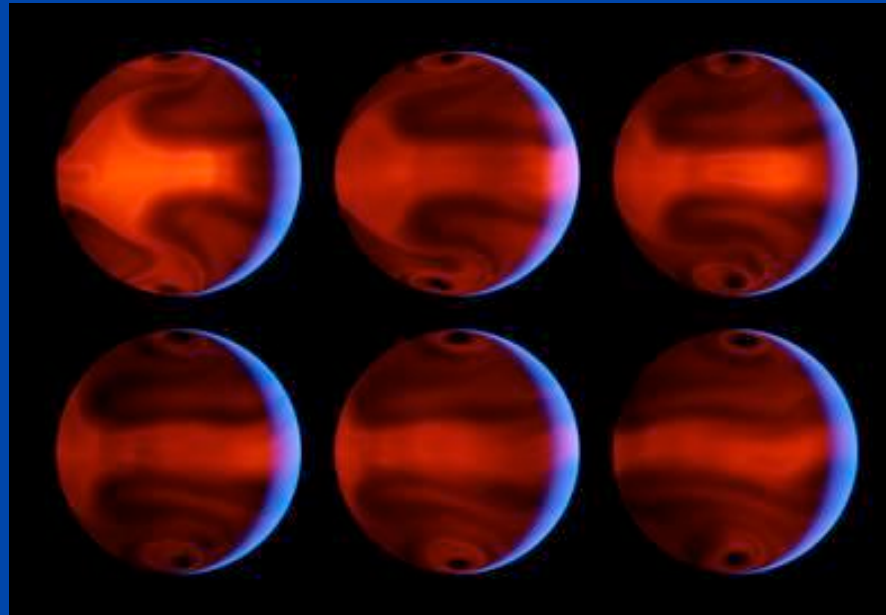


Lecture 8: Extrasolar Planets

Please
remind me to
take a break
at 12:45 pm!



Predicted
weather
patterns on
HD80606

Claire Max
April 29, 2014
Astro 18: Planets and Planetary Systems
UC Santa Cruz

Practicalities



- **Midterm**

- May 8th, week from Thursday; in this room, class time
- Multiple-choice questions (lectures and reading)
- Short-answer questions (calculations)

- **Review session**

- I will use the second half of *this Thursday's lecture* for our review session.
- I will post questions from previous exams on the web before this Thursday. Take a look at them ahead of time.

I am behind on grading your homework assignments



- I'm really really sorry!
 - (excuses excuses: no TA, no grader ...)
- I will do my best to have Homework 2 graded by class time this Thursday, and Homework 3 graded by next Tuesday at the latest

Midterm Thursday May 8th in class



- Be ready to do calculations using the following concepts:
 - Kinetic and potential energy
 - Newton's version of Kepler's 3rd law
 - Radiation (Wavelength/Frequency relation, photon energy, Wien and Stefan-Boltzmann's law, Doppler shift)
 - Telescopes and the diffraction limit
 - Small-angle formula and parallax
 - Solar System formation
- Some formulas will be given, but you need to know how to use them
- **BRING YOUR SCIENTIFIC CALCULATOR!**

Astro Colloquium Wed. (tomorrow) on Extrasolar Planets



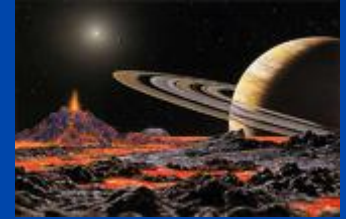
- Prof. Heather Knutson, Caltech

“Friends of Hot Jupiters:
A Search for Distant, Massive Companions
to Close-In Gas Giant Planets”



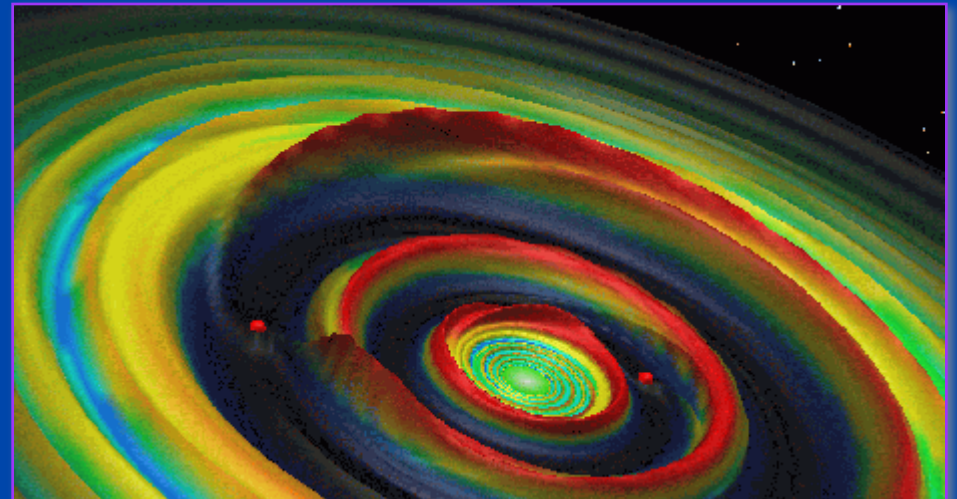
- Nat Sci Annex room 101, 3:45 – 5pm
 - Enter Nat Sci 2 on ground floor beneath concrete stairs, turn left into Nat Sci Annex
- If you attend, you can get extra credit on the next homework by writing a short paragraph on what you learned

Outline of lecture



- Almost 1700 planet candidates have now been observed around other stars; there are another approx. 3700 candidate planets not yet confirmed
 - How have they been detected?
 - What do they look like?
 - What do they tell us?
 - What does the future hold?

With thanks to Susan Cartwright
Simulation by Geoff Bryden, JPL:
Solar system and disk based on that observed
around the star Gl 876



The Main Points



- The ~ 1700 planets we have detected to date are only a sub-set of potential planets out there
- Many of the new solar systems don't look at all like our own (example: Jupiter-mass planets within the orbit of our Mercury)
- These new solar systems have raised big questions about how our own Solar System formed
- Future search methods have high probability of finding more (and more varied) planets
- It's hard to find Earth-like planets
 - But we are starting to find some!

Main Points, continued



- Planet formation and solar system evolution are in midst of a “paradigm shift”
 - Prevailing ideas of 15 years ago don’t work any more, in light of new data
 - Lots of ferment, discussion, computer simulations
 - Ultimately will confront data from other solar systems of varying ages
- **A VERY EXCITING TIME!**

Some key exoplanet websites



- Exoplanets.org: www.exoplanets.org/
- Exoplanet Encyclopaedia: www.exoplanet.edu
- NASA Archive: exoplanetarchive.ipac.caltech.edu
- Habitable Zone Gallery: www.hzgallery.org
- Open Exoplanet Catalog:
www.openexoplanetcatalogue.com
- Systemic: oklo.org
- Kepler mission: www.nasa.gov/mission_pages/kepler/

The ancient Greek “atomists” argued that there are other solar systems



- Leucippus (480 - 420 B.C.)
 - The worlds come into being as follows: many bodies of all sorts and shapes move from the infinite into a great void; they come together there and produce a single whirl, in which, colliding with one another and revolving in all manner of ways, they begin to separate like to like.
- Epicurus (341 - 270 B.C.)
 - There are infinite worlds both like and unlike this world of ours. For the atoms being infinite in number, as was already proven, ... there nowhere exists an obstacle to the infinite number of worlds.
- Unfortunately, the atomists were overshadowed by Aristotle (384 - 322 B.C.) who believed that
 - There cannot be more worlds than one.

Dangerous to believe in plurality of worlds!



- *“This space we declare to be infinite; since neither reason, convenience, possibility, sense-perception nor nature assign to it a limit. In it are an infinity of worlds of the same kind as our own ...”*



Giordano Bruno, “On the Infinite Universe and Worlds”

- Unfortunately, plurality of worlds was a heretical idea. Bruno was burned at the stake in 1600.

Why is it so hard to find planets around other stars?

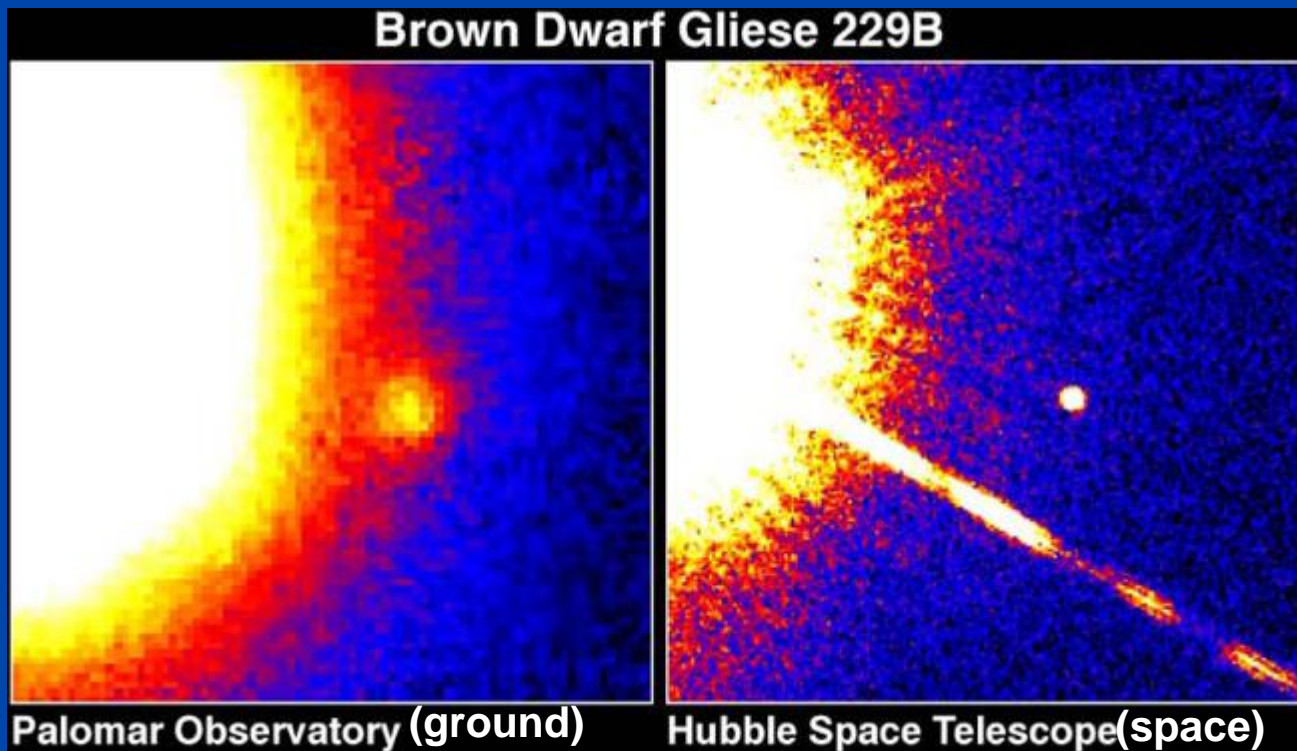


- **Faint planet glimmer is lost in glare from parent star**
 - Planets are small, close to their parent star, and shine by reflected starlight
- **Thought experiment:**
 - Imagine grain of rice an inch from a 100 Watt light bulb. Someone standing at end of a long dark hall would see only the light bulb, not the grain of rice.
- **Consider the case of Jupiter and the Sun:**
 - As seen from the nearest star, Alpha Centauri, Jupiter would appear a billionth as bright as the Sun.
 - Jupiter would also be extremely close to the Sun, only 4 arc sec away.
- **Since all other stars are farther than Alpha Centauri, Jupiter would be even harder to detect from other stars**

Planets are very hard to observe directly (by detecting their own light)



- Planets are too faint compared with their star
 - This brown dwarf star is barely visible - and its star is faint
- Planets shine by reflected light
 - Planets close to parent stars are brightest, but hardest to see



Planet Detection



- **Indirect: measurements of stellar properties revealing the effects of orbiting planets**
 - Stellar radial velocities, motions on the sky, dimming of star when planet passes in front
 - Most planets to date have been detected by indirect methods
- **Direct: pictures or spectra of the planets themselves**
 - Recently starting to be used very successfully

Observational techniques



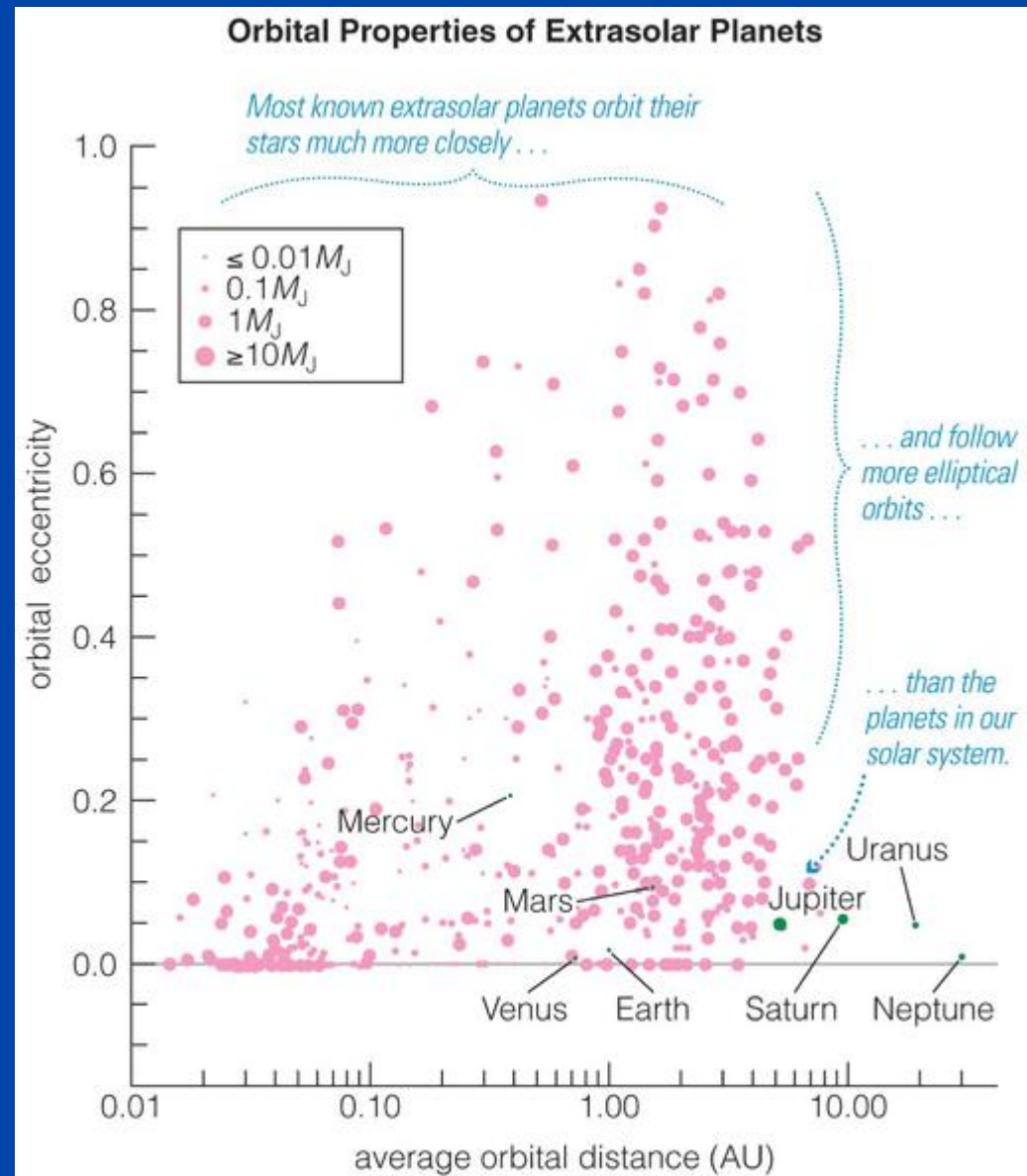
- Doppler spectroscopy
- Transit photometry and spectra
- Microlensing
- Astrometry
- Direct imaging

Observational techniques



- Doppler spectroscopy
- Transit photometry and spectra Direct
- Microlensing
- Astrometry
- Direct imaging Direct

What properties of extrasolar planets can we measure?

