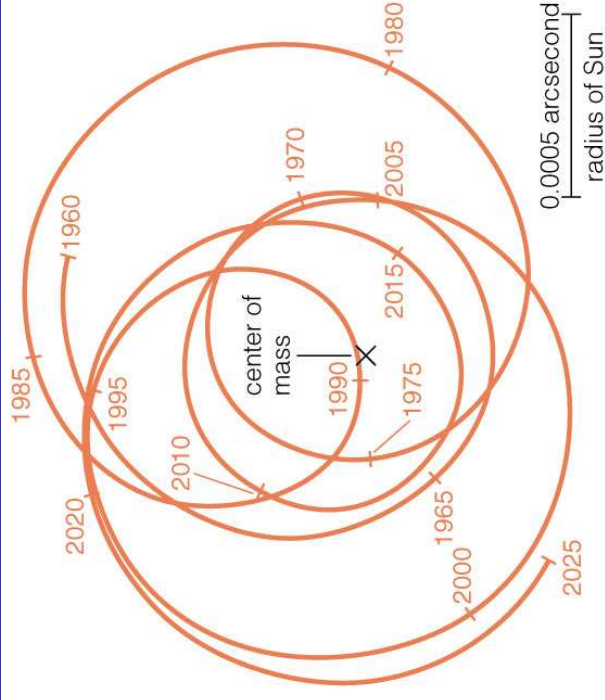
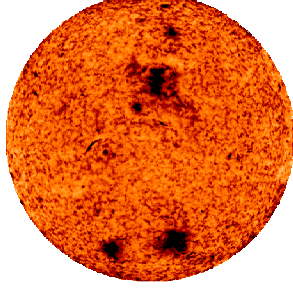


Fig 13.2

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

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

This can be detected! 

