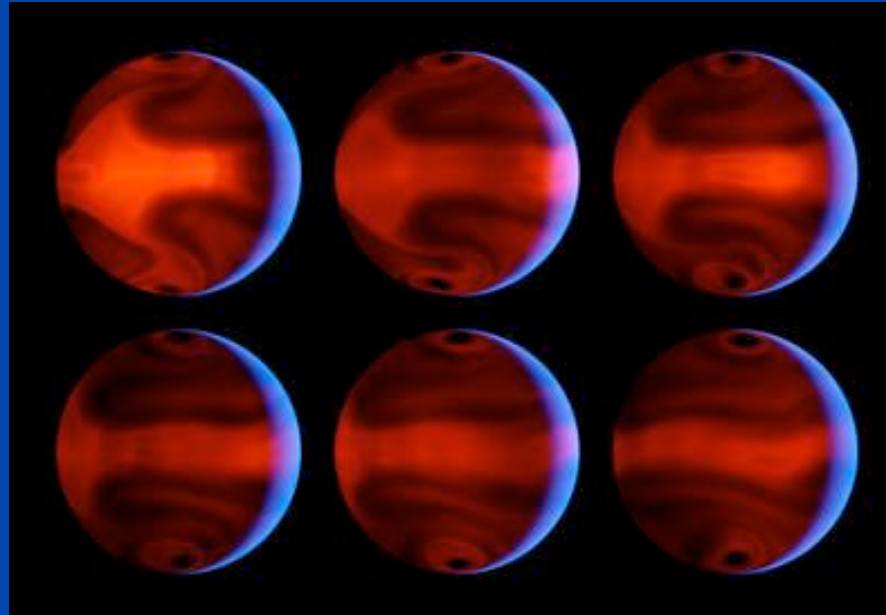


Lecture 8: Extrasolar Planets



Predicted
weather
patterns on
HD80606

Claire Max

October 19, 2010

Astro 18: Planets and Planetary Systems

UC Santa Cruz

Practicalities



- **Midterm**

- A week from today; in this room, regular time
- Multiple-choice questions (lectures and reading)
- Short-answer questions (calculations)

- **Review sessions**

- Section meetings this week will be review sessions for the mid-term exam

Midterm



- Be ready to do calculations using the following concepts:
 - Kinetic and potential energy
 - Newton's and Kepler's laws of gravitation
 - Radiation (Wavelength/Frequency relation, photon energy, Wien and Stefan-Boltzmann's law, Doppler shift)
 - Diffraction limit, Small-angle formula
- Be ready to discuss solar system formation, extrasolar planets
- Formulas will be given on the exam, but you need to know how to use them
- **BRING YOUR SCIENTIFIC CALCULATOR!**

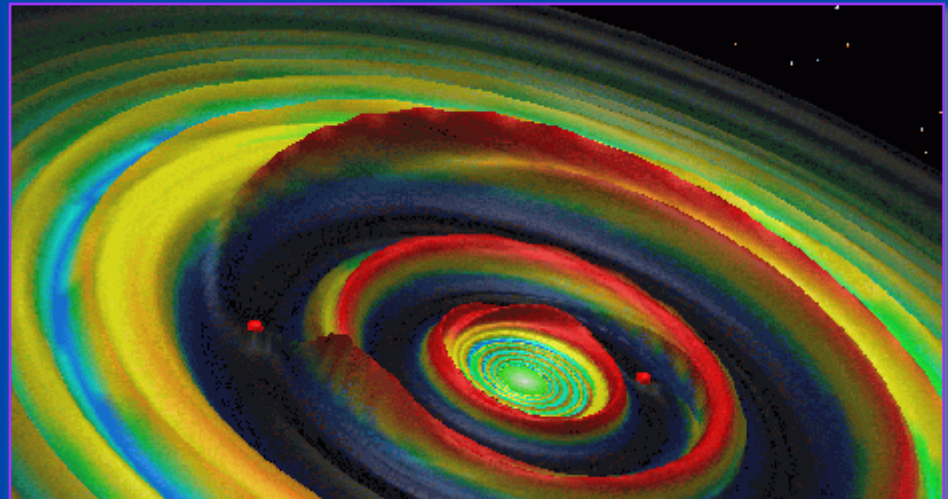
Outline of lecture



- Almost 500 planet candidates have now been observed around other stars
 - How have they been detected?
 - What do they look like?
 - What do they tell us?
 - What does the future hold?

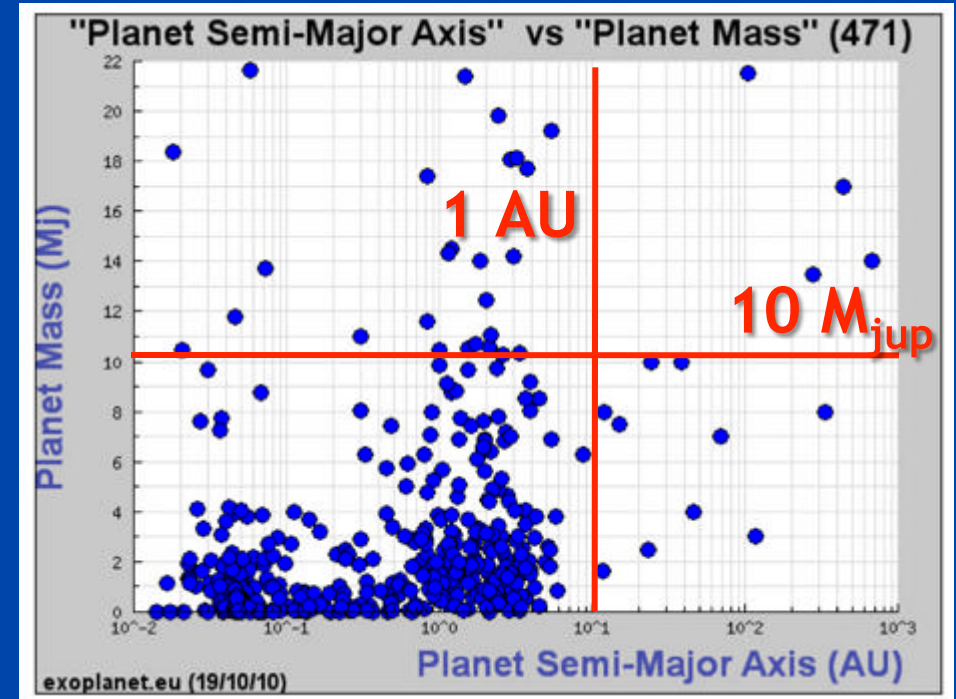
Please remind me to take a break at 12:45 pm

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



Known Exoplanets as of yesterday

- 494 planets
- 416 planetary systems
- 50 multiple planet systems
- Hundreds of planets inside orbit of Earth but more massive than Jupiter



The Main Points



- The ~ 500 planets we have detected to date are only a sub-set of potential planets out there
- 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 prospect of finding Earth-like planets is thrilling!

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!**
- Exoplanet Encyclopaedia

<http://www.exoplanet.eu/catalog.php>

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

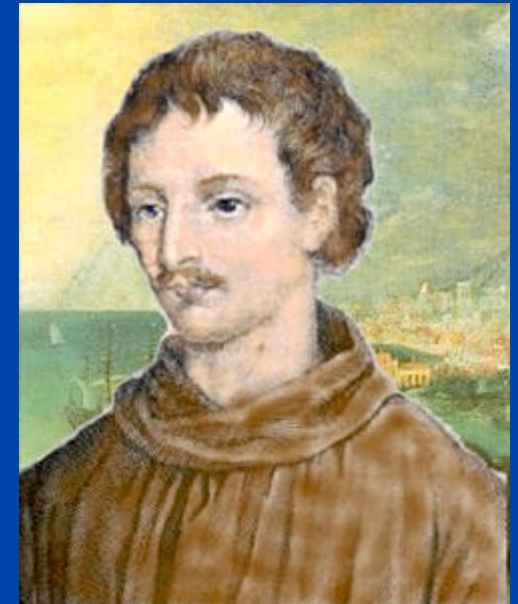


- Leucippus (480 - 420 B.C.)
 - The worlds come into being as follows: many bodies of all sorts and shapes move from the infinite into a great void; they come together there and produce a single whirl, in which, colliding with one another and revolving in all manner of ways, they begin to separate like 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?