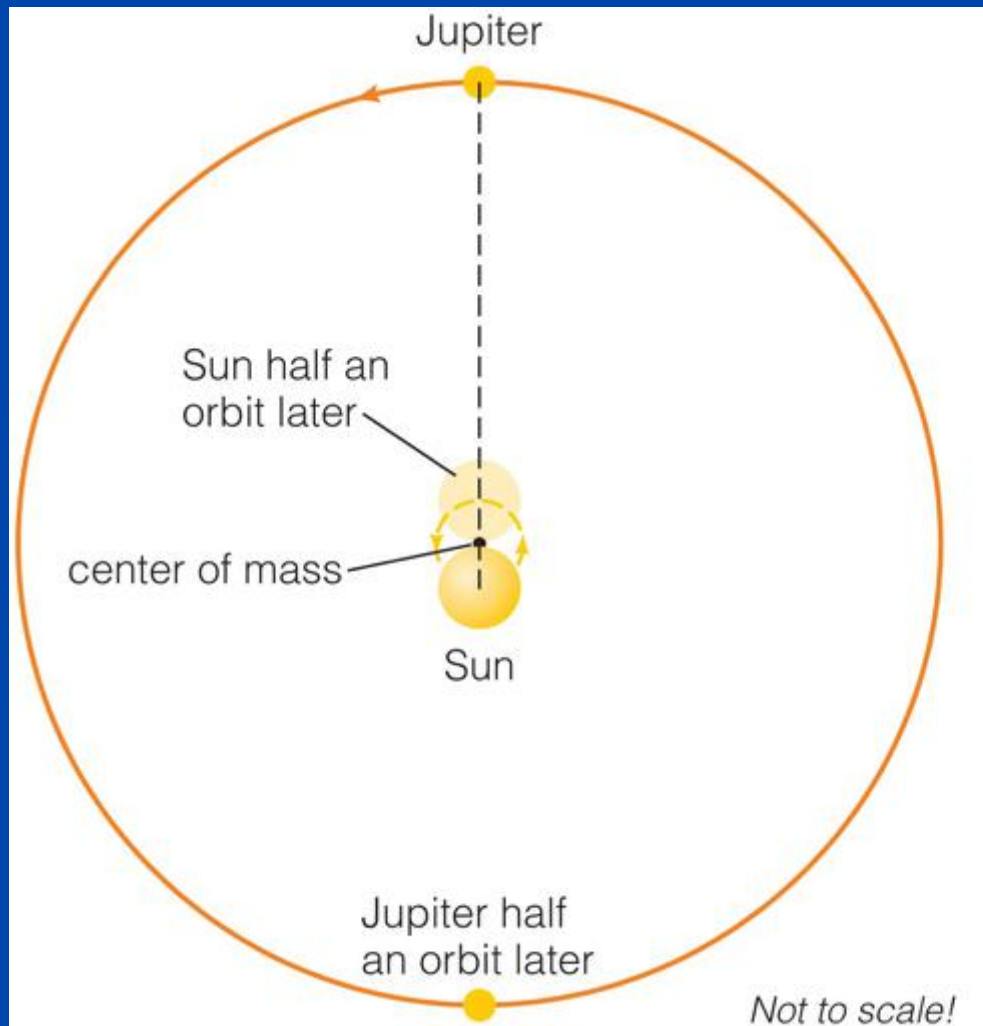


Observational techniques



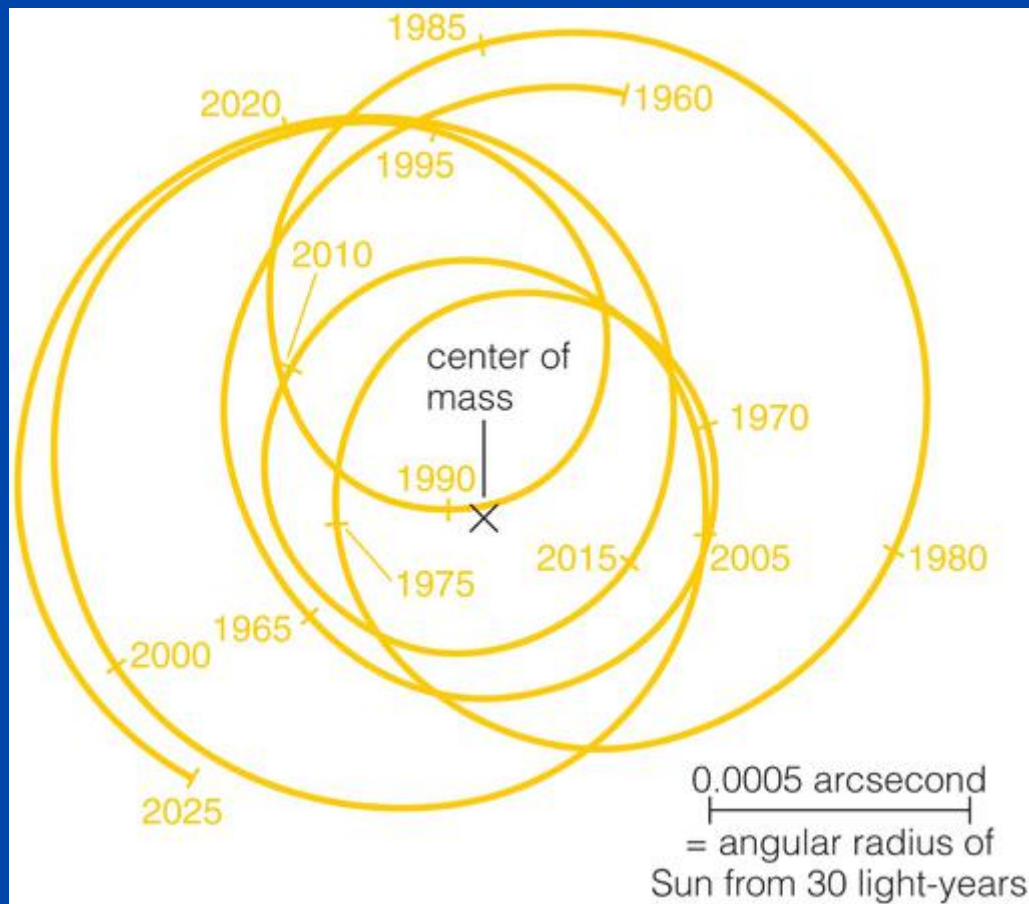
- Doppler spectroscopy
- Transit photometry and spectra
- Microlensing
- Astrometry
- Direct imaging

Gravitational Tugs



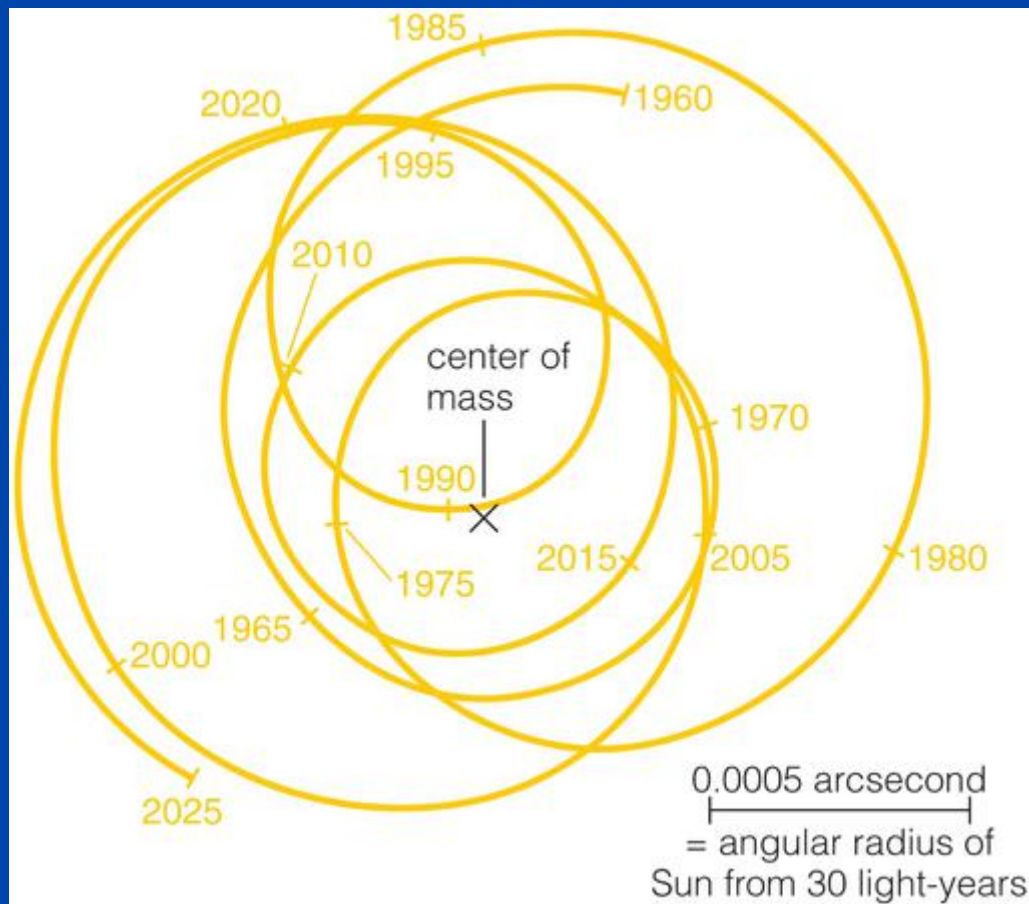
- The Sun and Jupiter orbit around their common center of mass.
- The Sun therefore wobbles around that center of mass with same period as Jupiter.

Gravitational Tugs



- The Sun's motion around the solar system's center of mass depends on tugs from all the planets.
- Astronomers around other stars that measured this motion could determine the masses and orbits of all of our planets.

Astrometric Technique

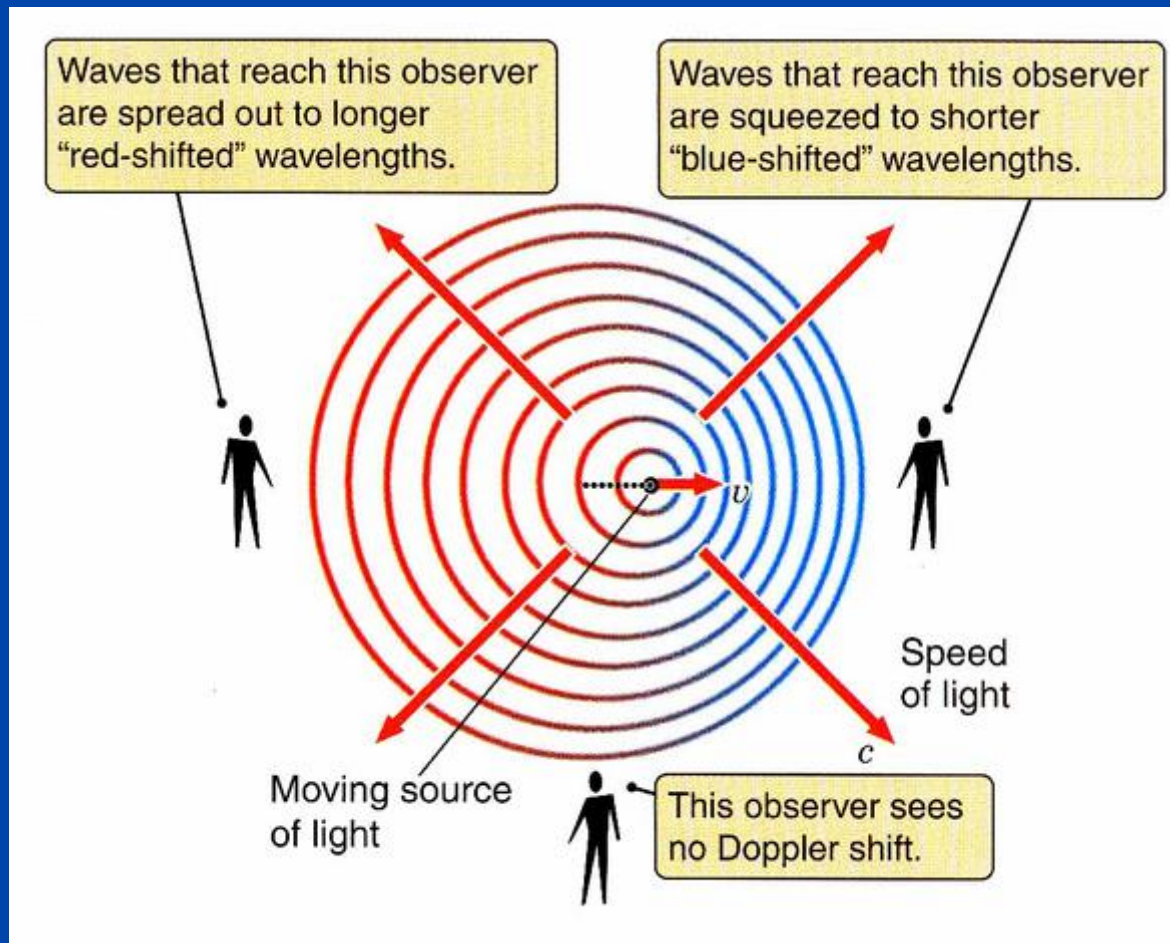


- We can detect planets by measuring the change in a star's position on sky.
- However, these tiny motions are very difficult to measure (~ 0.001 arcsecond).

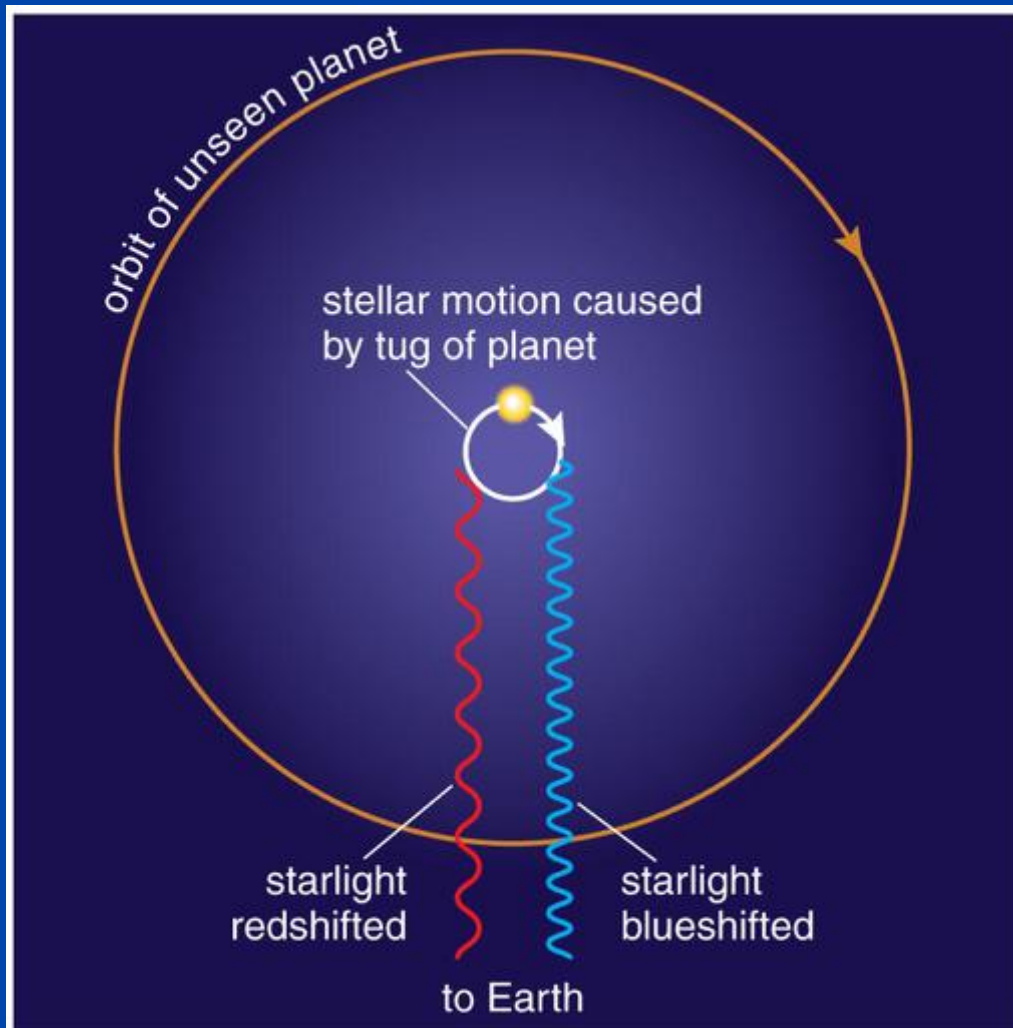
Doppler shift: a moving object can change frequency of emitted or reflected waves