Radial Velocity: The Doppler Effect

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

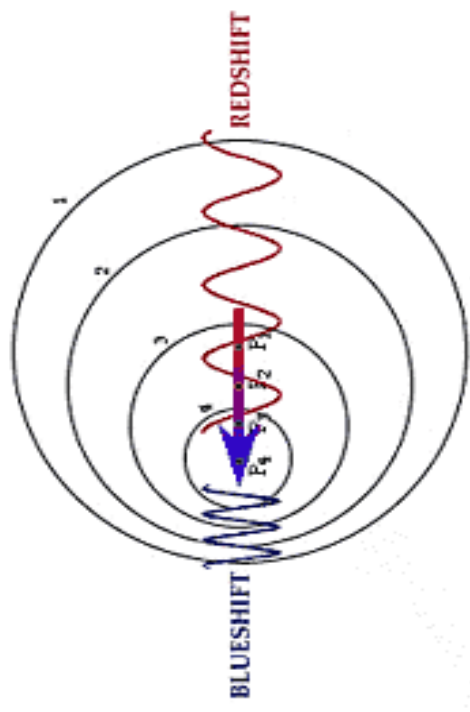
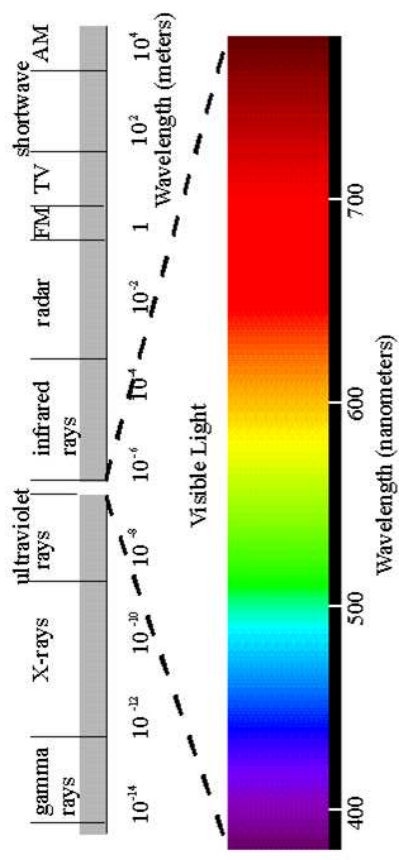
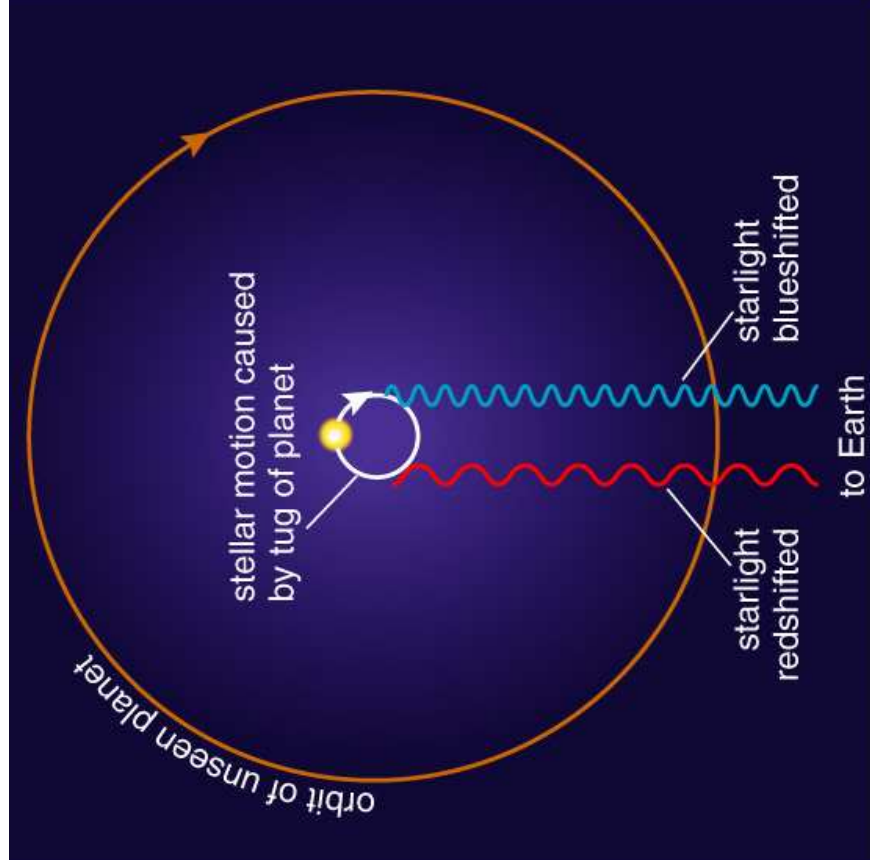
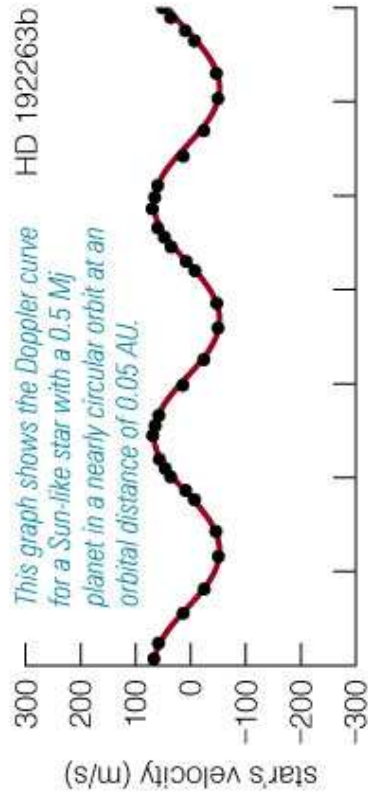
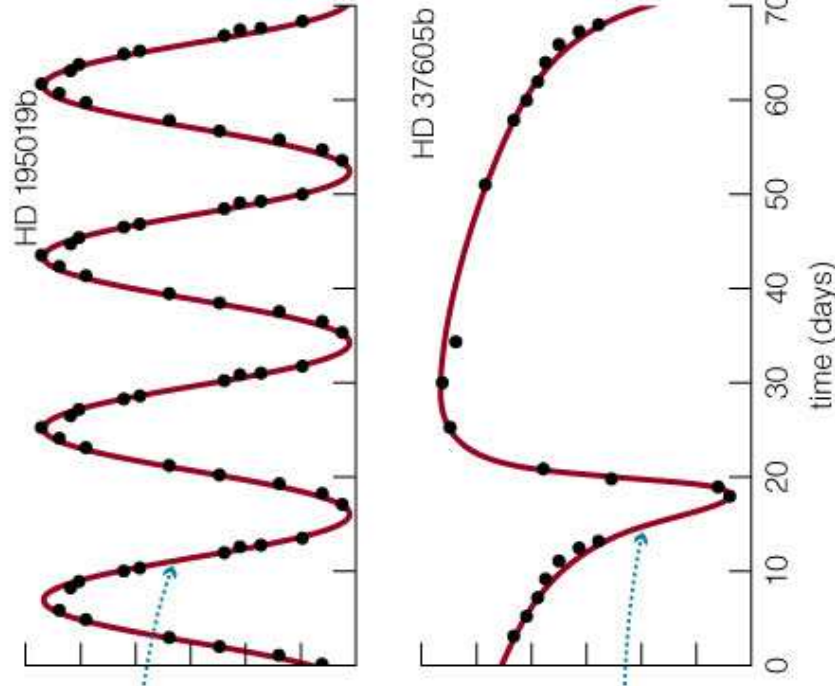