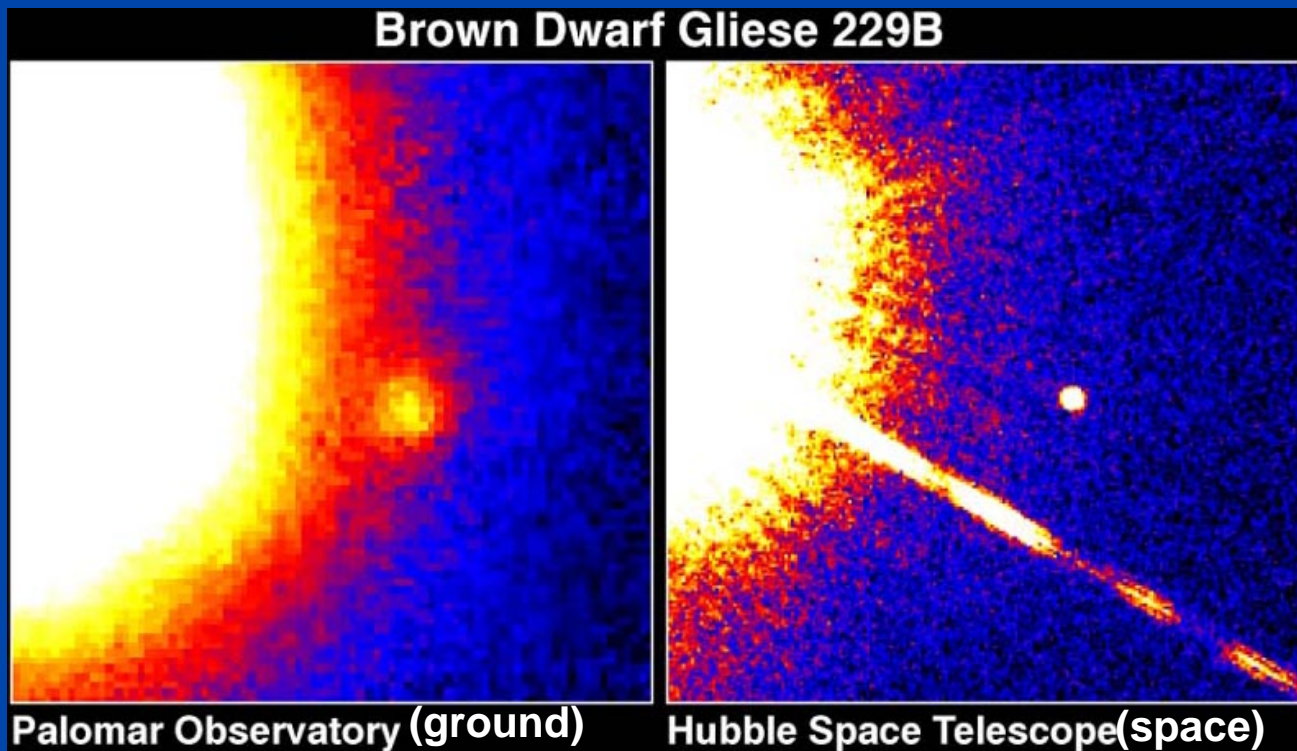


- **Faint planet glimmer is lost in glare from parent star**
 - Planets are small, close to their parent star, and shine by reflected starlight
- **Thought experiment:**
 - Imagine grain of rice an inch from a 100 Watt light bulb. Someone standing at end of a long dark hall would see only the light bulb, 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
 - **Most planets to date have been detected by indirect methods**
- **Direct:** pictures or spectra of the planets themselves
 - **Only recently starting to be used successfully**

Observational techniques



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

Observational techniques



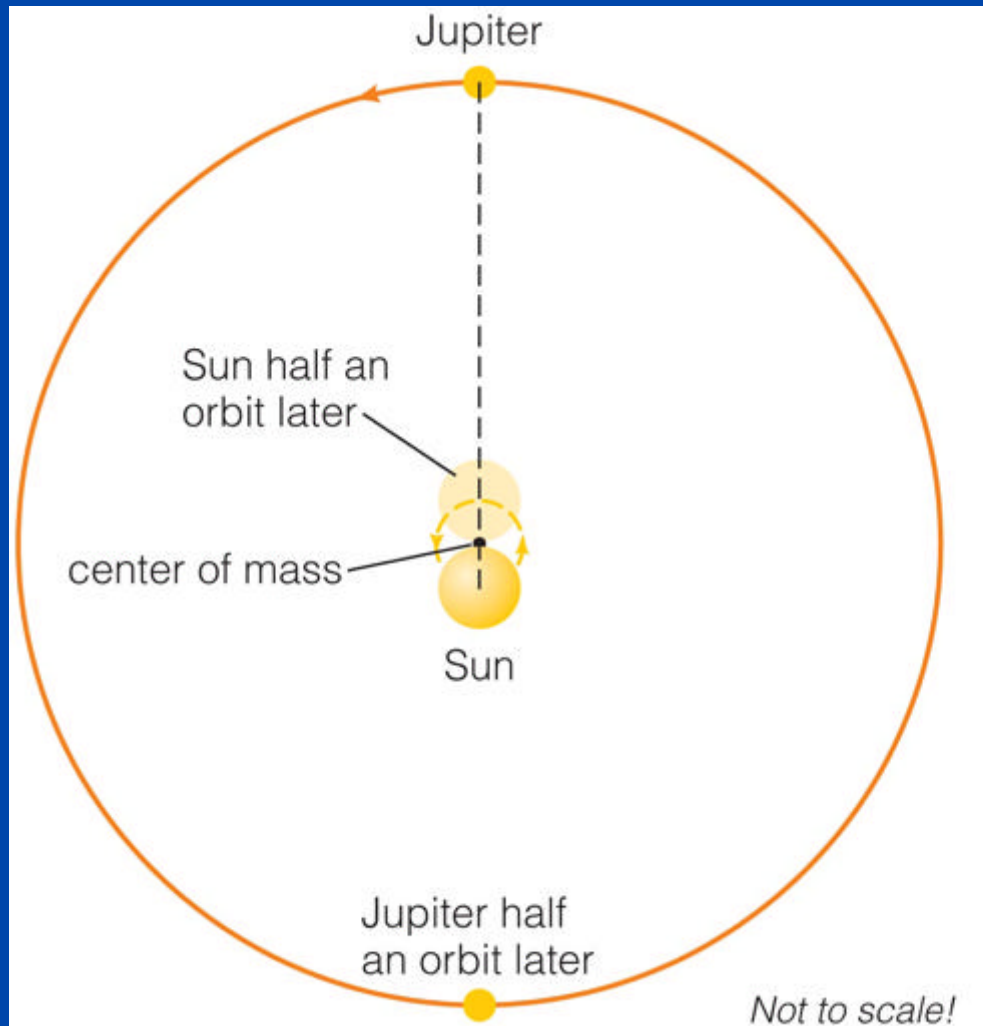
- Doppler spectroscopy
- Transit photometry and spectra Direct
- Microlensing
- Astrometry
- Direct imaging Direct

Observational techniques



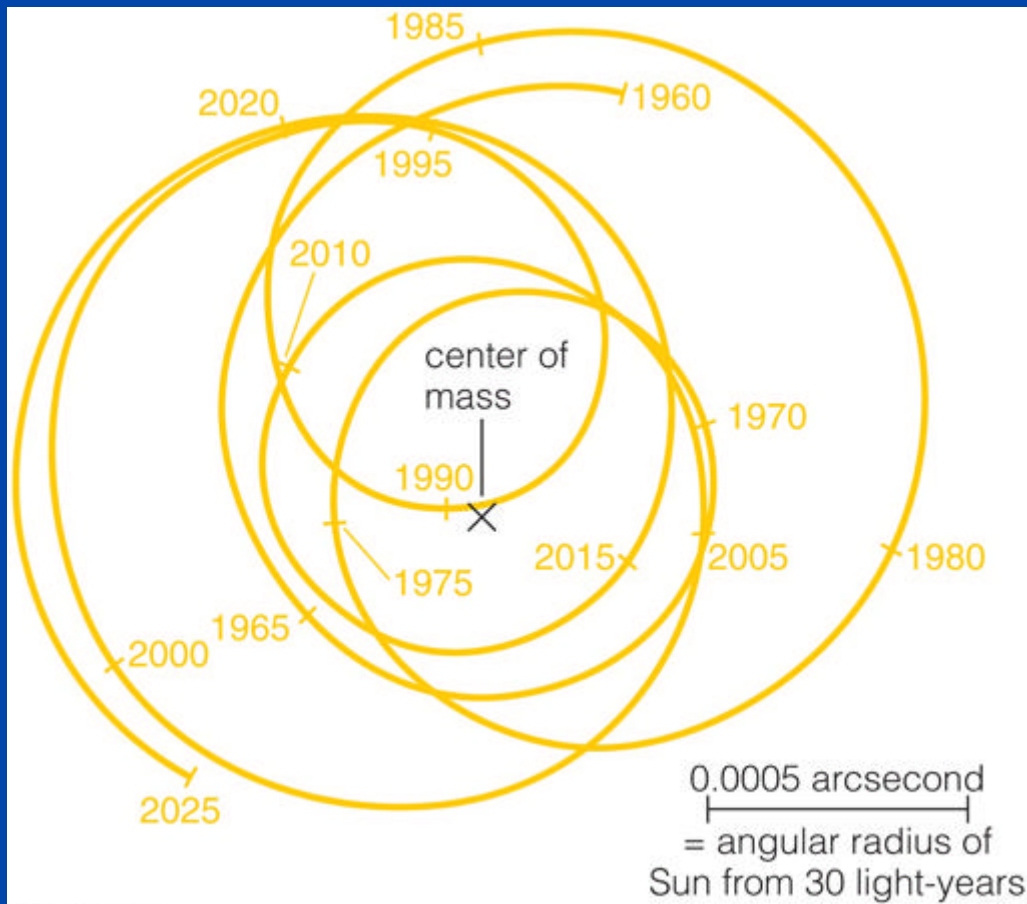
- Doppler spectroscopy
- Transit photometry and spectra
- Microlensing
- Astrometry
- Direct imaging