Light waves:



Doppler Technique

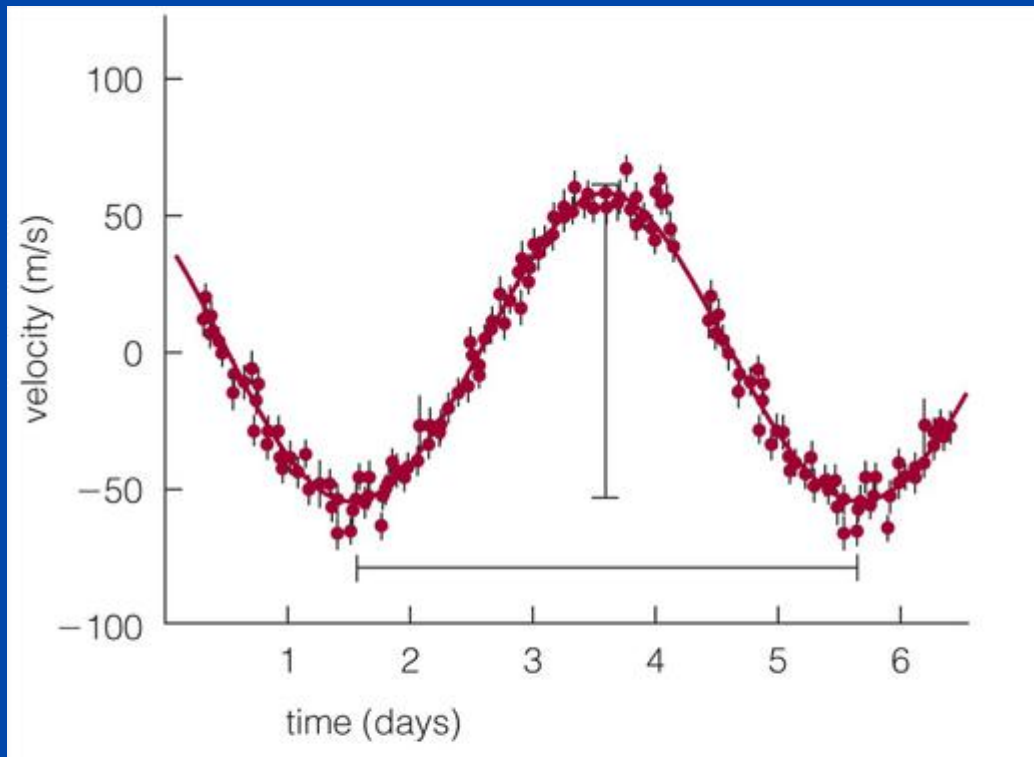


- Measuring a star's Doppler shift can tell us its motion toward and away from us.
- Current techniques can measure motions as small as 1-2 m/s (walking speed!).

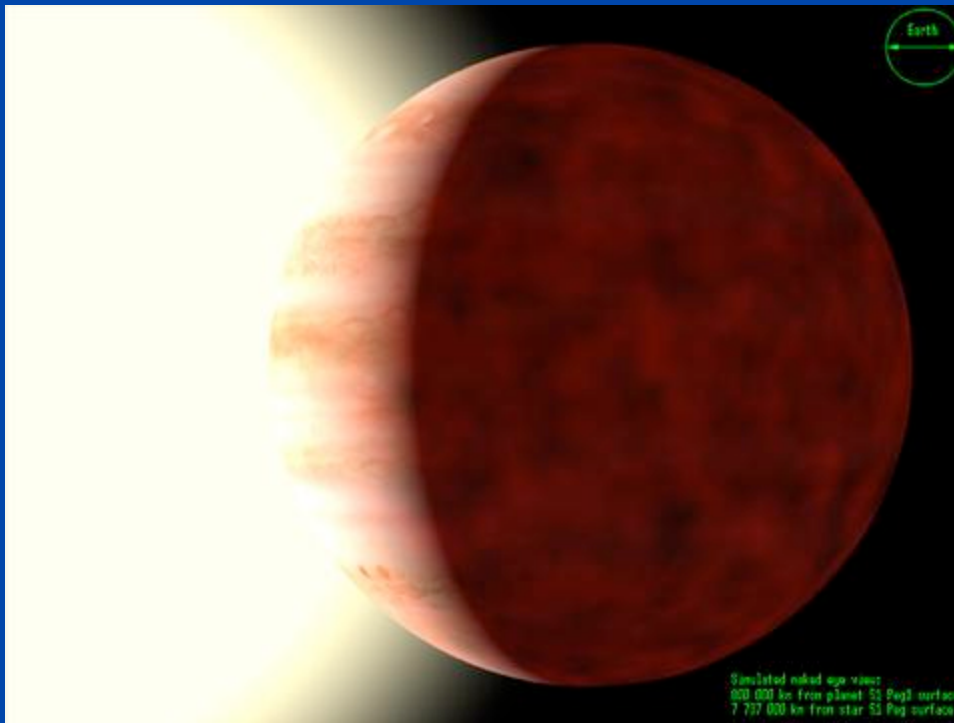
First Extrasolar Planet: 51 Pegasi



- Doppler shifts of the star 51 Pegasi indirectly revealed a planet with 4-day orbital period.
- This short period means that the planet has a small orbital distance – well within orbit of Mercury.
- This was the first extrasolar planet to be discovered (1995).

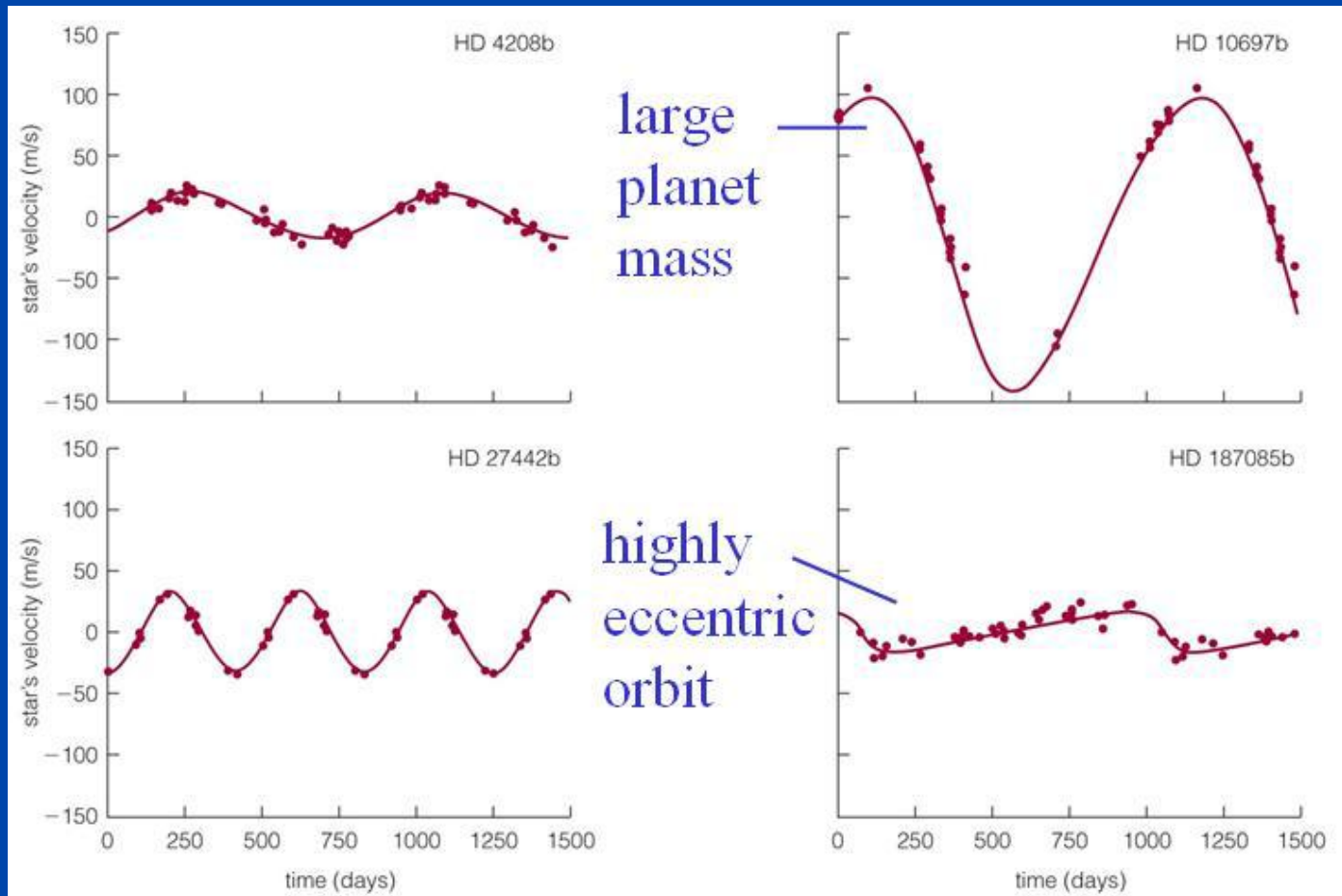


51 Peg b (1995)



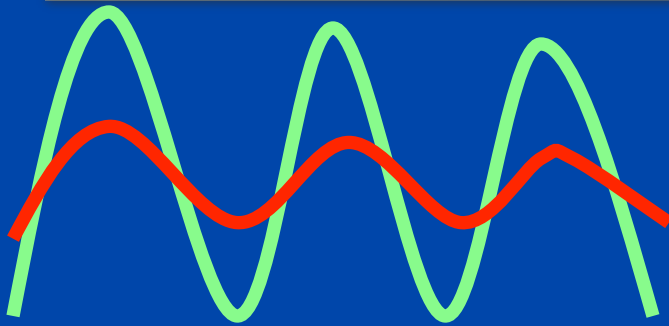
Half the mass of Jupiter, yet orbiting much closer to the Sun than Mercury!

Other Extrasolar Planets



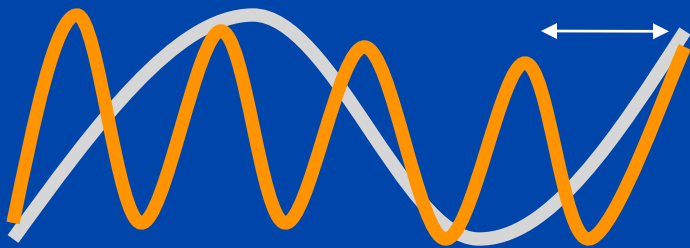
- Doppler shift data tell us about a planet's mass and the shape of its orbit.

Planetary signatures



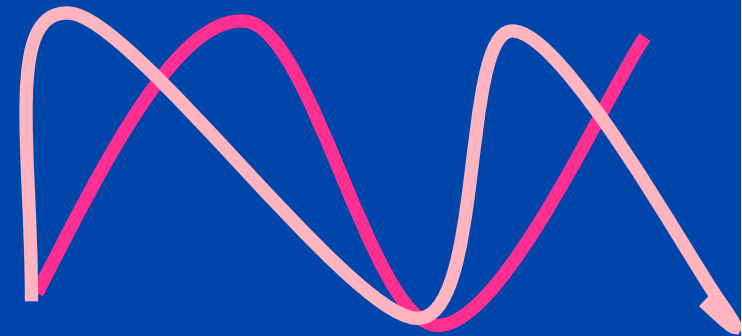
Size depends on mass of planet

Low mass, high mass



Periodicity depends on period of planet

Small period, large period



Circular, eccentric

Shape depends on eccentricity of planet

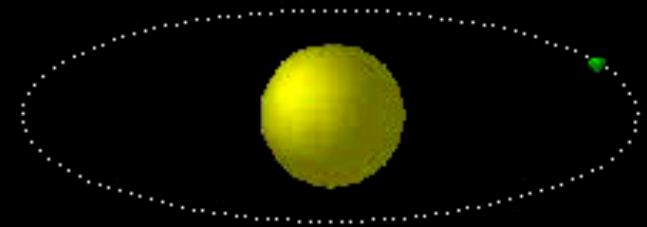
Stellar wobble depends on mass, period and eccentricity of planet

Doppler shift



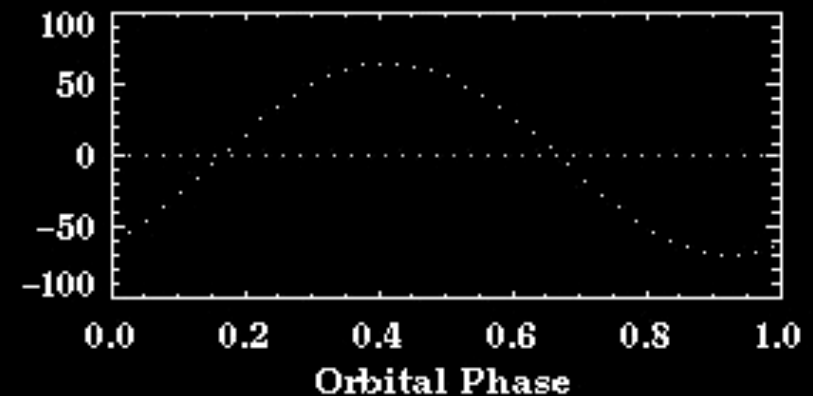
- Look for periodic shift in star's spectrum
 - Does not depend on distance of star
 - Need **massive** planet **near** star
 - » the closer the planet, the faster the orbital speed (of both planet and star)
 - Need very good spectrum
 - » measure Doppler shifts of < 1 part in 1,000,000
- 90% of planet detections to date
- Incredibly hard measurements have now become standard

Circular Orbit: rho CrB

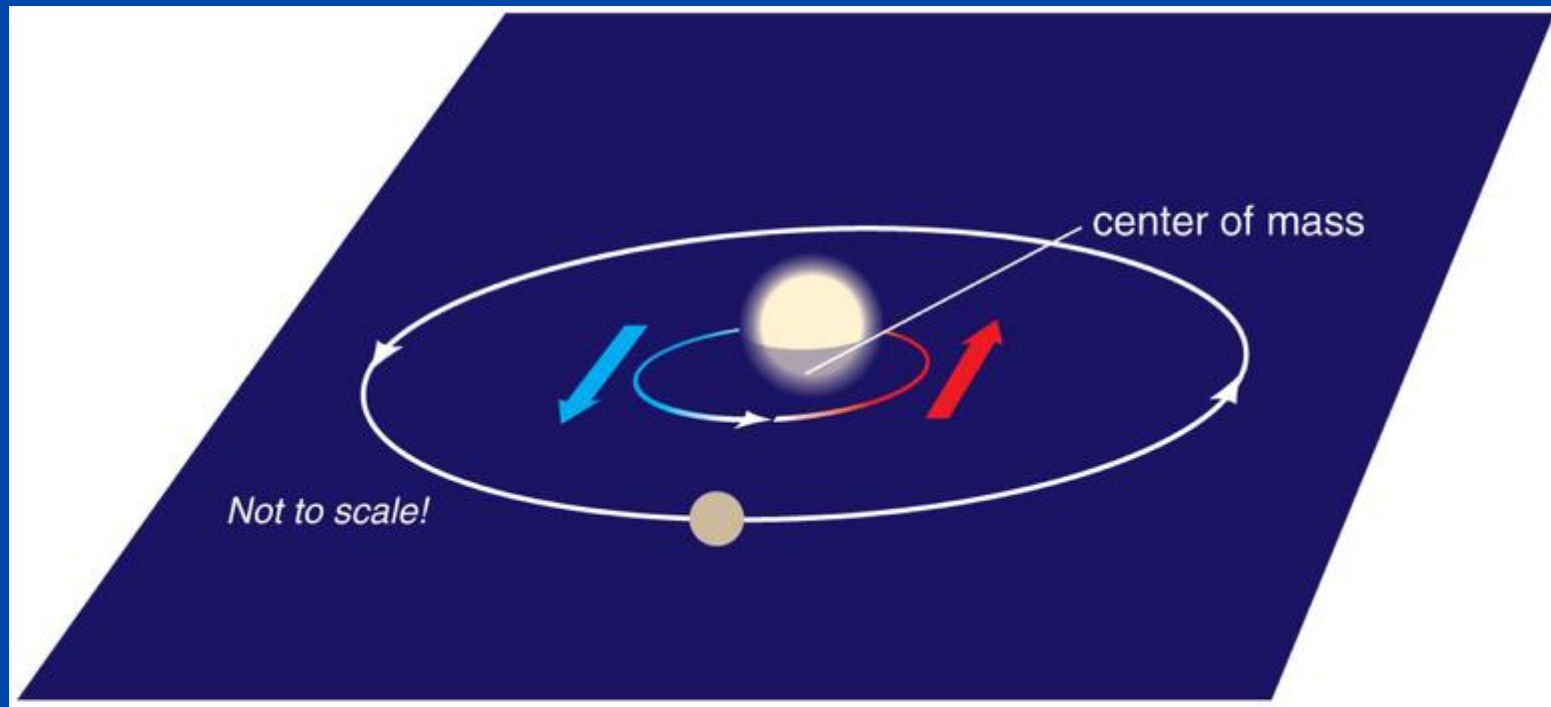


$$K = 67.4 \text{ m/s} \quad e = 0.03$$
$$\omega = 210.0 \text{ deg.} \quad \sin(i) = 0.3 (^{\circ})$$

Radial Velocity Curve of the Star [m/s]



Planet Mass and Orbit Tilt

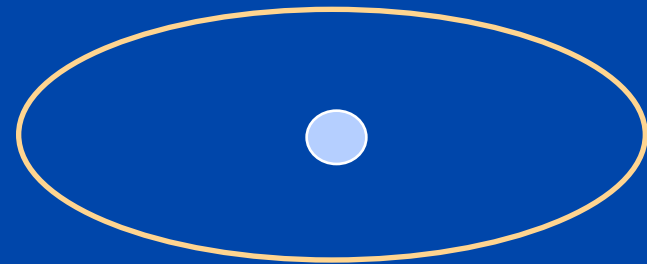


- We cannot measure an exact mass for a planet without knowing the tilt of its orbit, because Doppler shift tells us only the velocity toward or away from us.
- Doppler data give us lower limits on masses.