Fig 13.3 a

Stellar RV Leads to Planet Info

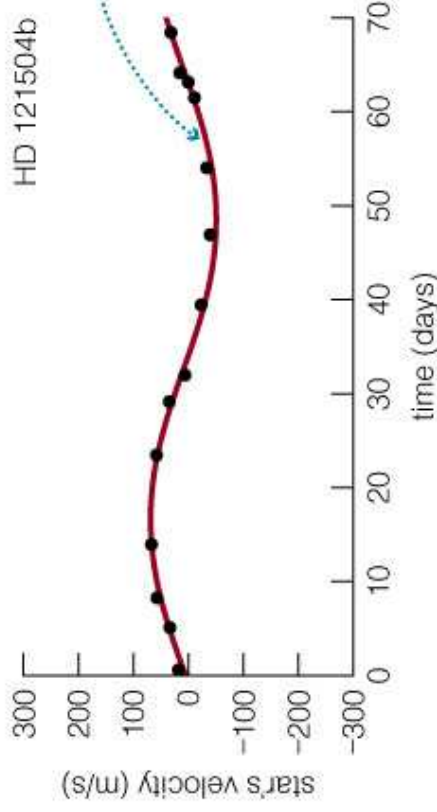


For a more massive planet... in a similar orbit, we observe a larger Doppler shift with the same period.



For a planet with a similar mass in a more distant orbit, we observe a smaller Doppler shift with a longer period.

For a more massive planet... in a more distant and highly eccentric orbit, we observe an asymmetric Doppler curve.



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?