Gravitational Tugs



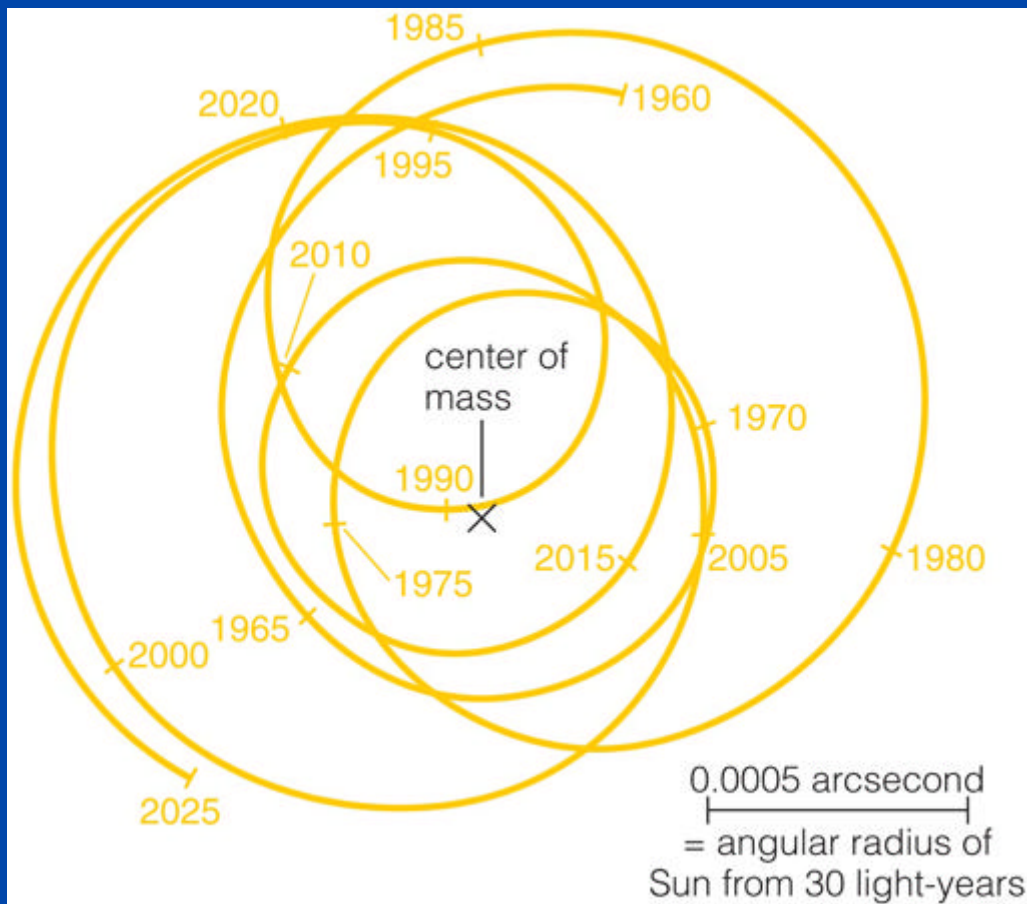
- The Sun and Jupiter orbit around their common center of mass.
- The Sun therefore wobbles around that center of mass with same period as Jupiter.

Gravitational Tugs



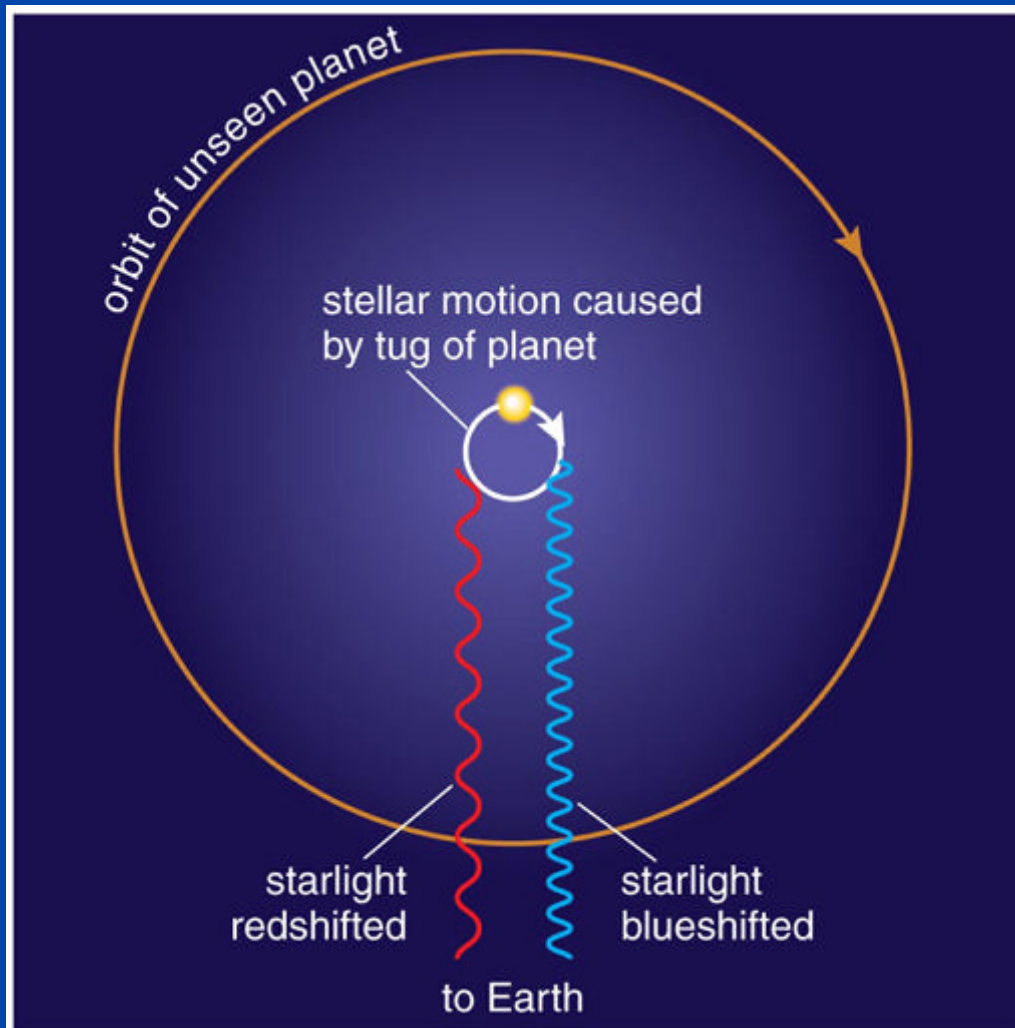
- The Sun's motion around the solar system's center of mass depends on tugs from all the planets.
- Astronomers around other stars that measured this motion could determine the masses and orbits of all the planets.

Astrometric Technique



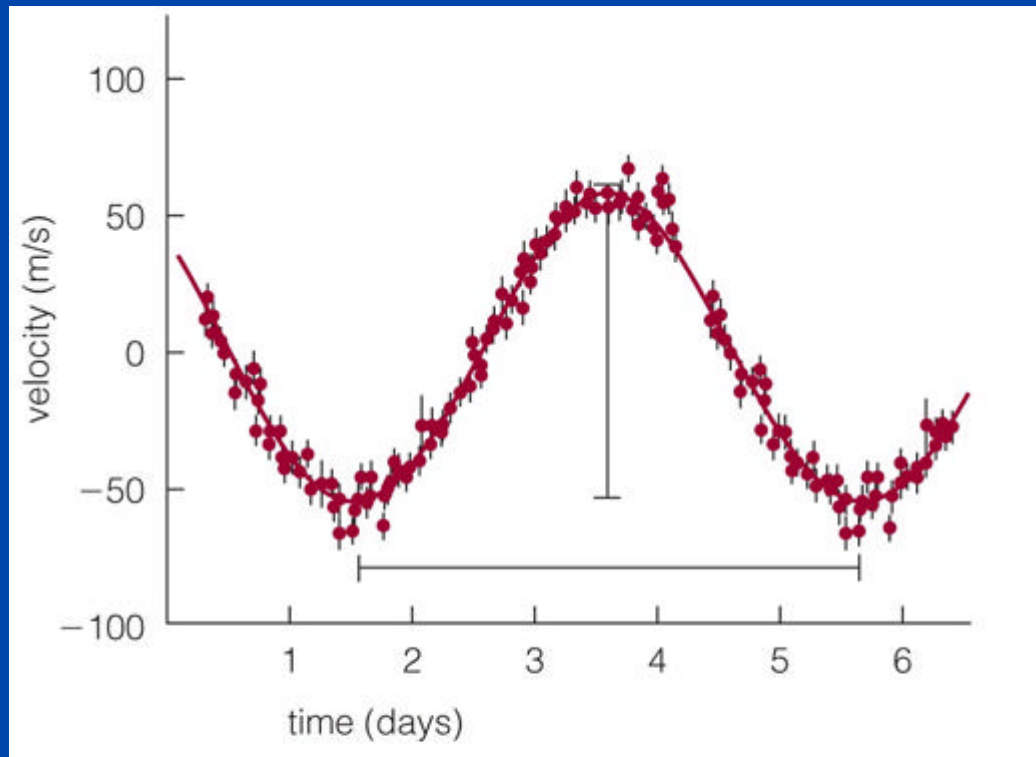
- We can detect planets by measuring the change in a star's position on sky.
- However, these tiny motions are very difficult to measure (~ 0.001 arcsecond).