Radial velocity method doesn't give all the orbital information



- Doppler shift only detects velocity along line of sight
 - Can't distinguish massive planet (or brown dwarf!) in tilted orbit from less massive planet in edge-on orbit
 - They both have the same line-of-sight velocity
- The only way to resolve this ambiguity is to observe using another method



WHY?



Thought Question



Suppose you found a star with the same mass as the Sun moving back and forth with a period of 16 months. What could you conclude?

- A. It has a planet orbiting at less than 1 AU.
- B. It has a planet orbiting at greater than 1 AU.
- C. It has a planet orbiting at exactly 1 AU.
- D. It has a planet, but we do not have enough information to know its orbital distance.

Thought Question



Suppose you found a star with the same mass as the Sun moving back and forth with a period of 16 months. What could you conclude?

- A. It has a planet orbiting at less than 1 AU.
- B. It has a planet orbiting at greater than 1 AU.
- C. It has a planet orbiting at exactly 1 AU.
- D. It has a planet, but we do not have enough information to know its orbital distance.

Find your own planet!

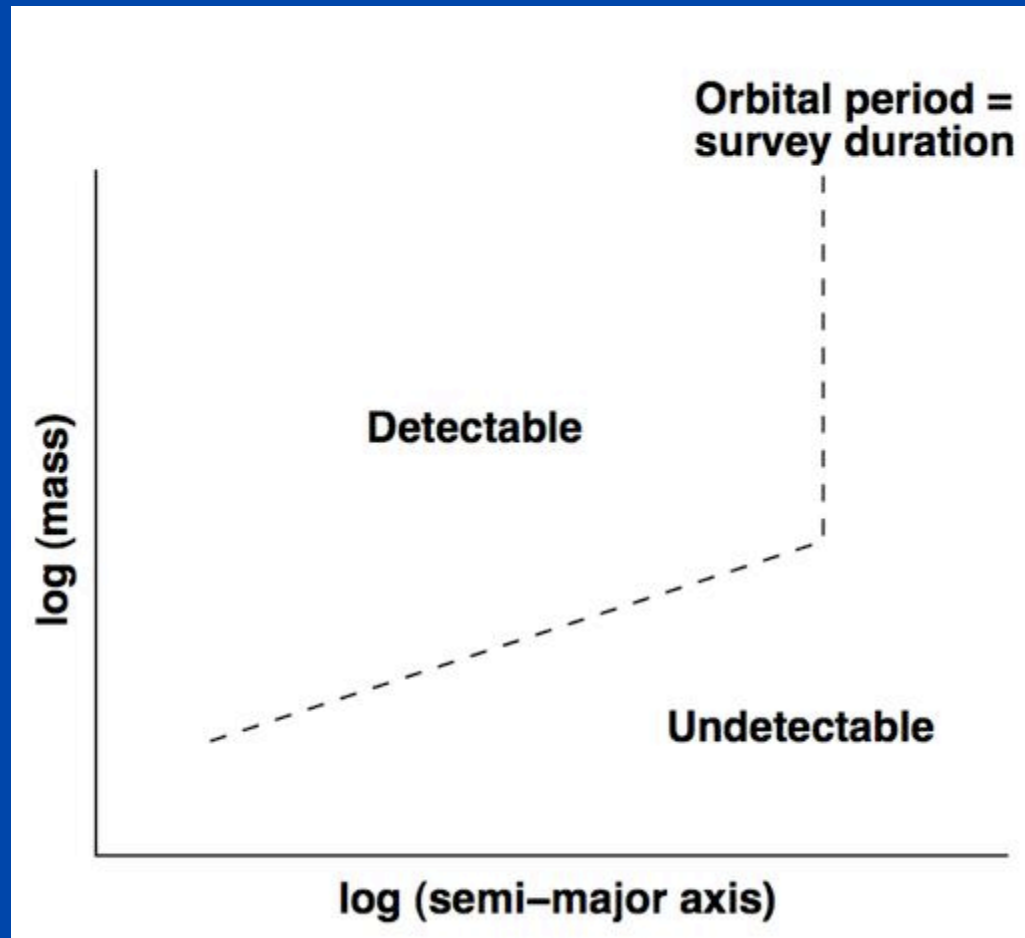


- <http://www.stefanom.org/systemic/>
- “Systemic” console: you participate in finding signals of planets from telescope data that others have obtained

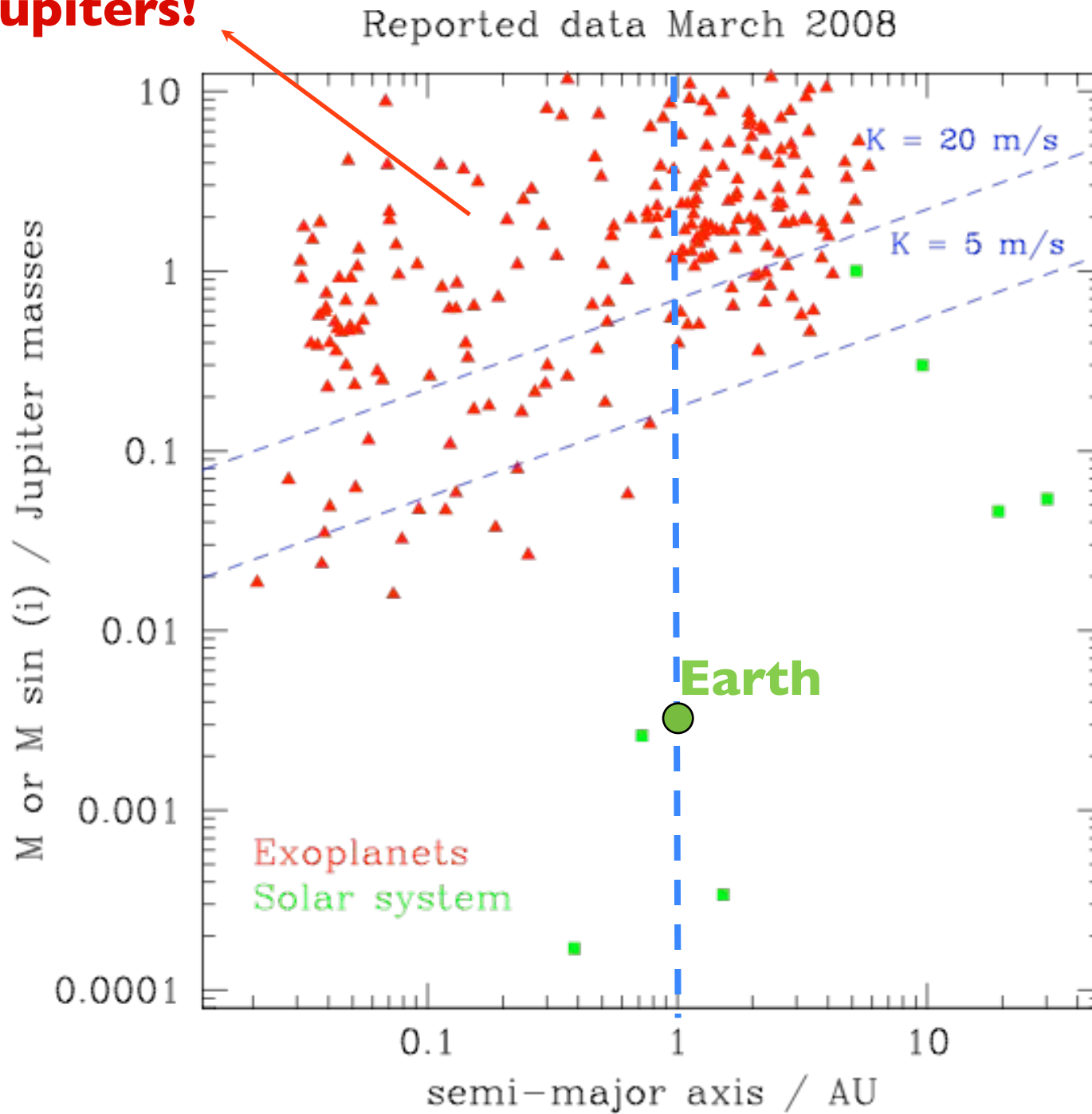
Limitations of Doppler technique



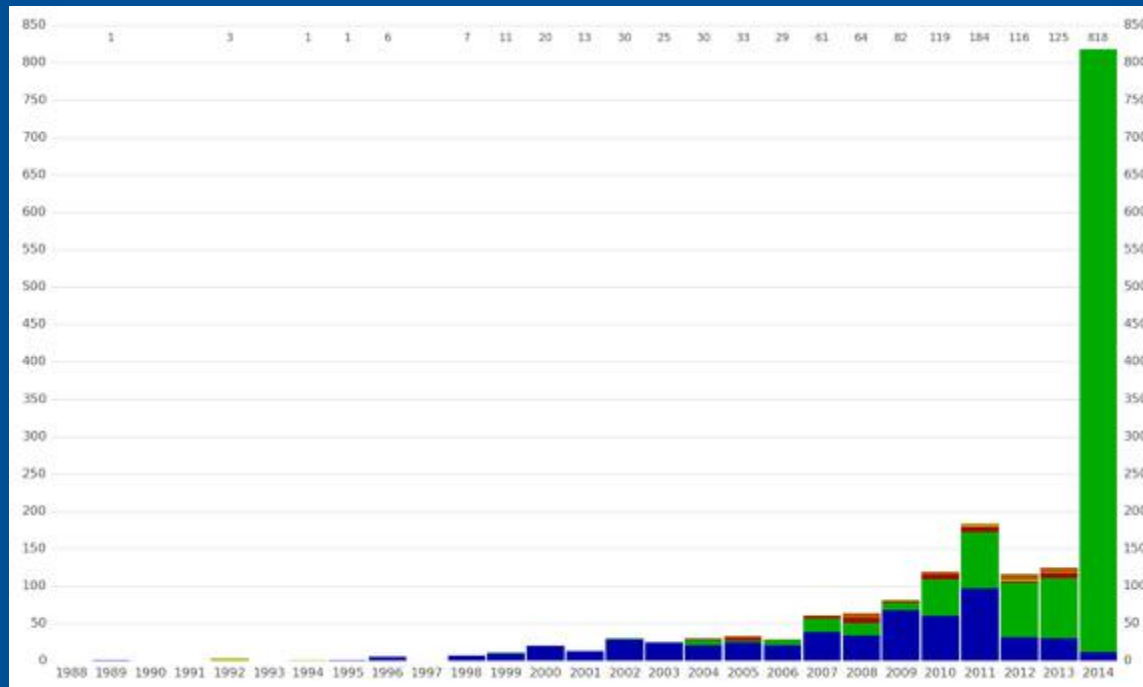
- From ground-based observatories, detect velocity shifts $> 1\text{-}2$ m/sec
- The nearer to the star and the more massive the planet, the easier to detect
- Corresponds to about 33 earth masses at 1 AU for a solar mass star.



Hot Jupiters!



Huge number of new exoplanets, due to Kepler transit mission



English: Bar chart of exoplanet discoveries by year, through 2013-02-26, indicating the discovery method using distinct colors:

- radial velocity (dark blue)
- transit (dark green)
- timing (dark yellow)
- direct imaging (dark red)
- microlensing (dark orange)

Exoplanet data is from the Open Exoplanet Catalogue,^[1] version [ecc9ca5](#)

Observational techniques

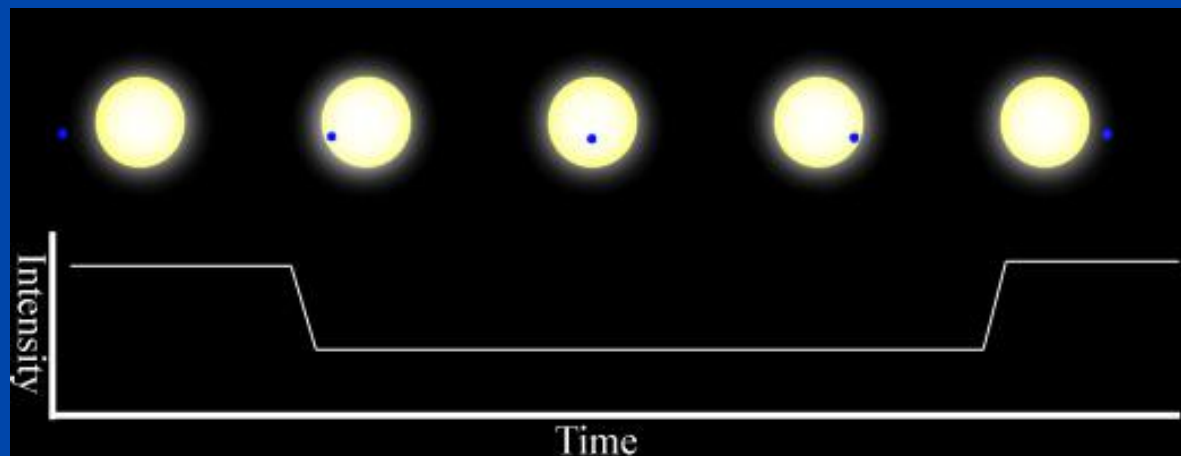


- Doppler spectroscopy
- Transit photometry and spectra
- Microlensing
- Astrometry
- Direct imaging

Transits



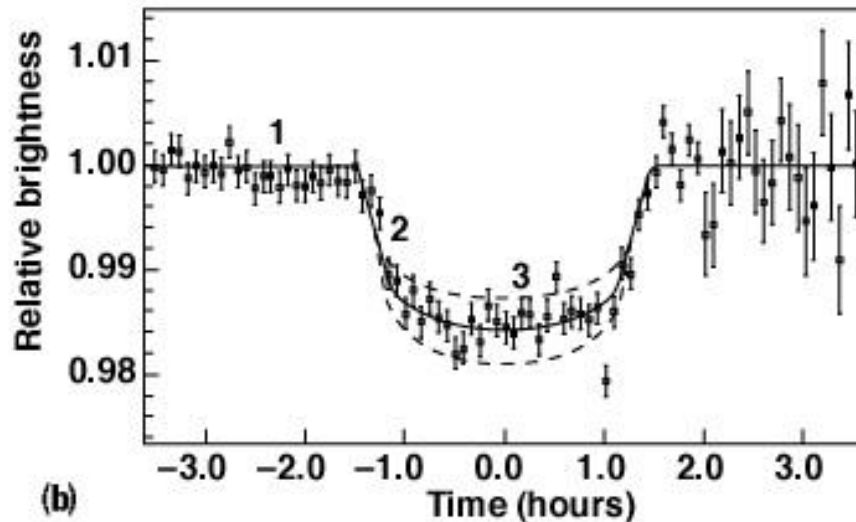
- As planet moves across face of star, it blocks a tiny bit of starlight
- Watch for periodic dimming of star