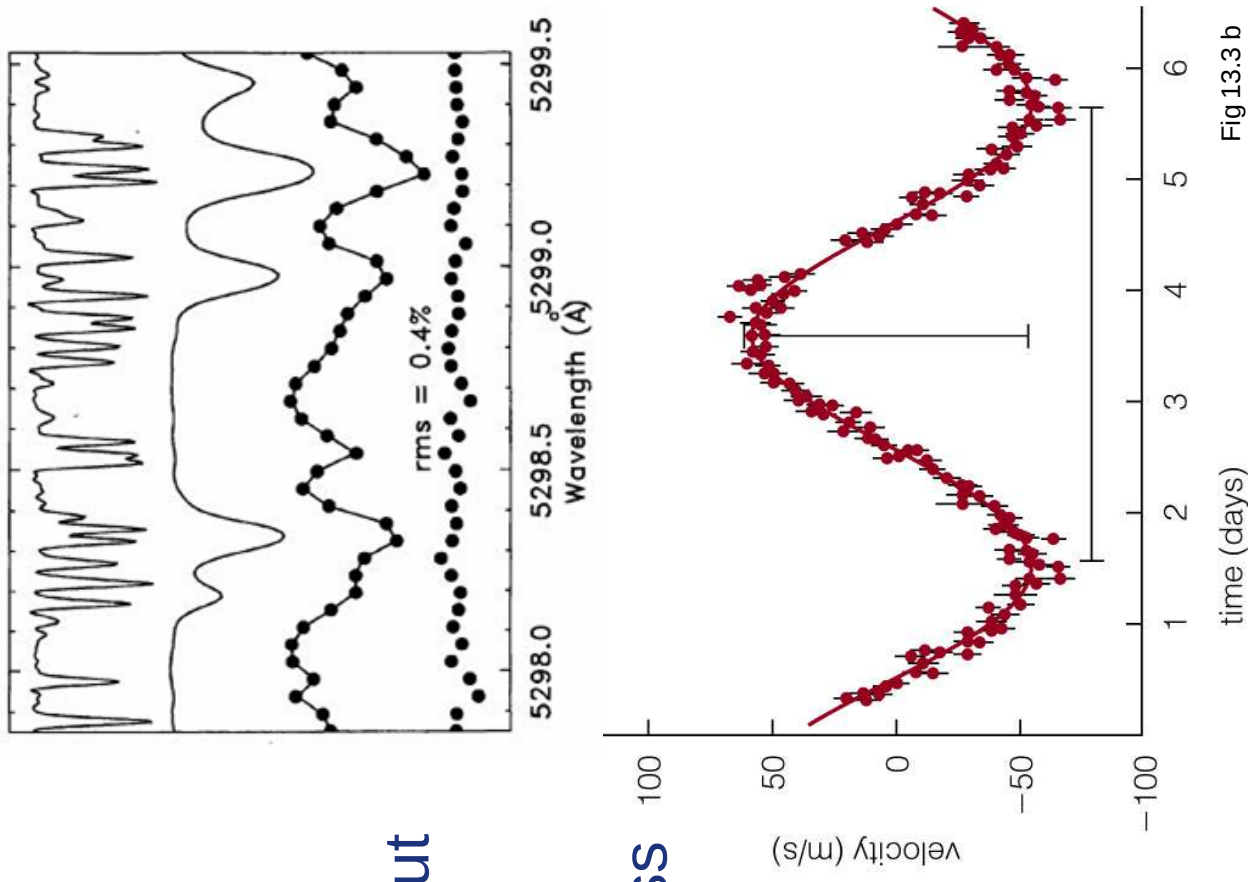
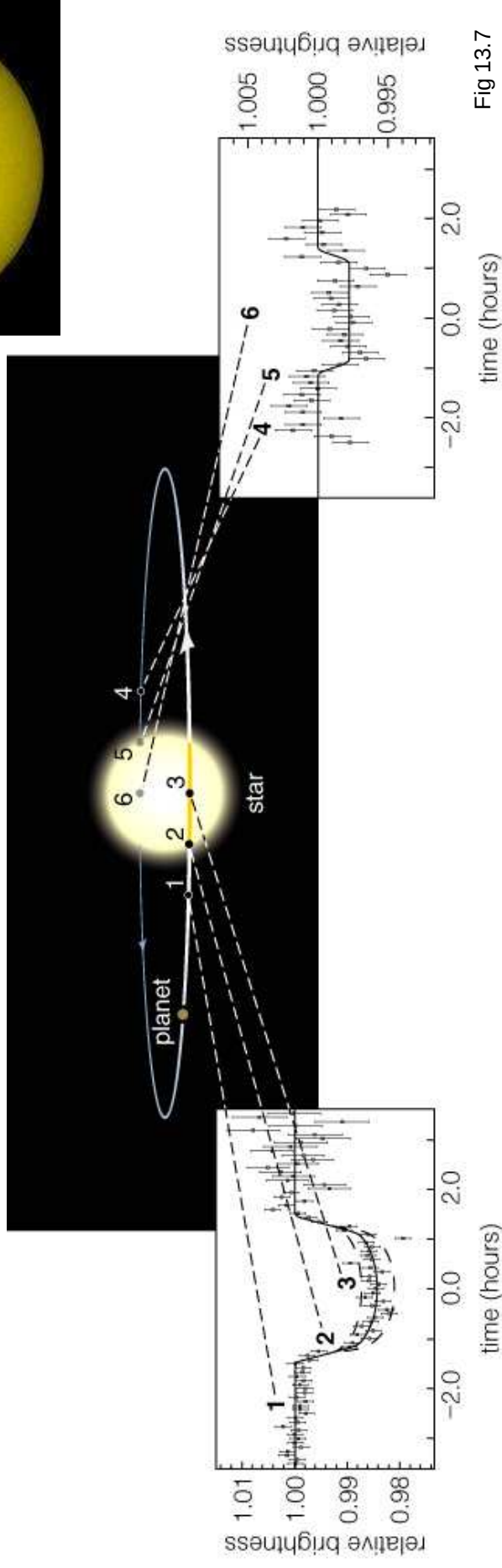
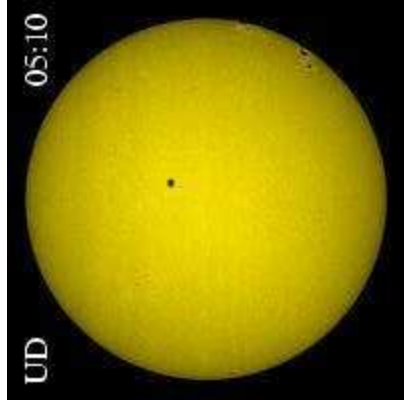