Doppler Technique



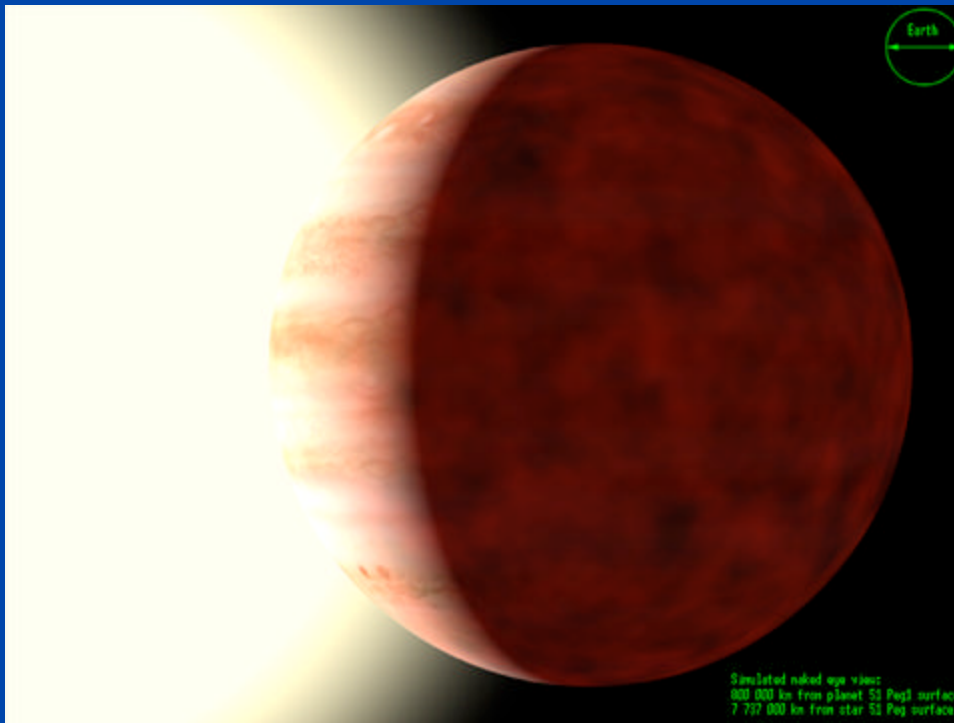
- Measuring a star's Doppler shift can tell us its motion toward and away from us.
- Current techniques can measure motions as small as 1-2 m/s (walking speed!).

First Extrasolar Planet: 51 Pegasi



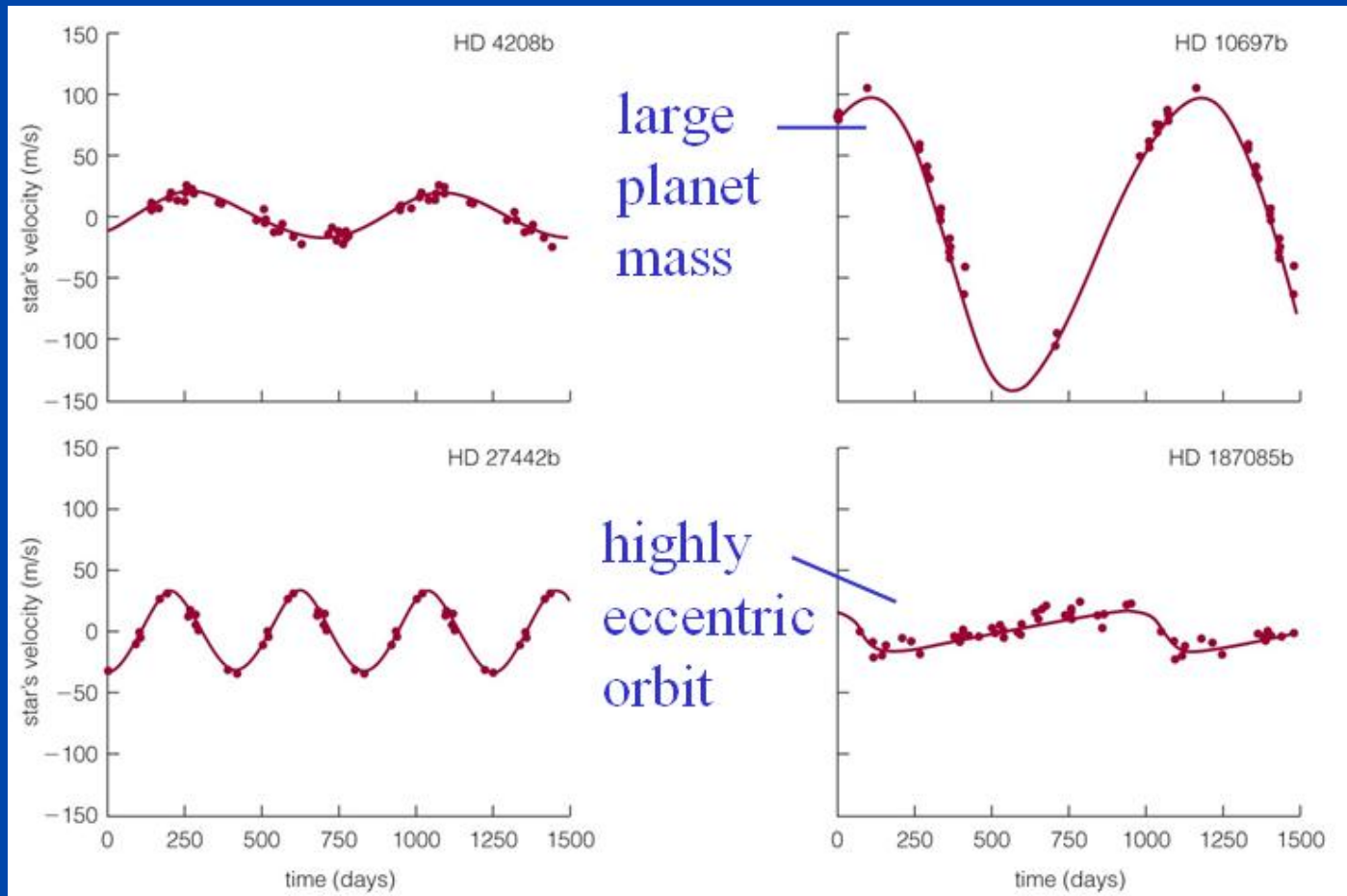
- Doppler shifts of the star 51 Pegasi indirectly revealed a planet with 4-day orbital period.
- This short period means that the planet has a small orbital distance – well within orbit of Mercury.
- This was the first extrasolar planet to be discovered (1995).

51 Peg b (1995)



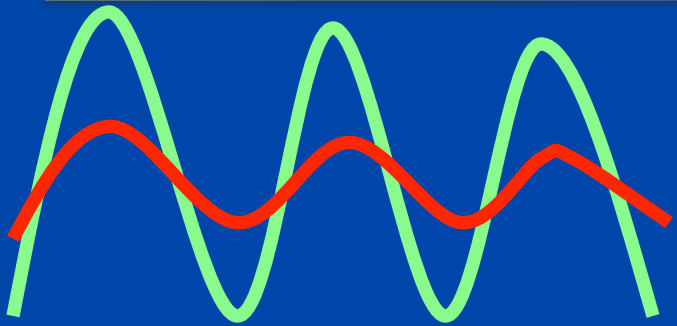
Half the mass of Jupiter, yet orbiting much closer to the Sun than Mercury!

Other Extrasolar Planets



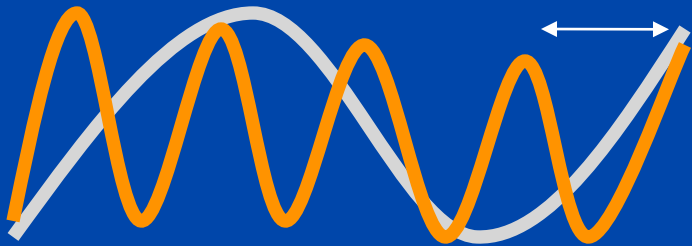
- Doppler shift data tell us about a planet's mass and the shape of its orbit.