Planet detected around the star HD209458 by transit method



(a)

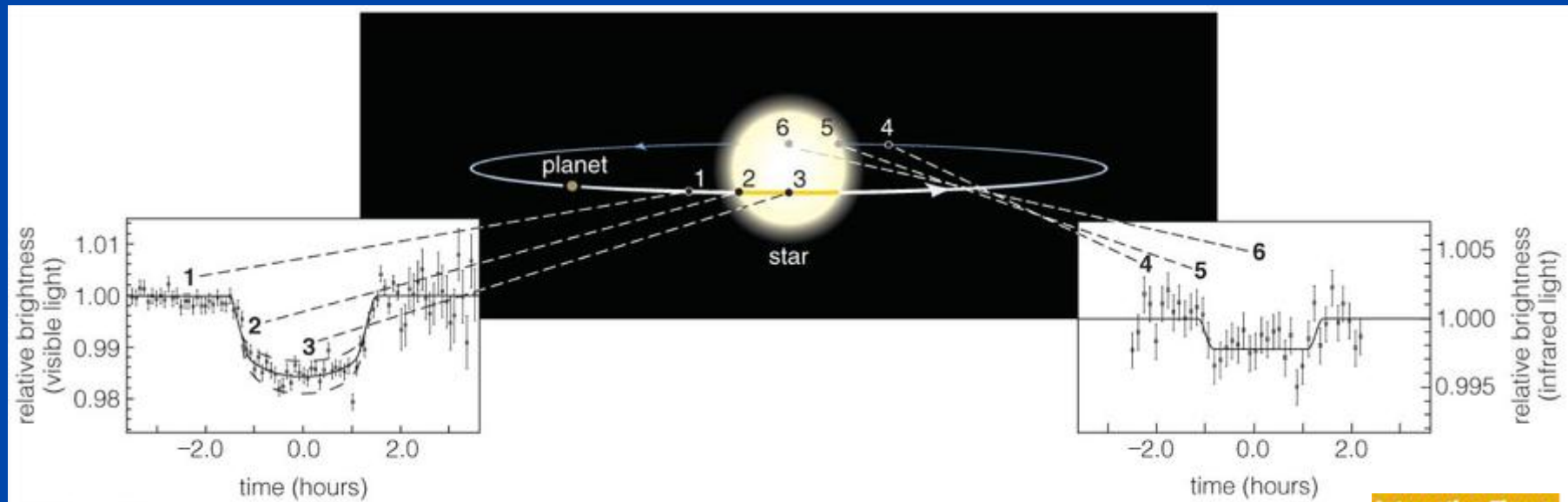


(b)

Copyright © Addison Wesley

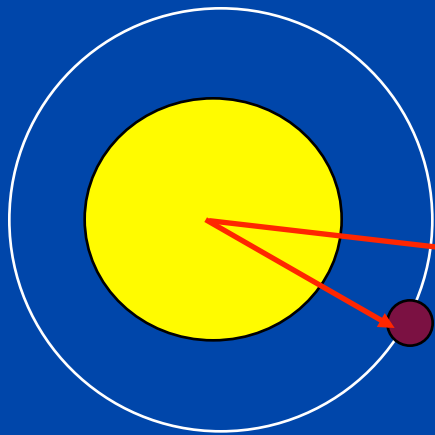
- Planet is 70% mass of Jupiter, but orbits in just 3.5 days
- So it is very close to its parent star
- Thus far 33 planets have been found this way
- Amateur astronomers have organized to watch for fluctuations in star brightness

Transits and Eclipses



Interactive Figure

- A **transit** is when a planet crosses in front of a star.
- The resulting eclipse reduces the star's apparent brightness and tells us planet's radius.
- No orbital tilt: accurate measurement of planet mass



observer

A transit is more likely observed when the planet is close to its star. This technique is best for close-in, large planets.

Transiting planets



- Can measure size, mass, temperature and spectra
- Can test the atmospheric models that have been developed for planets in our solar system
- Some of these planets are subject to more exciting conditions than the ones in the Solar System:
 - Small distance from star
 - Extreme eccentricities

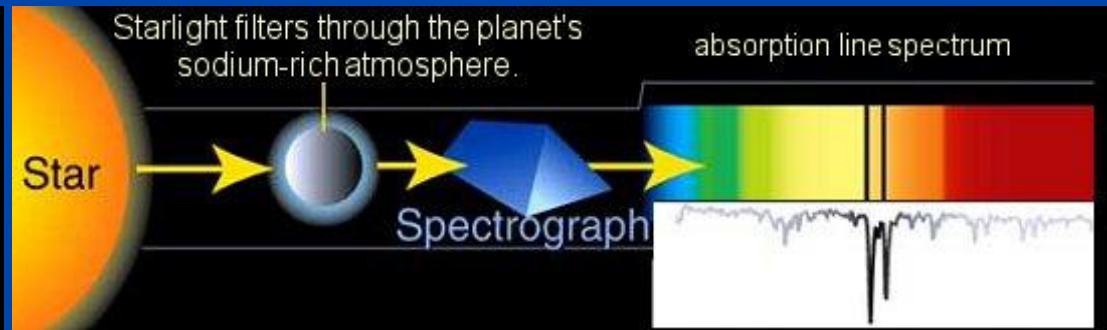
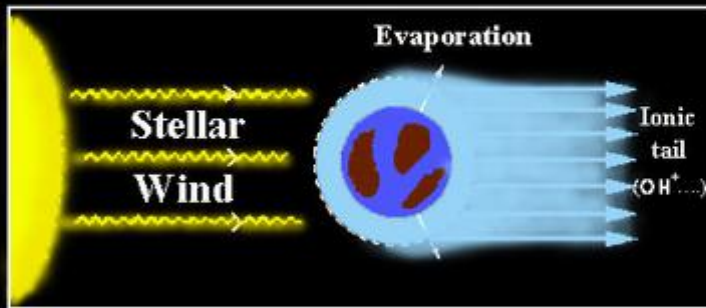
HD 209458b



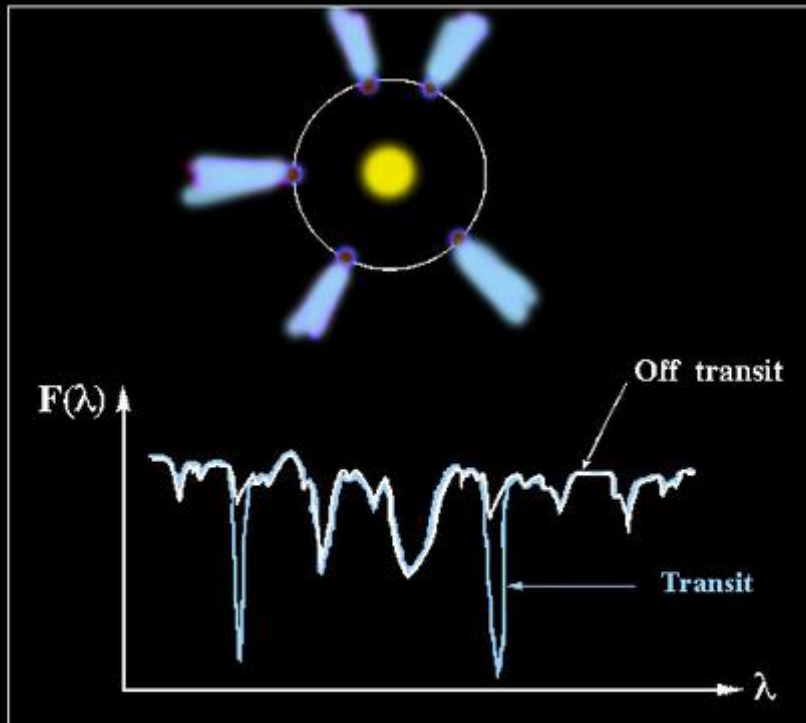
We have detected both the planet's atmosphere and a “cometary” tail

Orbit: very close to star (1/10th of Mercury's distance from Sun)

HD 209458b



- Detection of Hydrogen, Sodium, Carbon and Oxygen
- Compatible with “Cometary-type” atmosphere



PROPOSAL FOR A PROJECT OF HIGH-PRECISION STELLAR
RADIAL VELOCITY WORK

By Otto Struve

But there seems to be no compelling reason why the hypothetical stellar planets should not, in some instances, be much closer to their parent stars than is the case in the solar system. It would be of interest to test whether there are any such objects.

We know that stellar companions can exist at very small distances. It is not unreasonable that a planet might exist at a distance of 1/50 astronomical unit, or about 3,000,000 km. Its period around a star of solar mass would then be about 1 day.

We can write Kepler's third law in the form $V^3 \sim \frac{1}{P}$. Since the orbital velocity of the Earth is 30 km/sec, our hypothetical planet would have a velocity of roughly 200 km/sec. If the mass of this planet were equal to that of Jupiter, it would cause the observed radial velocity of the parent star to oscillate with a range of ± 0.2 km/sec—a quantity that might be just detectable with the most powerful Coudé spectrographs in existence. A planet ten times the mass of Jupiter would be very easy to detect, since it would cause the observed radial velocity of the star to oscillate with ± 2 km/sec. This is correct only for those orbits whose inclinations are 90° . But even for more moderate inclinations it should be possible, without much difficulty, to discover planets of 10 times the mass of Jupiter by the Doppler effect.

There would, of course, also be eclipses. Assuming that the mean density of the planet is five times that of the star (which may be optimistic for such a large planet) the projected eclipsed area is about 1/50th of that of the star, and the loss of light in stellar magnitudes is about 0.02. This, too, should be ascertainable by modern photoelectric methods, though the spectrographic test would probably be more accurate. The advantage of the photometric procedure would be its fainter limiting magnitude compared to that of the high-dispersion spectrographic technique.

Berkeley Astronomical Department,
University of California.
1952 July 24.

Otto Struve
advocated these
techniques in
1952!

"An intrinsically improbable event may become highly probable if the number of events is very great. ... [I]t is probable that a good many of the billions of planets in the Milky Way support intelligent forms of life."

Observational techniques



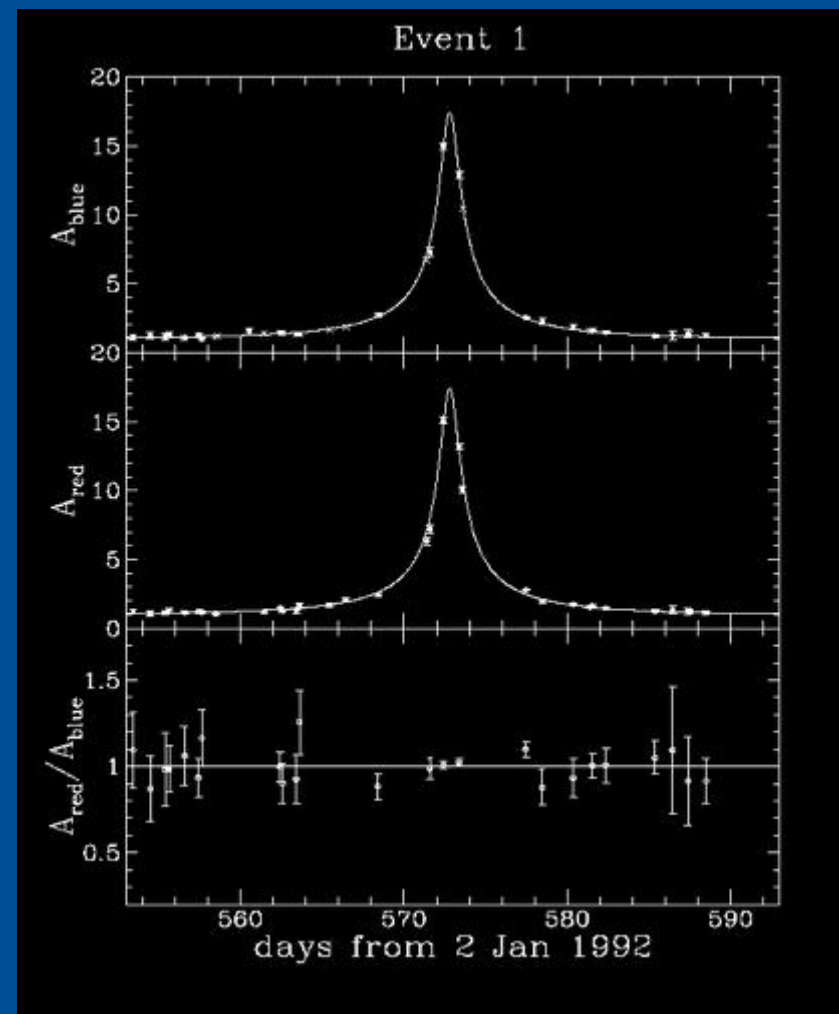
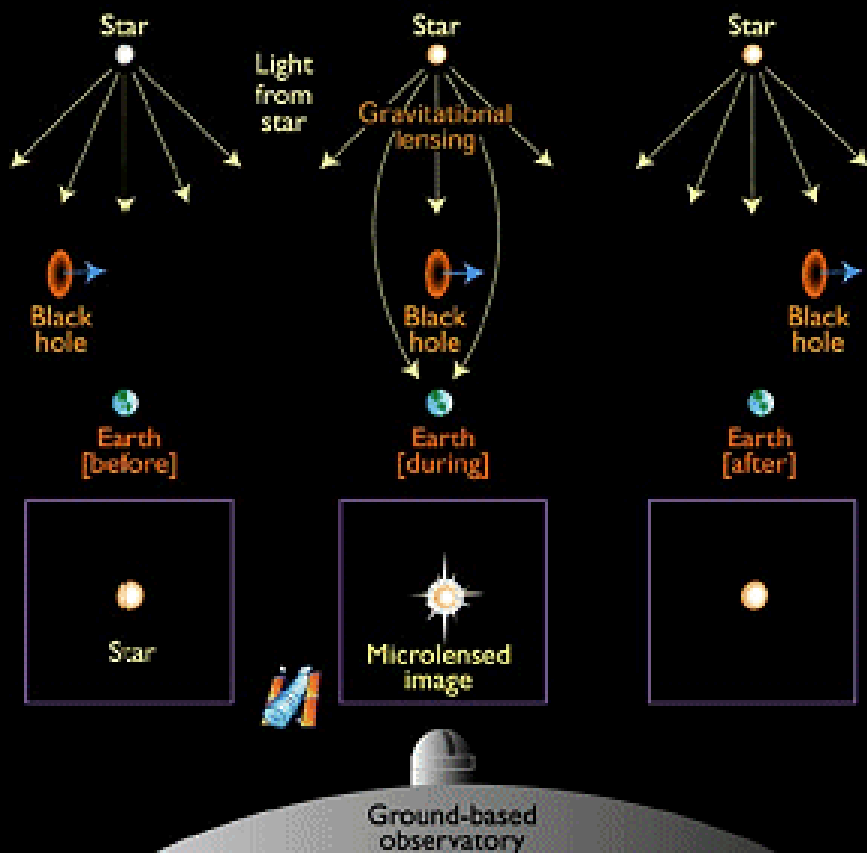
- Doppler spectroscopy
- Transit photometry and spectra
- **Microlensing**
- Astrometry
- Direct imaging