Fig 13.3 b

Transits

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



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!

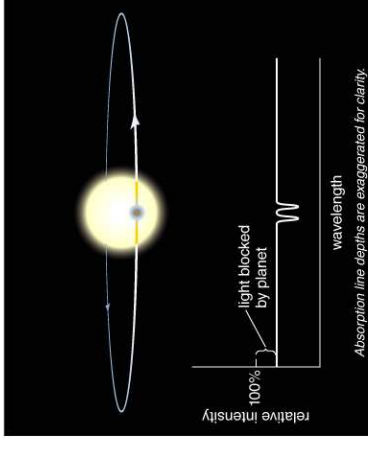
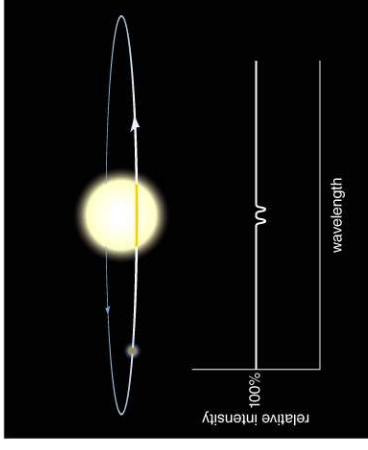
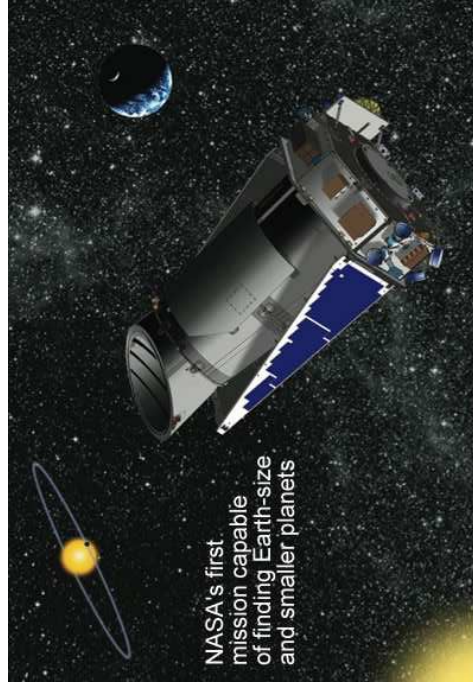
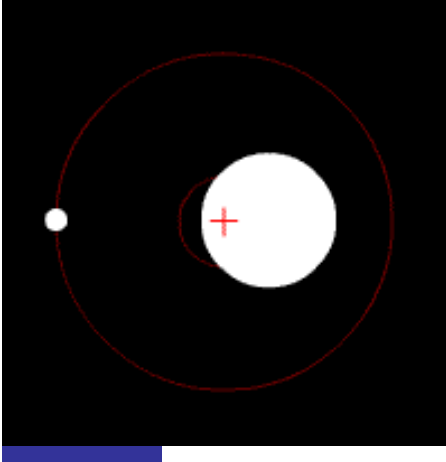