Planetary signatures



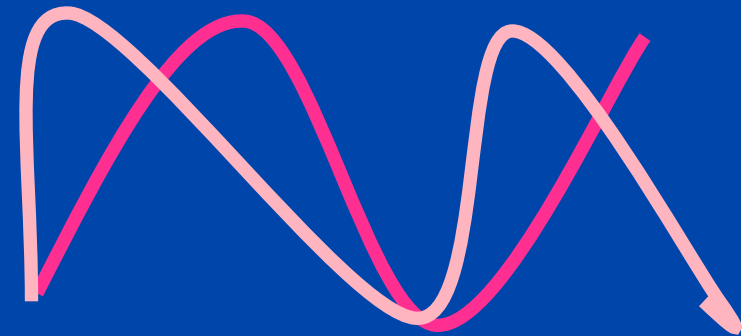
Size
depends
on mass
of planet

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



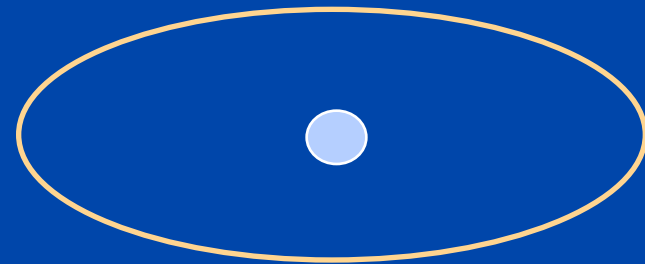
- **Look for periodic shift in star's spectrum**
 - Does not depend on distance of star
 - Need **massive planet near star**
 - » the closer the planet, the faster the orbital speed (of both planet and star)
 - Need very good spectrum
 - » measure Doppler shifts of < 1 part in 1,000,000
- **90% of planet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

<http://rml3.com/a10p/detecting.htm>

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

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- D. It has a planet, but we do not have enough information to know its orbital distance.

Find your own planet!

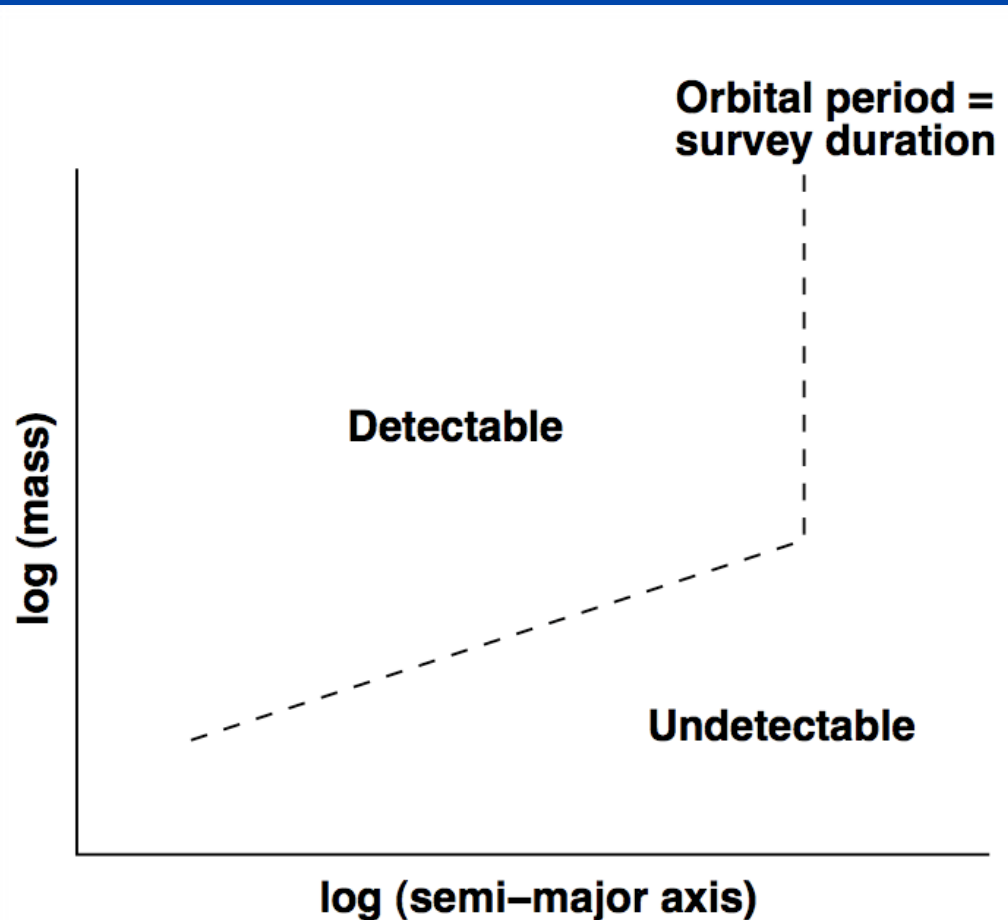


- <http://oklo.org/category/exoplanet-detection/>
- “Systemic” console: you participate in finding signals of planets from telescope data that others have obtained

Limitations of Doppler technique



- From ground-based observatories, detect shifts $> 1\text{-}2$ m/sec
- The nearer to the star and the more massive the planet, the easier to detect



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

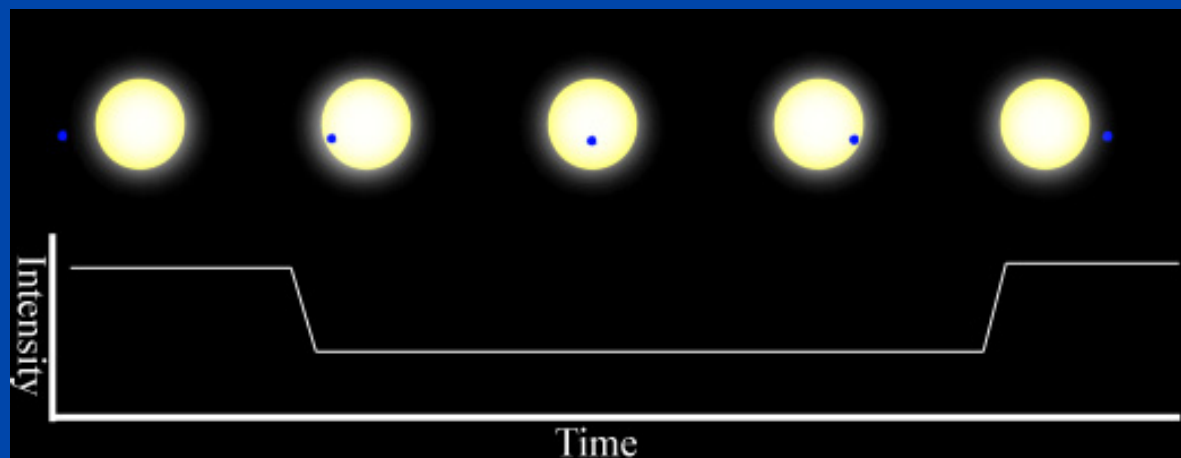


- Doppler spectroscopy
- Transit photometry and spectra
- Microlensing
- Astrometry
- Direct imaging

Transits



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



Animation of transit planet detection technique

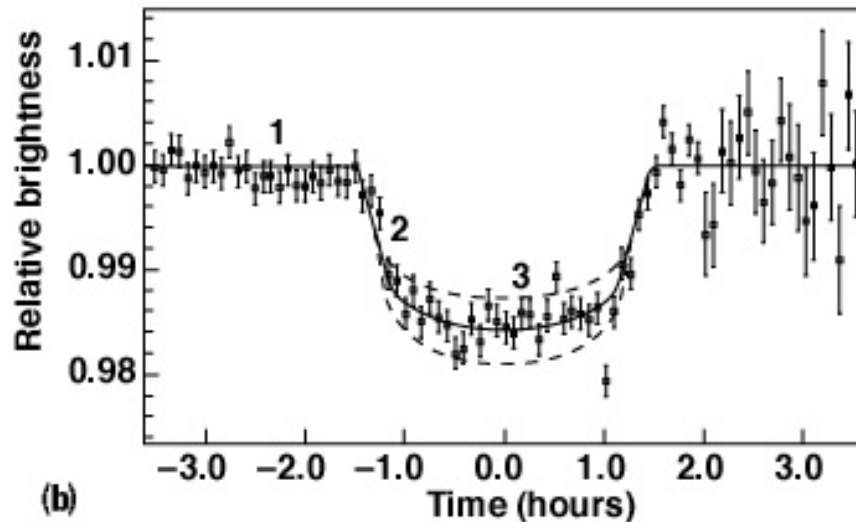


[file:///Users/max/Desktop/AY18%202010/
Bennett6e_IG_0321634411_PDF/13_Lecture_Outline/
IF_13_07_PlanetaryTransits.htm](file:///Users/max/Desktop/AY18%202010/Bennett6e_IG_0321634411_PDF/13_Lecture_Outline/IF_13_07_PlanetaryTransits.htm)

Planet detected around the star HD209458 by transit method



(a)