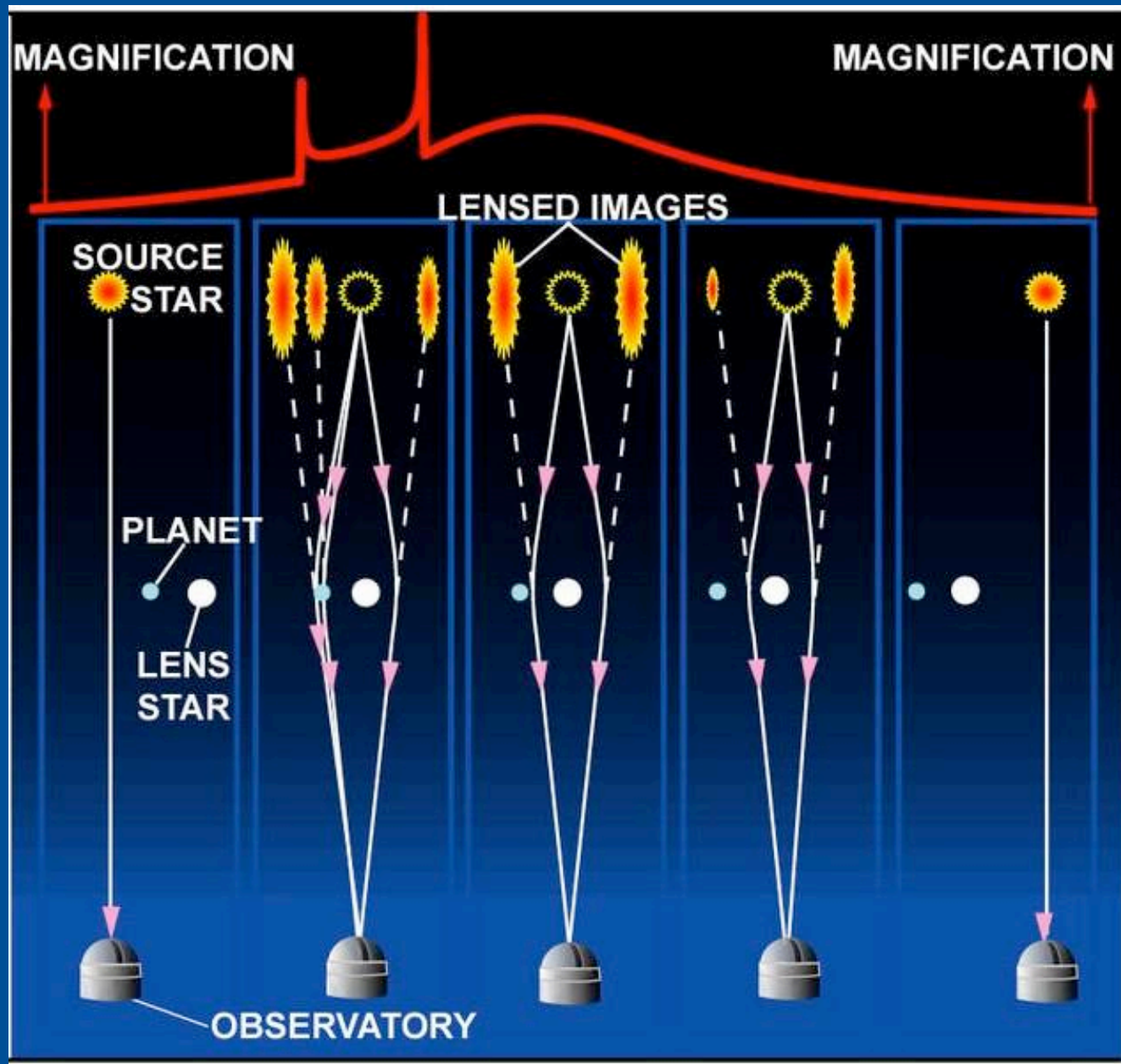
Method three: Microlensing



- Background: Microlensing around a star (or black hole)

Gravitational Microlensing by Black Hole





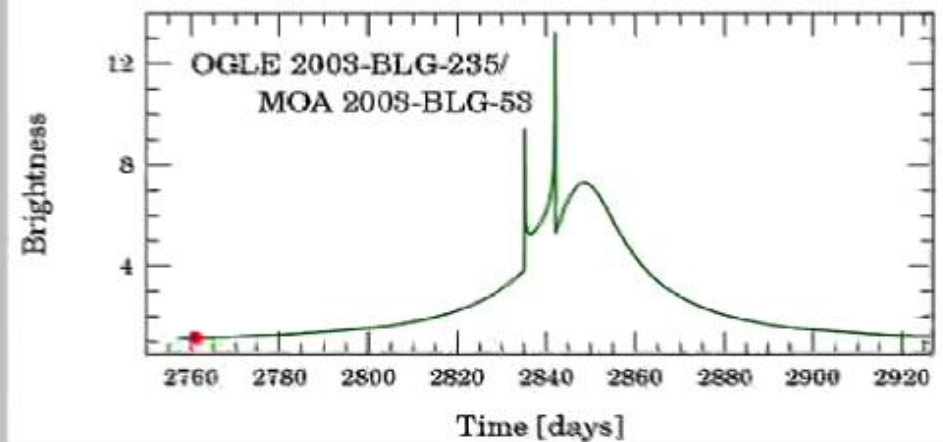
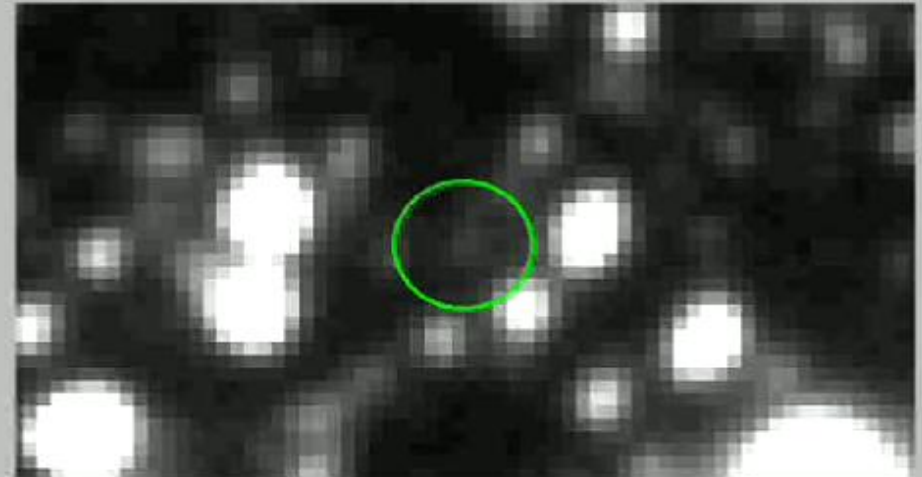
Needs almost perfect alignment between source and lens.

One-time events!

Planet detection: fine structure on microlensing light curve



- Candidates for several planets have been discovered this way
- Potentially very useful: can detect planets at large distances from us
 - Even farther away than transit method can
 - Much farther than radial velocity or astrometry can



Observational techniques

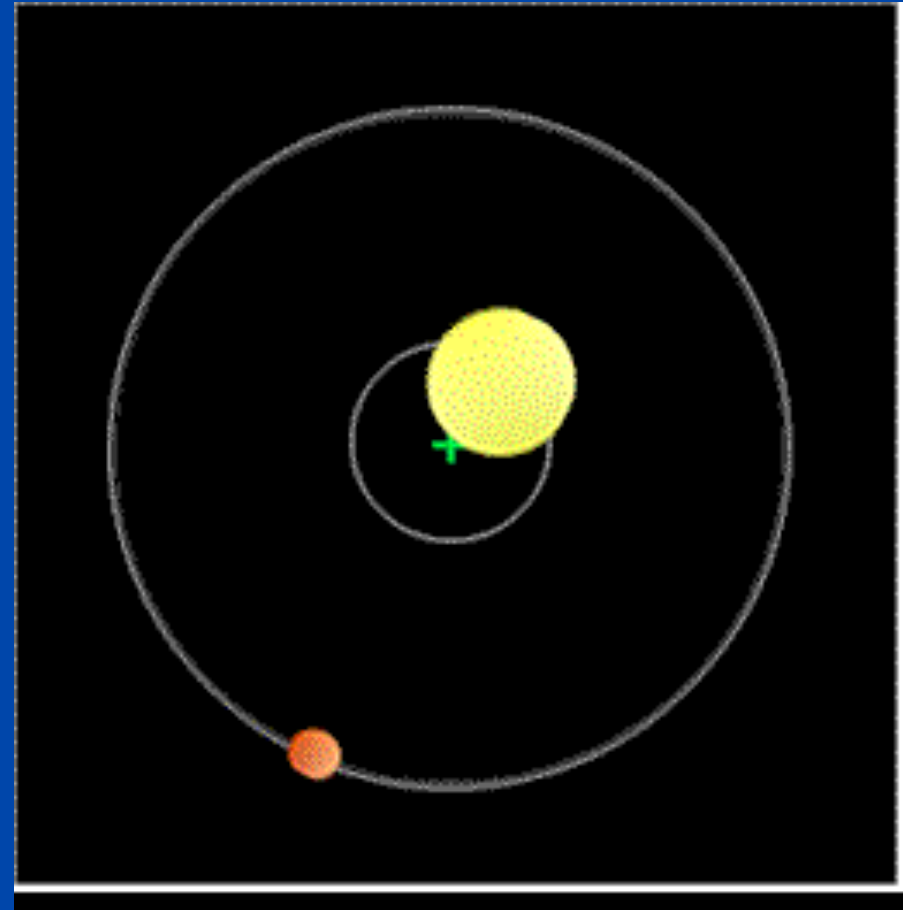


- Doppler spectroscopy
- Transit photometry and spectra
- Microlensing
- **Astrometry**
- Direct imaging

Astrometry



- Look for star moving on the sky (with respect to other stars)
- Need to measure angles (motion on sky) of $< 10^{-4}$ arc seconds
- This is very difficult, but will be possible in future
- No confirmed candidates yet



Finding invisible planets via the wobble of their parent star



- Gravitational force is mutual: planet pulls on star as much as star on planet
 - Star and planet both move around system center of mass
 - » Star changes position in the plane of the sky (astrometry)
 - » Star moves along line of sight (radial velocity)
 - Problem: star is much more massive than planet
 - » so won't move very much, or very quickly
- Need very sensitive measurements of position on sky (astrometry) and/or velocity (via Doppler shift of star's spectral lines)

Sensitivity needed for astrometry detection of Jupiter around our Sun



- Sun's mass is about 1000x Jupiter's mass
- Astrometric accuracy needed:
 - Radius of Jupiter's orbit around center of mass: 5.2 AU
 - Radius of Sun's orbit around center of mass: 0.0052 AU
- **From nearest star, Sun's motion on the sky is like a penny seen from 600 km away!**

Observational techniques



- Doppler spectroscopy
- Transit photometry and spectra
- Microlensing
- Astrometry
- Direct imaging



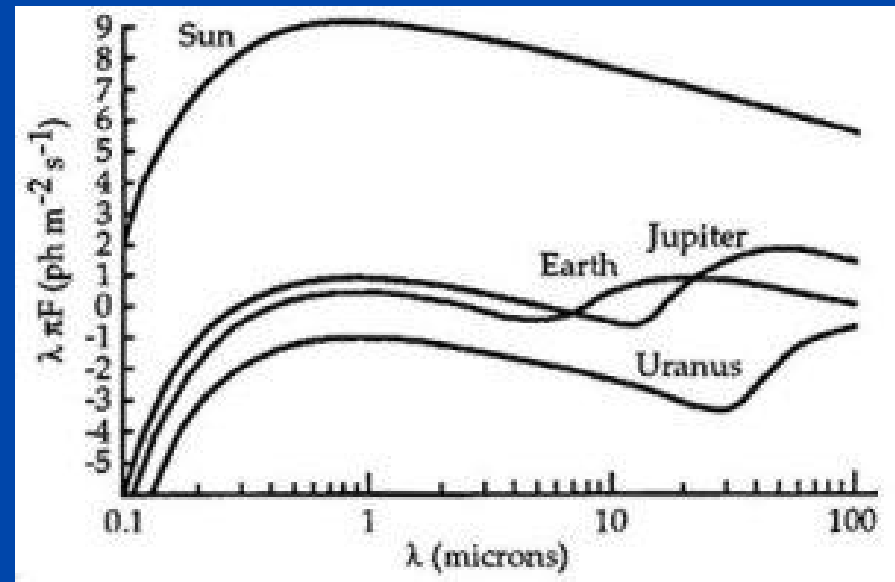
Planetary art

Collage by Willy Benz

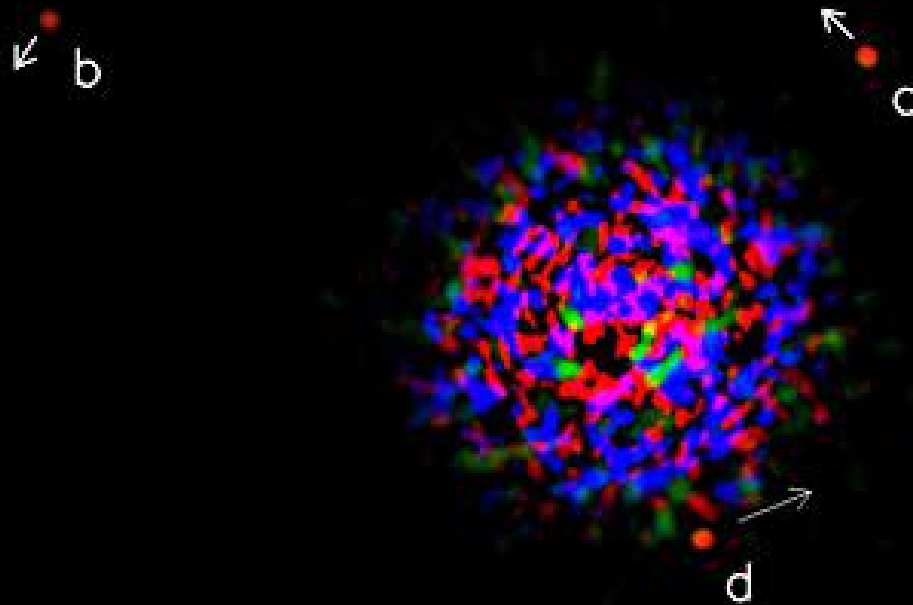
Direct Detection



- Use planet's own light
- Take image of it
 - Can reconstruct full orbit by watching it go around
- Can also obtain spectra
 - Learn about physical conditions, atmosphere, maybe even presence of life
- Jupiter is a billion times fainter than the Sun, in visible light!