Fig 13.8



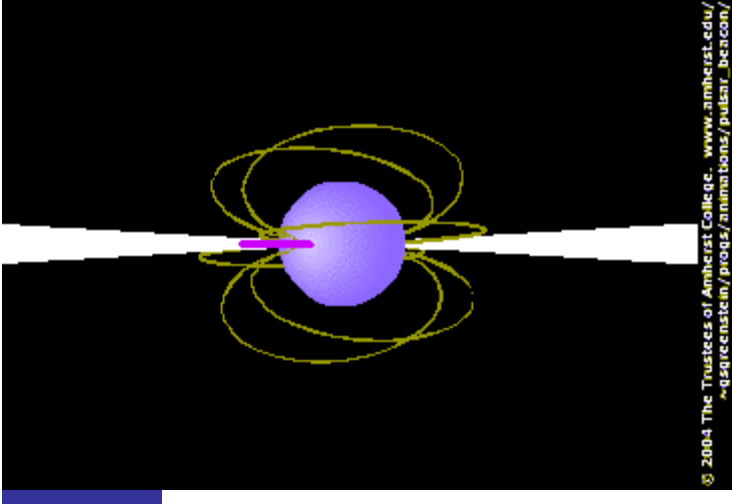
Astrometry

- 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



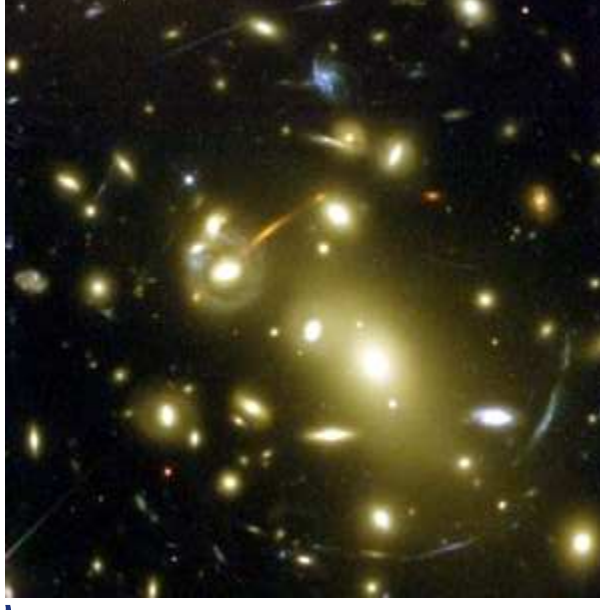
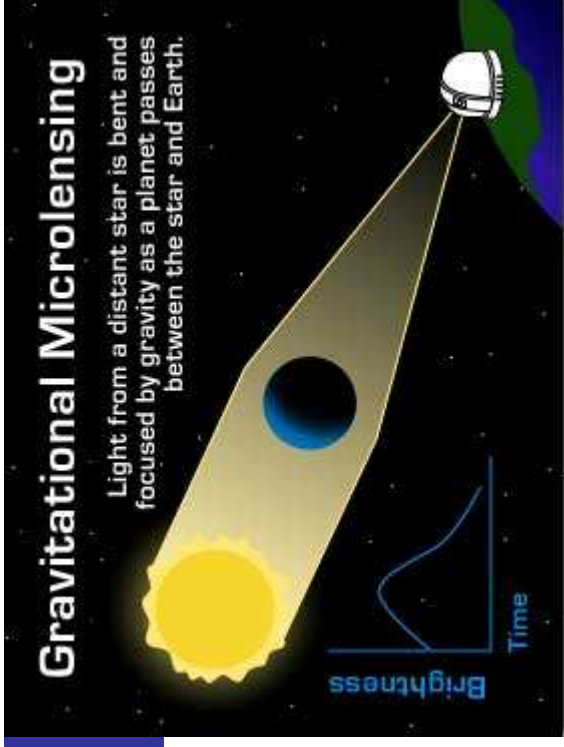
Pulsar Timing

- 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 $\frac{1}{2}$!
- 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