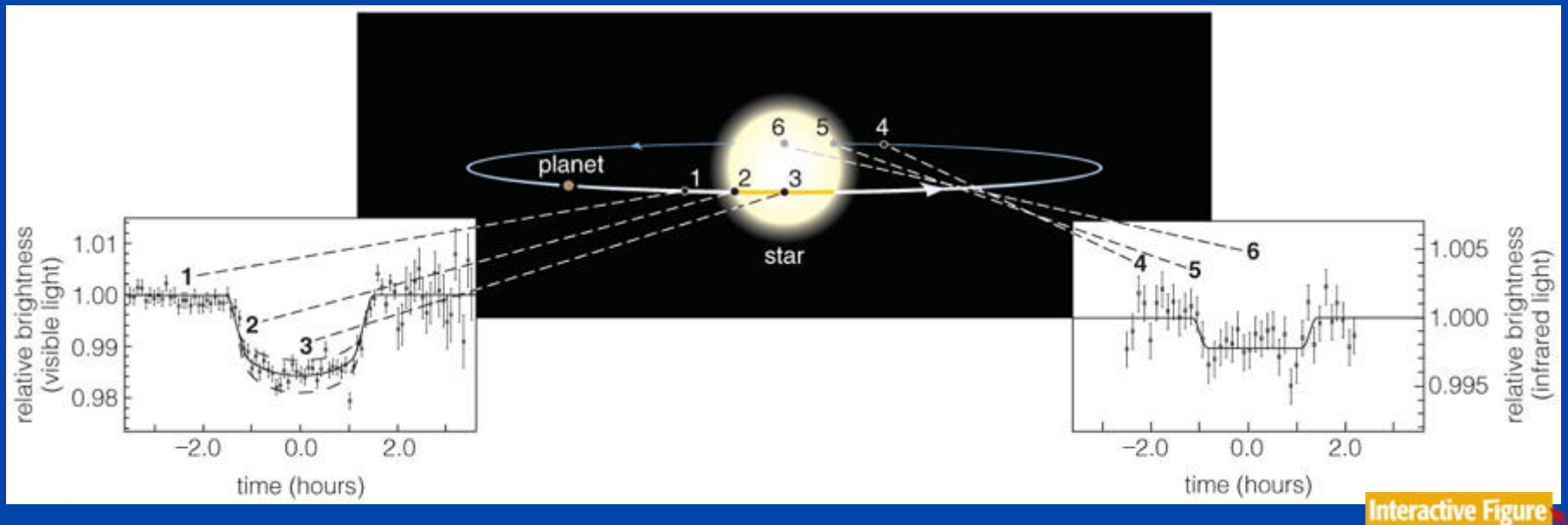


(b)

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 ~ 70 planets have been found this way
- Amateur astronomers have organized to watch for fluctuations in star brightness
- <http://www.transitsearch.org/>

Transits and Eclipses



- A **transit** is when a planet crosses in front of a star.
- **Eclipse** is when a planet goes behind a star
- From both, can learn about atmosphere of planet (beginning and end of transit, eclipse)

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

NASA's Kepler Space Mission to detect transiting planets

- **March 2009: NASA mission Kepler was launched**
- **Scans a hundred thousand stars in the constellation Cygnus for planets**
- **Measurement precision expected to detect and characterize Earth-sized planets**
- **Kepler has already been able to detect the light from a known transiting extrasolar gas giant, HAT-P-7b**
- **Many discoveries to be announced soon**

Observational techniques



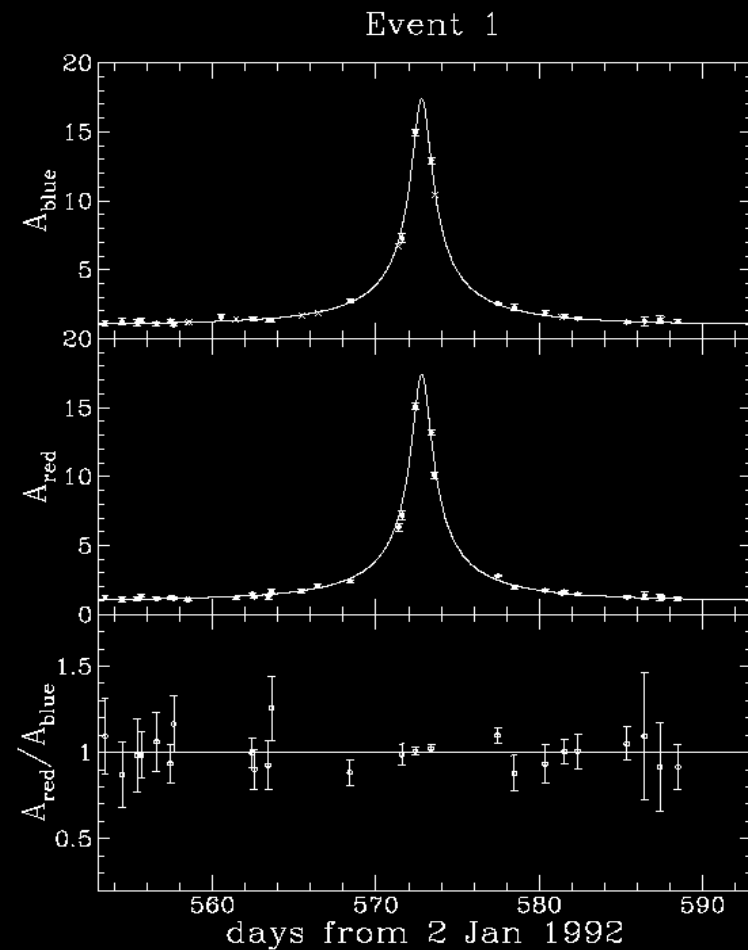
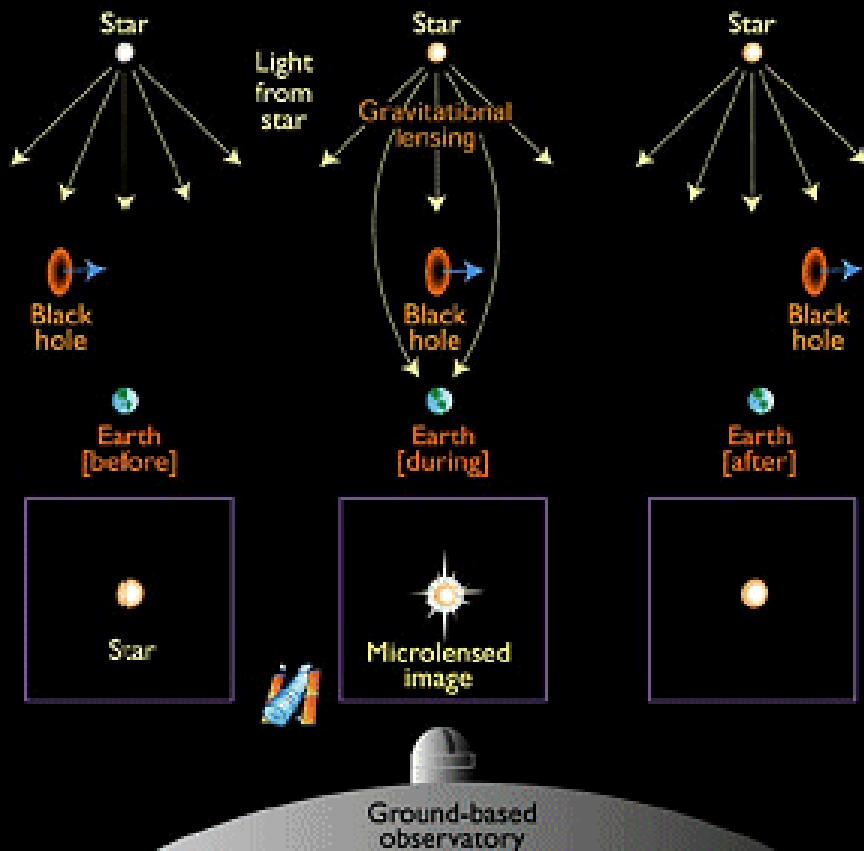
- Doppler spectroscopy
- Transit photometry and spectra
- **Microlensing**
- Astrometry
- Direct imaging