First Images of Exoplanets: HR 8799 Solar System



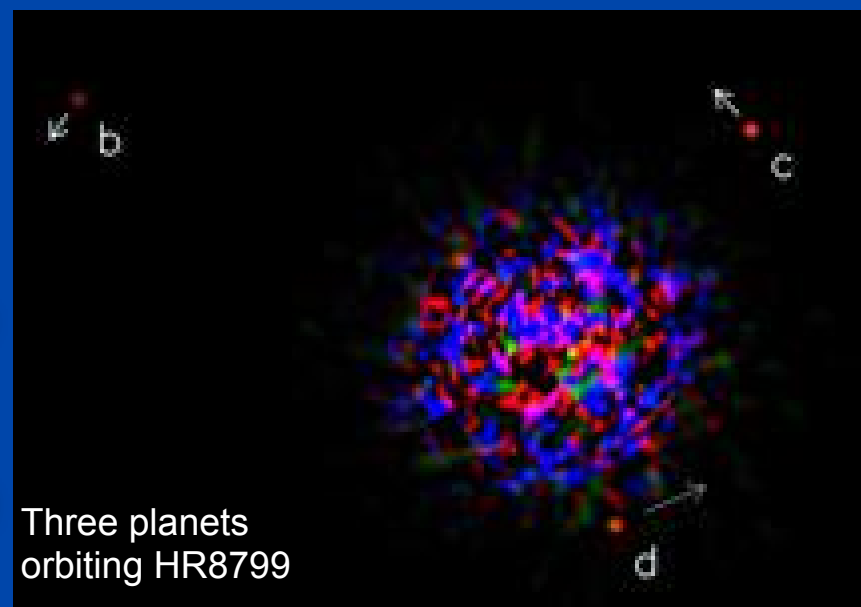
Marois et al. 2008, Science Magazine

$\frac{0.5''}{20 \text{ AU}}$

Glowing young planets



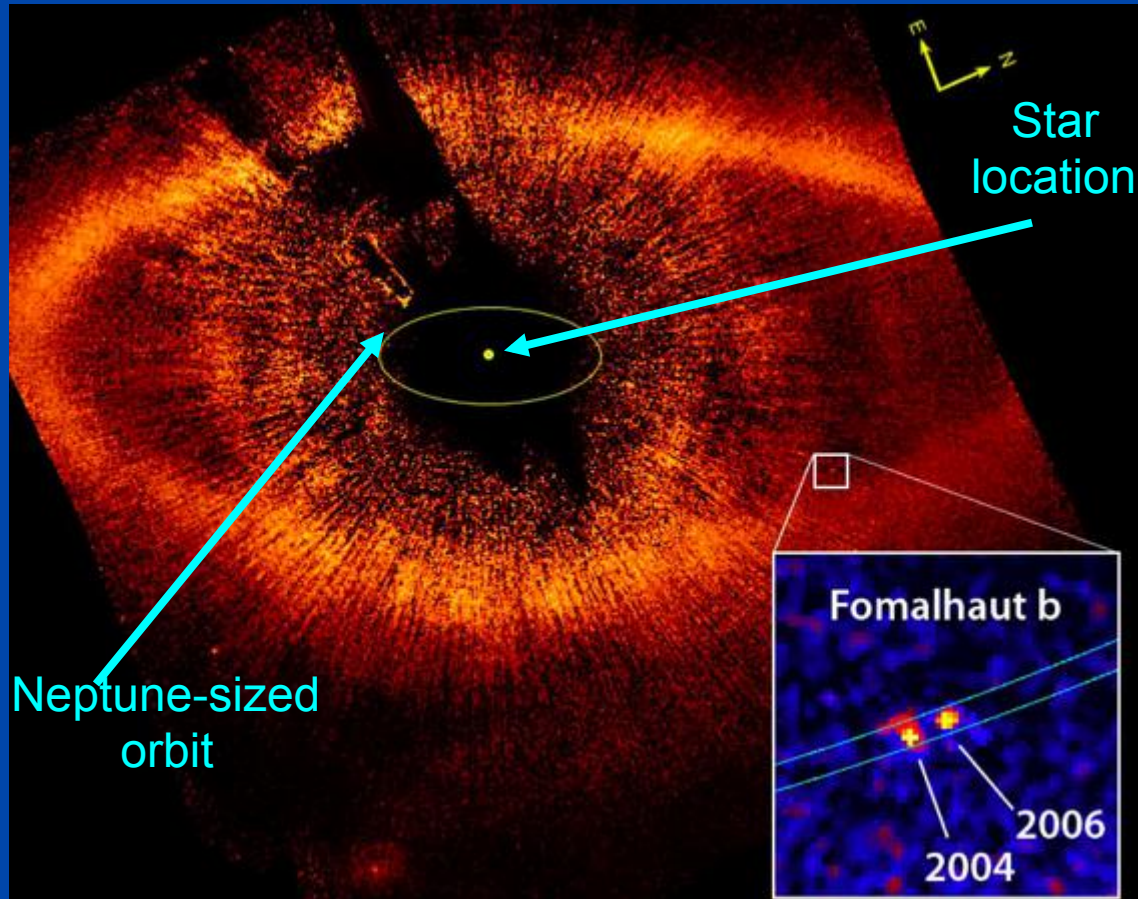
- This star has 3 orbiting planets - the first imaged *planetary system*!
- Advanced observing techniques were used to block the star's light
- Adaptive Optics was used to sharpen images
- Observations were repeated over years, confirming planetary motion
- The planets are young and hot, and therefore glow more brightly than by reflected starlight alone



Three planets orbiting HR8799

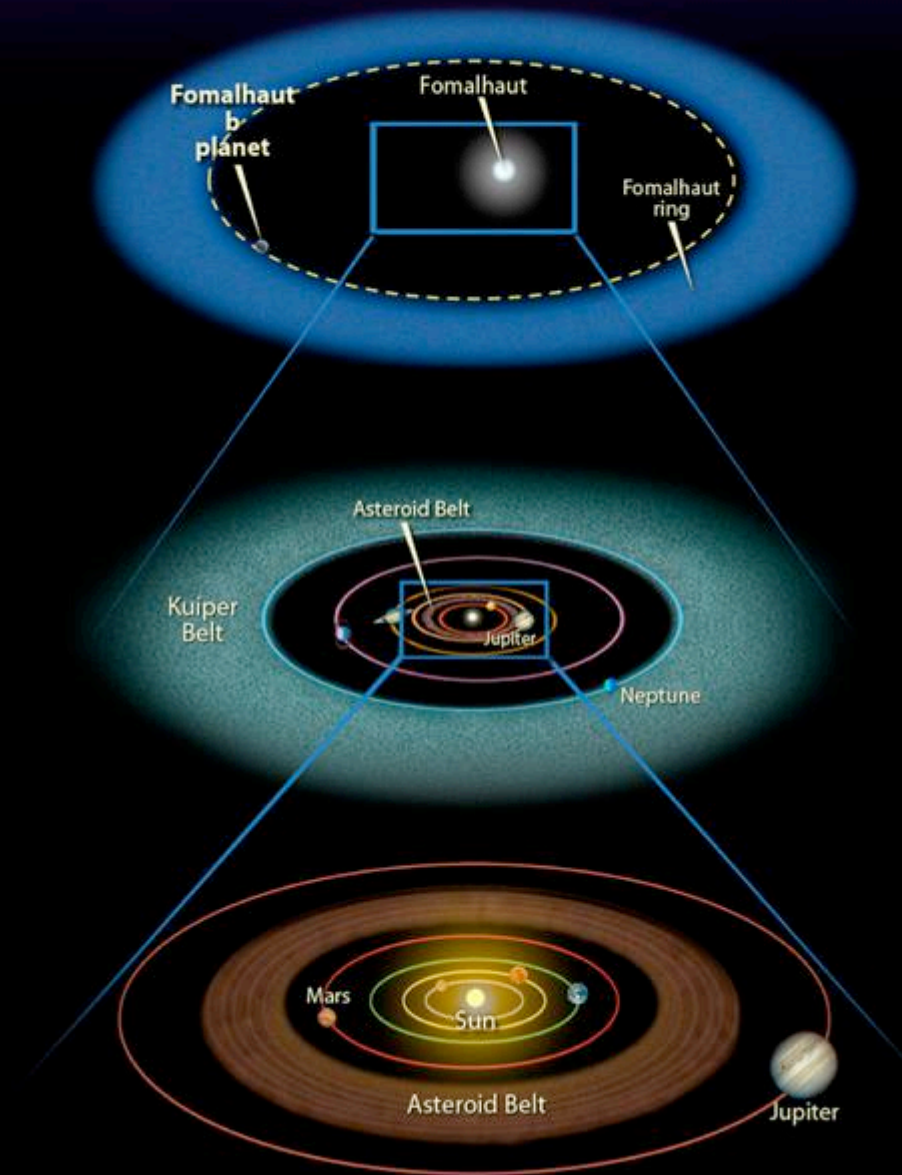
Keck Observatory infrared image of star HR8799 and three orbiting planets with orbital directions indicated by arrows. The light from the star was subtracted, but a lot of 'noise' remains.

First images of exoplanets: Fomalhaut

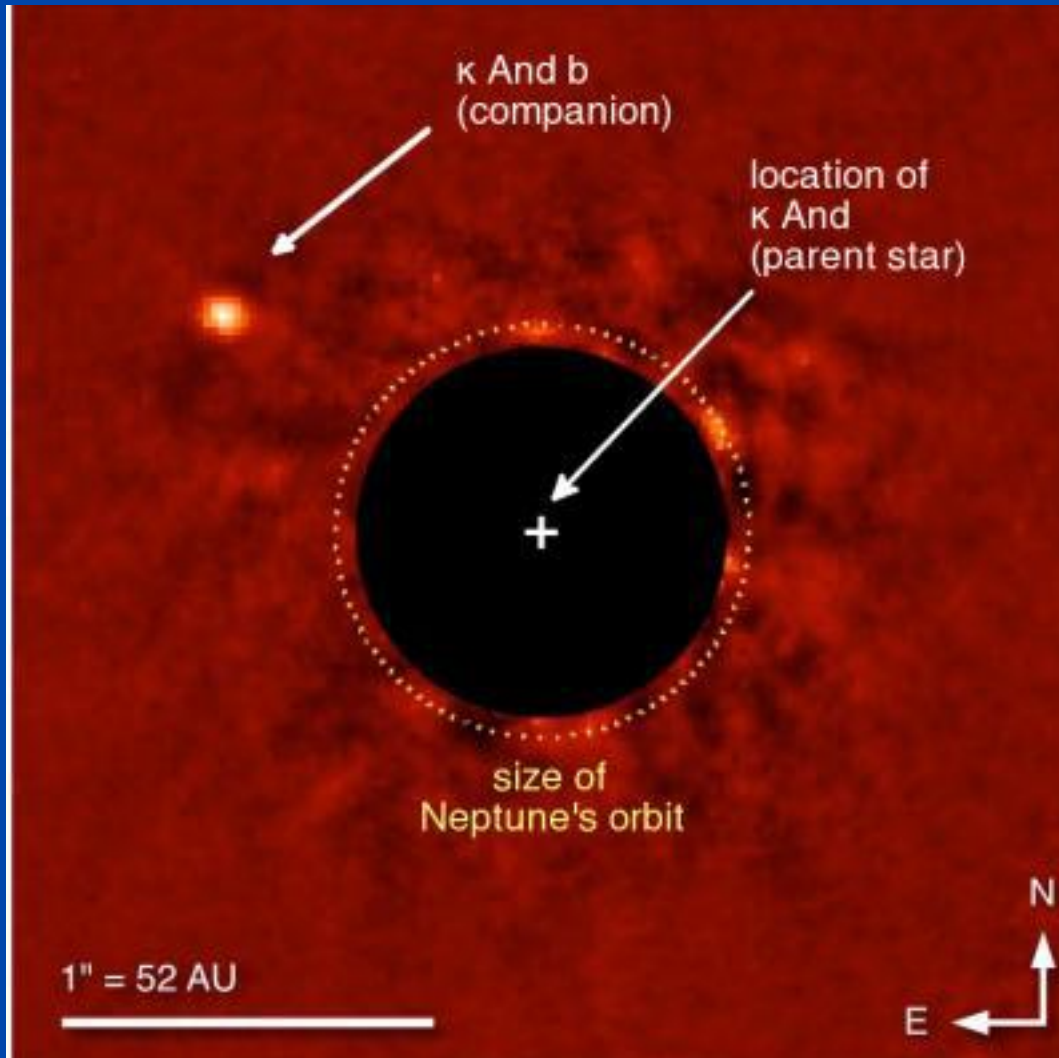


Hubble Space Telescope visible image of the star Fomalhaut (whose light was blocked), with a dust belt similar to the Kuiper belt. Inset: Images taken ~2 years apart show a planet moving around the star.

Comparison of Fomalhaut System and Solar System



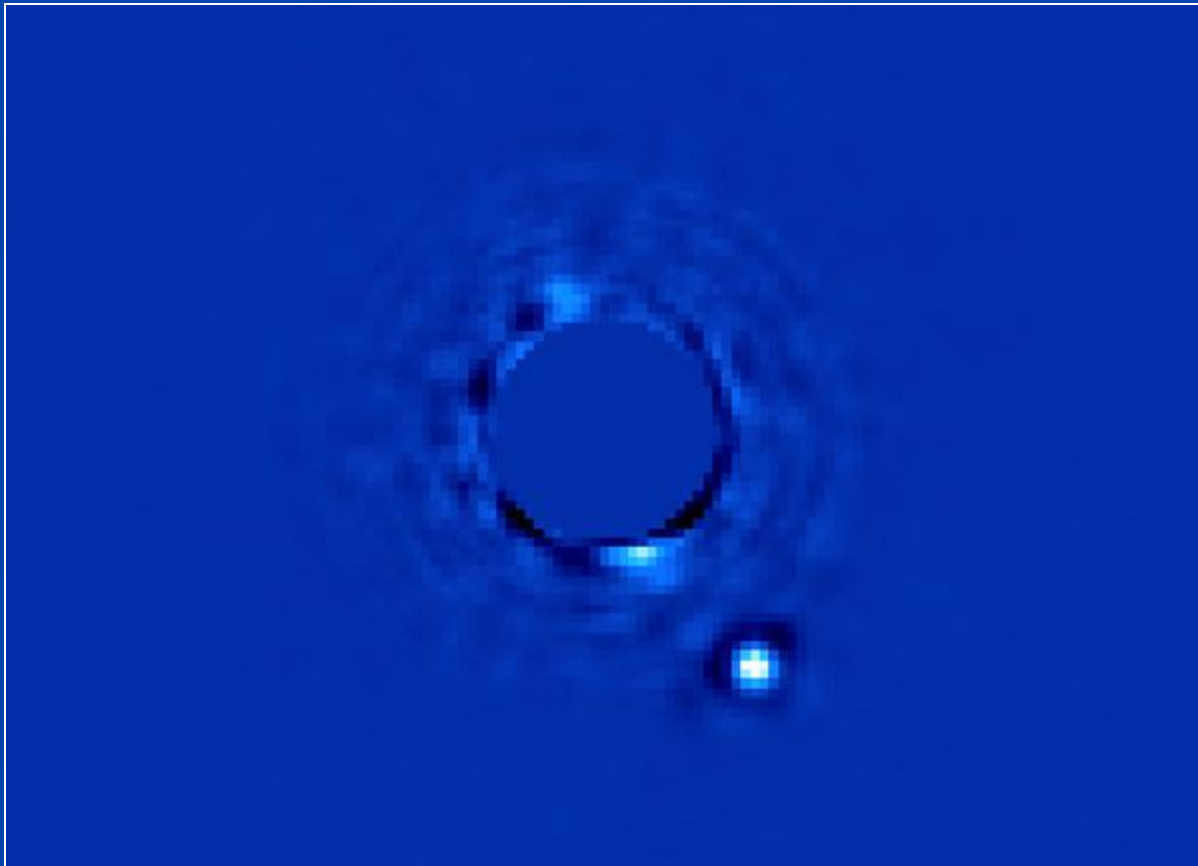
Directly imaged planet around the star Kappa Andromedae



Adaptive optics
image of Kappa
Andromeda b

Subaru Telescope,
Mauna Kea Hawaii

Directly imaged planet around the star Beta Pictoris



Adaptive optics
image of the star
Beta Pictoris

Gemini South
Telescope, Chile

Gemini Planet
Imager

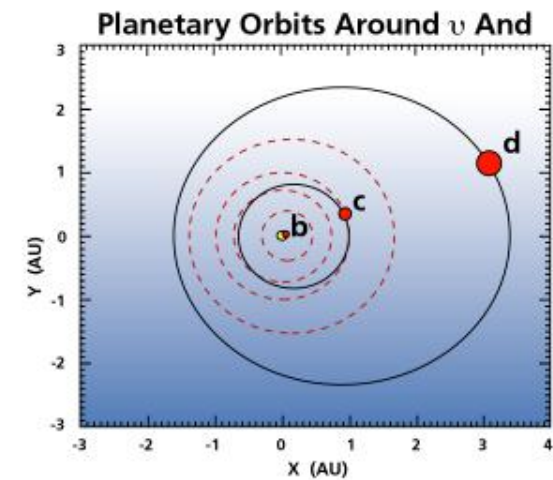
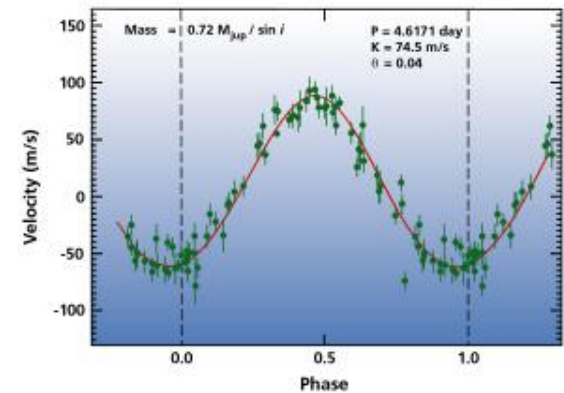
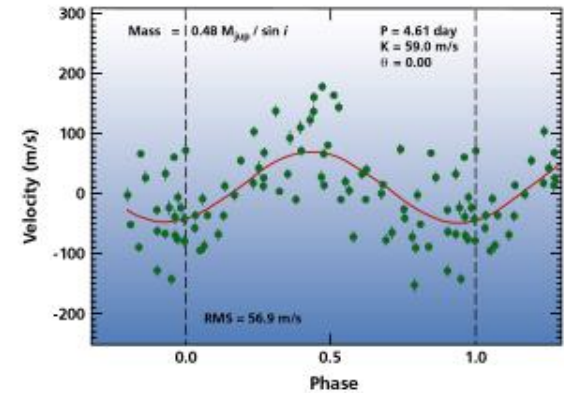
Web lists of all planets, searchable