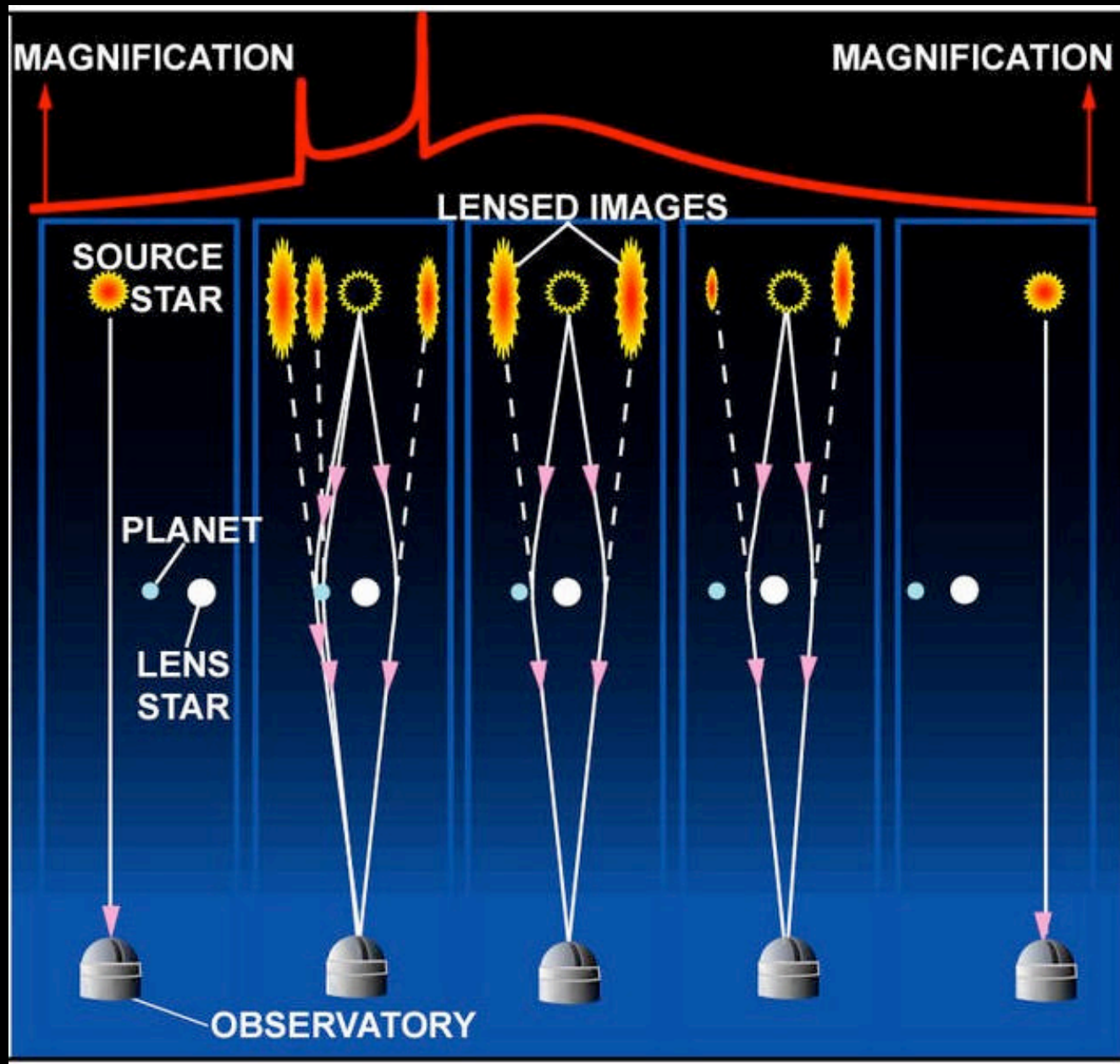
Method three: Microlensing



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

Gravitational Microlensing by Black Hole





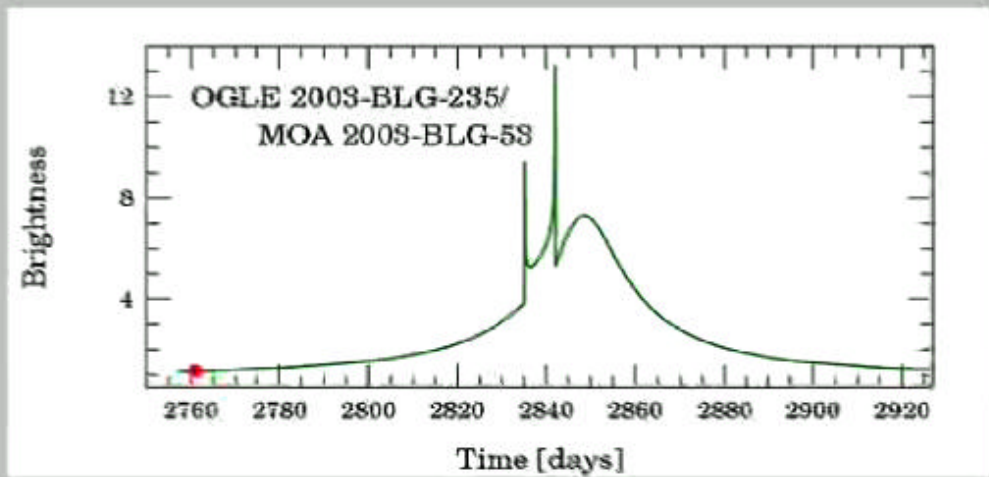
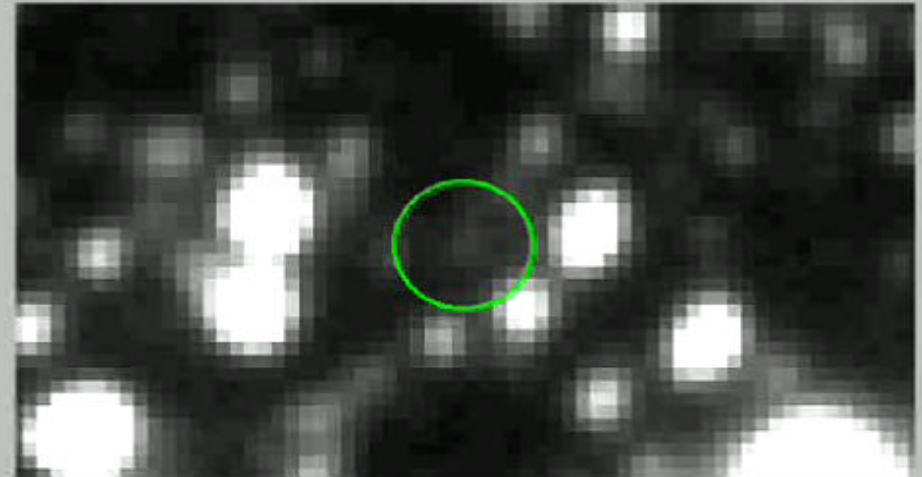
Needs almost perfect alignment between source and lens.

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

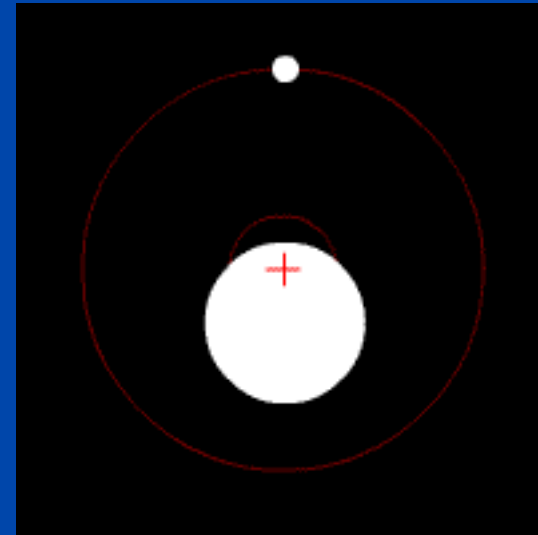


- Doppler spectroscopy
- Transit photometry and spectra
- Microlensing
- **Astrometry**
- Direct imaging

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
- No confirmed candidates yet



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

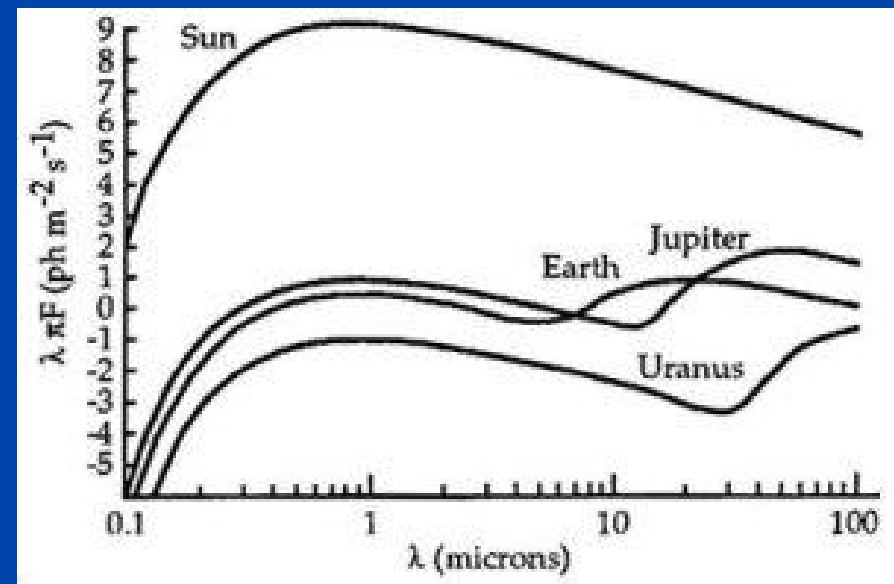


- Doppler spectroscopy
- Transit photometry and spectra
- Microlensing
- Astrometry
- Direct imaging