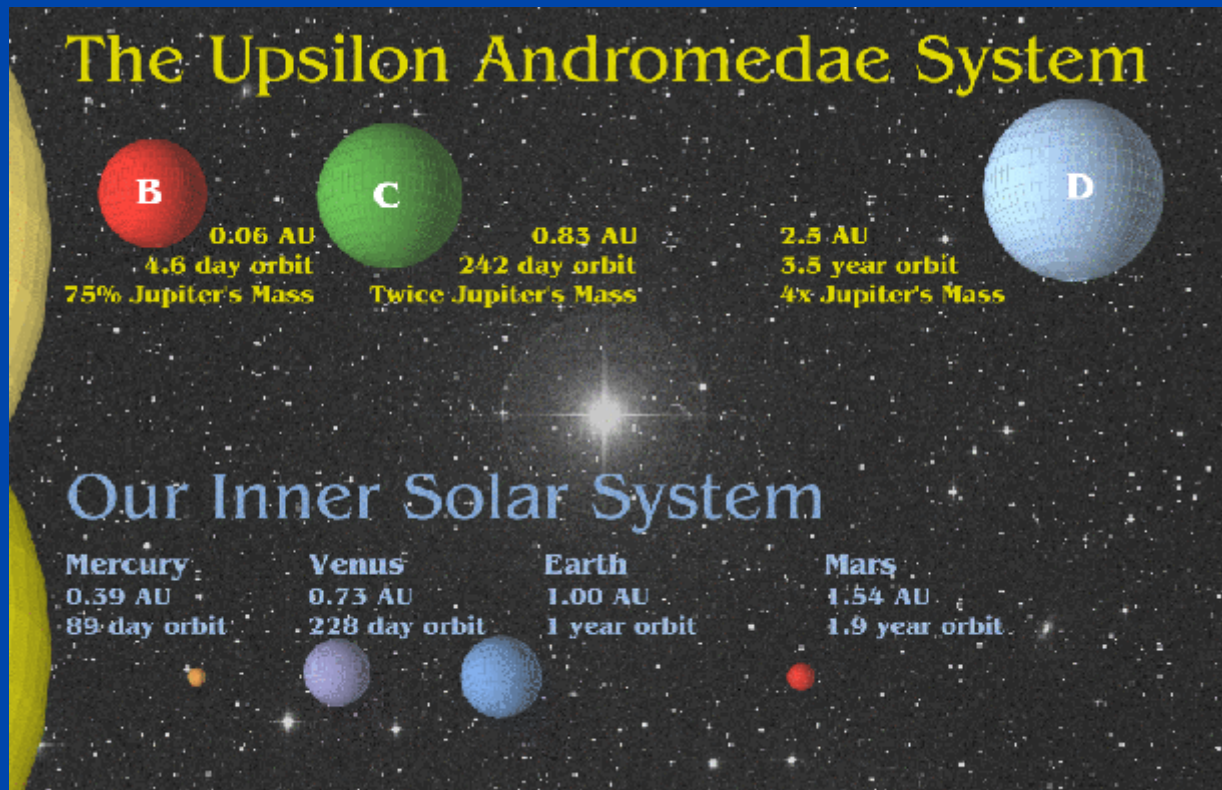
- Exoplanets.org: www.exoplanets.org/
- Exoplanet Encyclopaedia: www.exoplanet.edu
- These sites are continually updated as new planets are discovered

Multi-planet solar system discovered by Doppler method

- Upsilon Andromedae
- Three-planet system

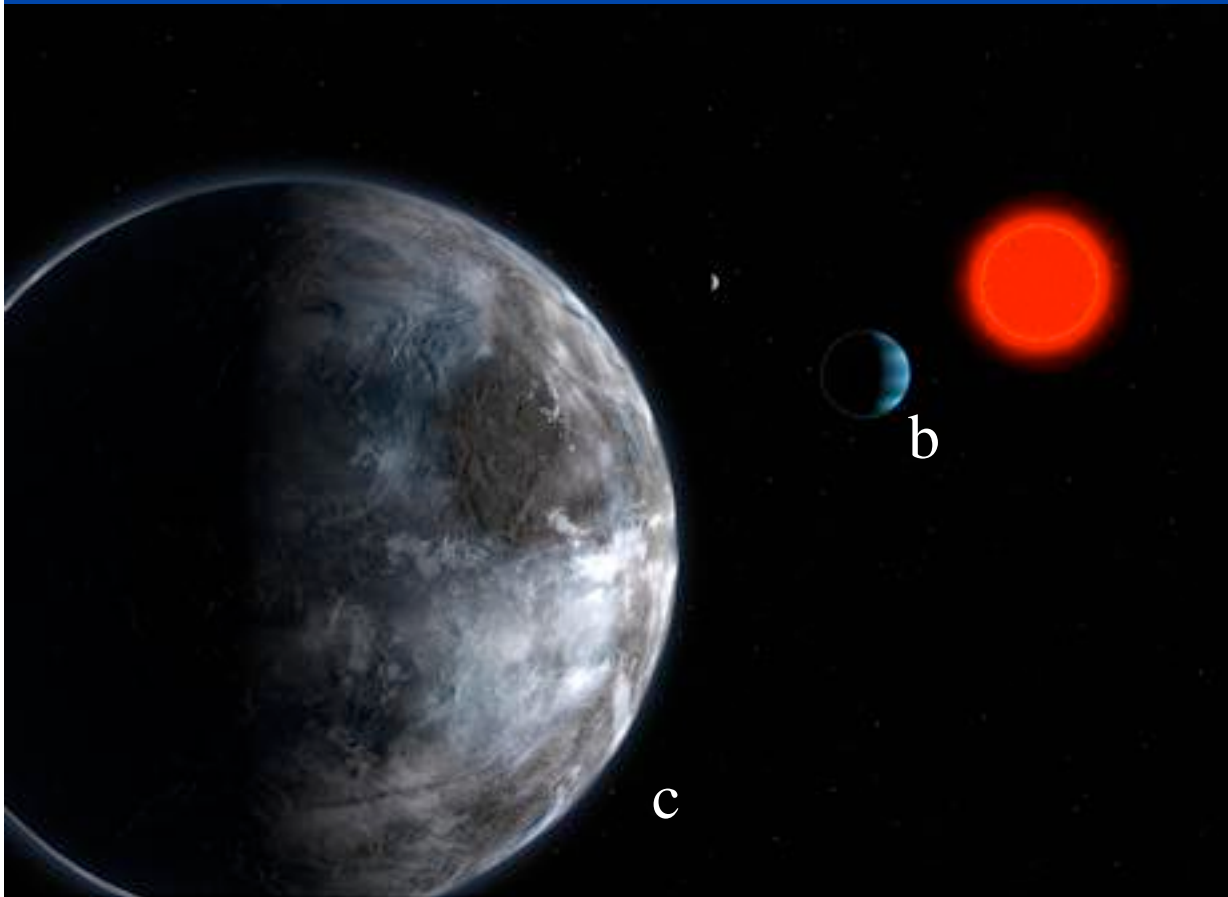


Upsilon Andromedae



- Two planets are several times more massive than Jupiter
- The third planet, mass 75% that of Jupiter, is so close to the star that it completes a full orbit every 4.6 Earth days

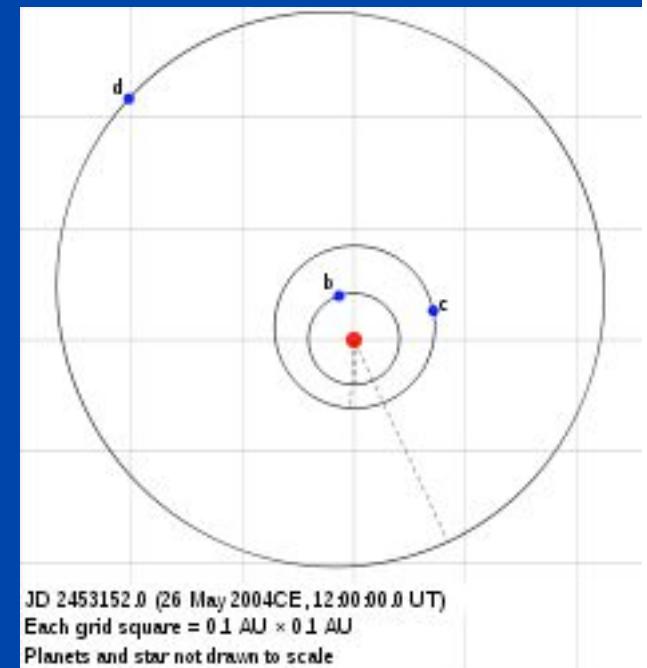
The GJ581 system



The Planetary System in Gliese 581
(Artist's Impression)

ESO Press Photo 22a/07 (25 April 2007)

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- Three planets of 15, 5 and 7 Earth masses
- Small, red star

Questions



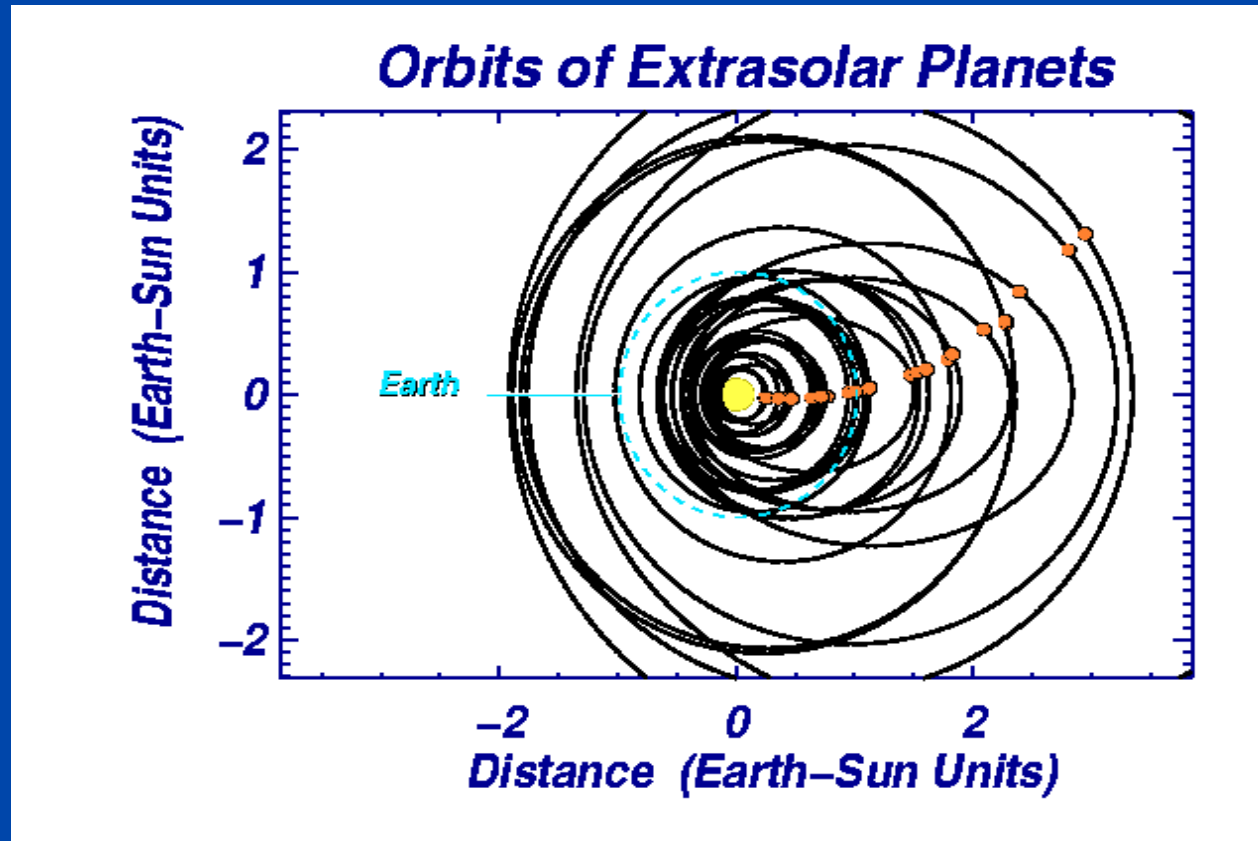
- Has the discovery of other solar systems changed your own feelings about the universe?
- Are you comfortable or uncomfortable with the idea that they are so different from our own?

Unanticipated characteristics of extra-solar planets



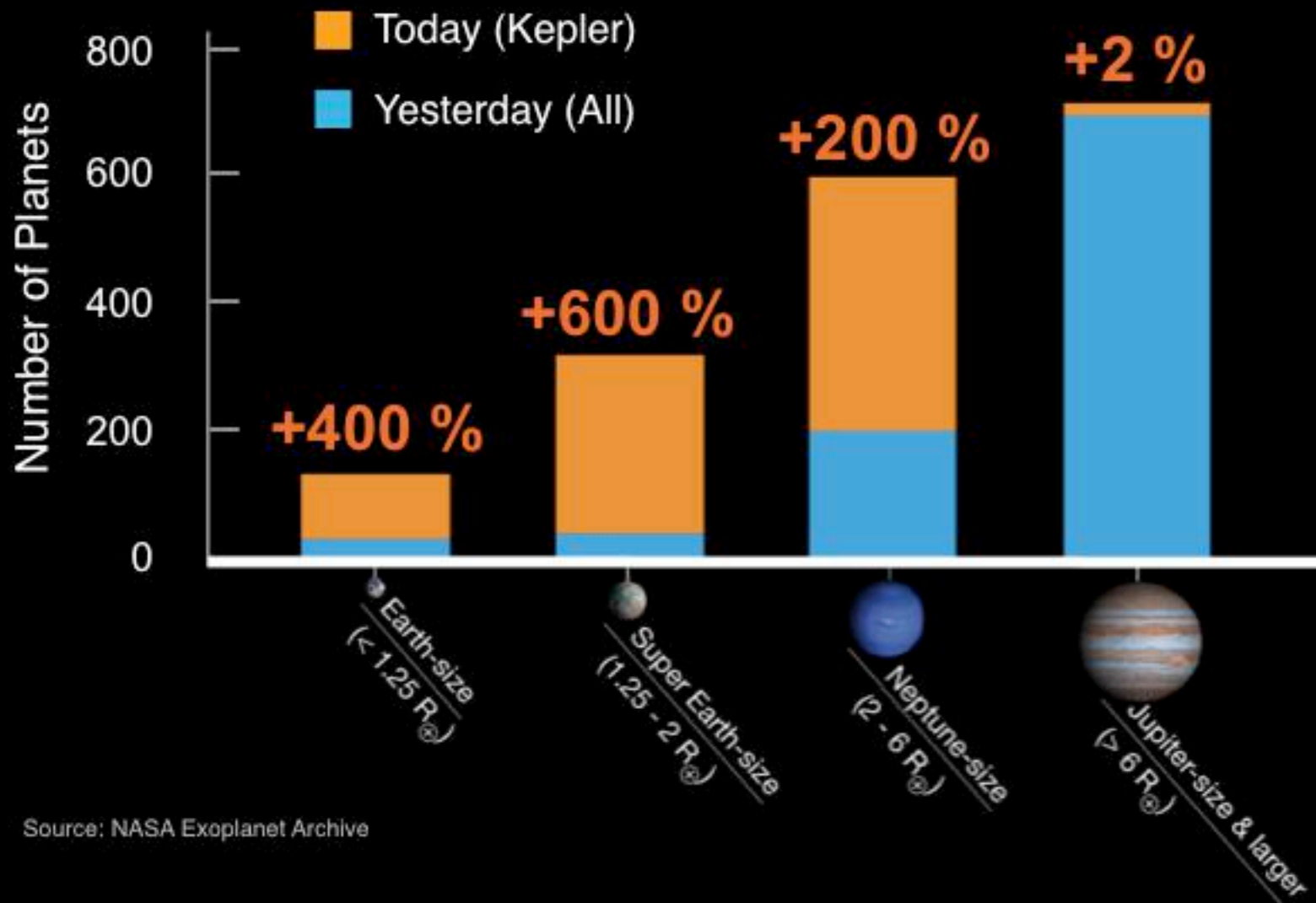
- Many have higher eccentricity in most of their orbits
- Higher fraction of planets very close to their parent stars
- Many planets are “super-Jupiters” (up to 10 times more massive than Jupiter)

Eccentric Orbits



Sizes of Known Exoplanets

As of February 26, 2014



Source: NASA Exoplanet Archive

The Main Points



- The ~ 1700 planets we have detected to date are only a sub-set of potential planets out there
- Many of the new solar systems don't look at all like our own (example: Jupiter-mass planets within the orbit of our Mercury)
- These new solar systems have raised big questions about how our own Solar System formed
- Future search methods have high probability of finding more (and more varied) planets
- It's hard to find Earth-like planets
 - But we are starting to find some!

Thursday's lecture will continue exoplanet discussion



- What we are learning about atmospheres, orbits, origins of extrasolar planets