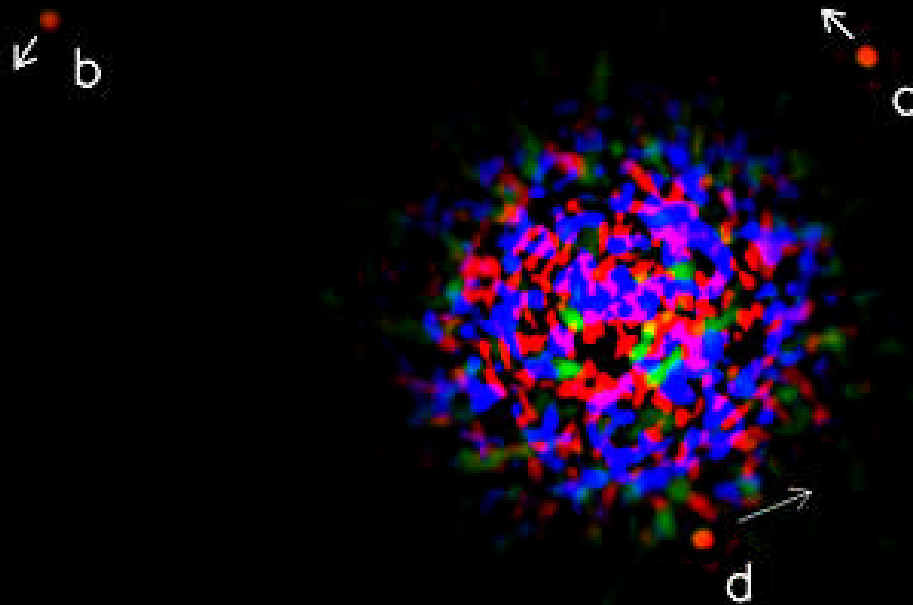
Direct Imaging



- 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



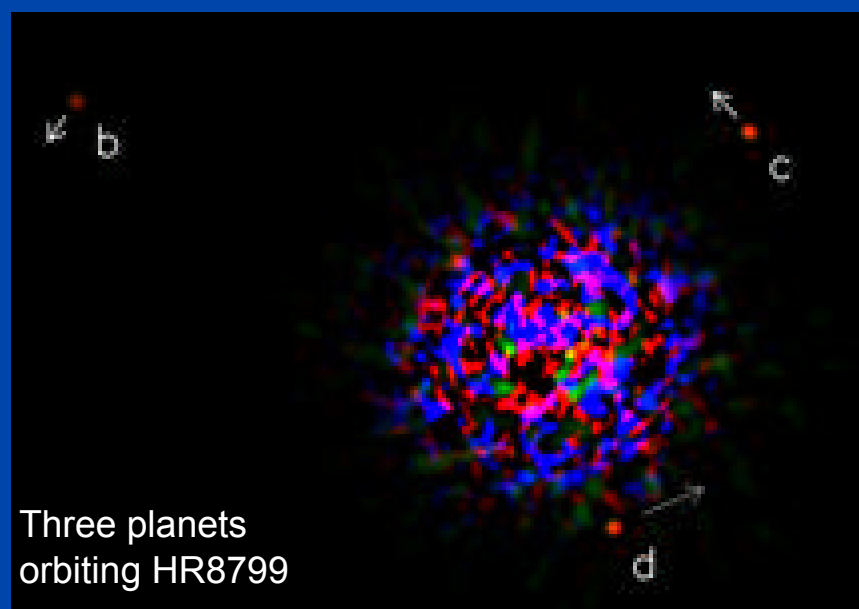
Marois et al. 2008, Science Magazine

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

Glowing young planets



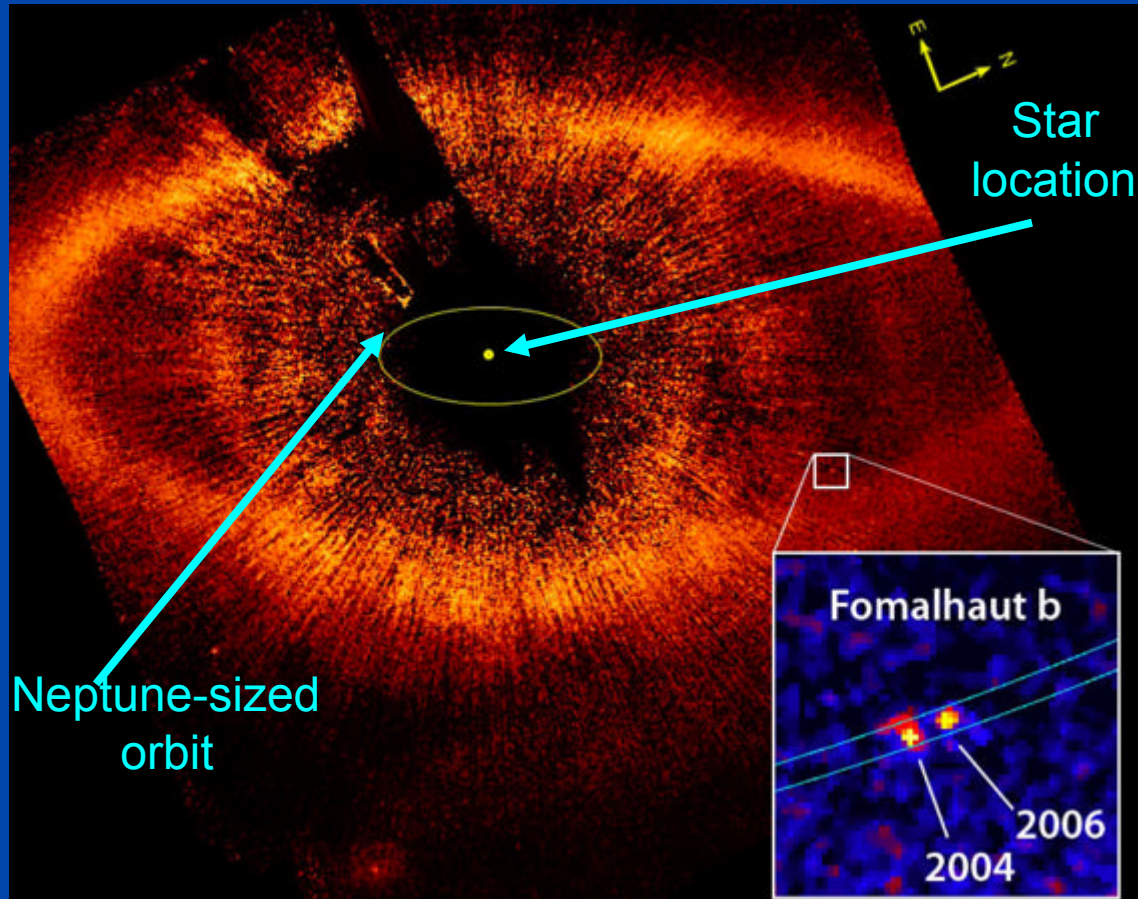
- This star has 3 orbiting planets - the first imaged planetary system!
- Advanced observing techniques were used to block the star's light
- Adaptive Optics was used to sharpen images
- Observations were repeated over years, confirming planetary motion
- The planets are young and hot, and therefore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



Three planets orbiting HR8799

Keck Observatory infrared image of star HR8799 and 3 orbiting planets; orbital directions indicated by arrows. The light from the star was subtracted, but a lot of 'noise' remains.

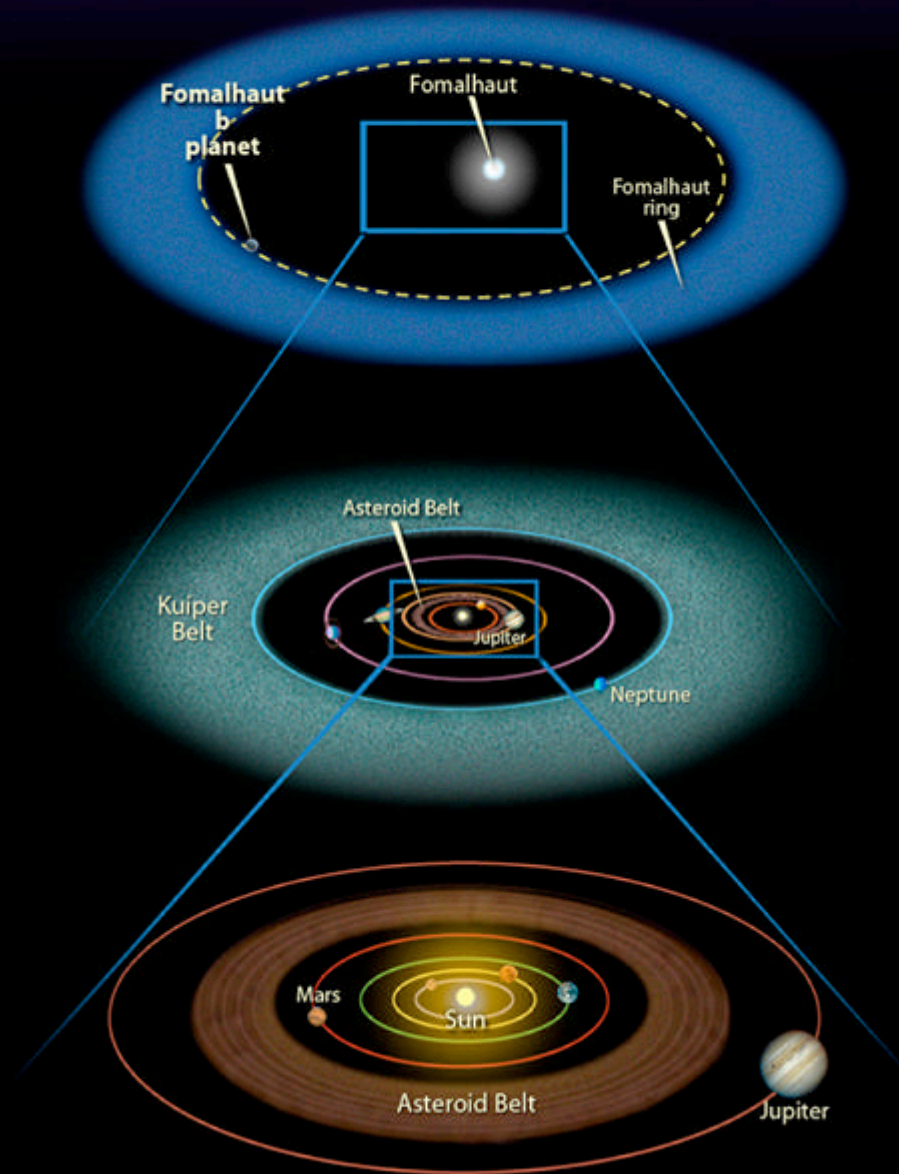
First images of exoplanets: Fomalhaut



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

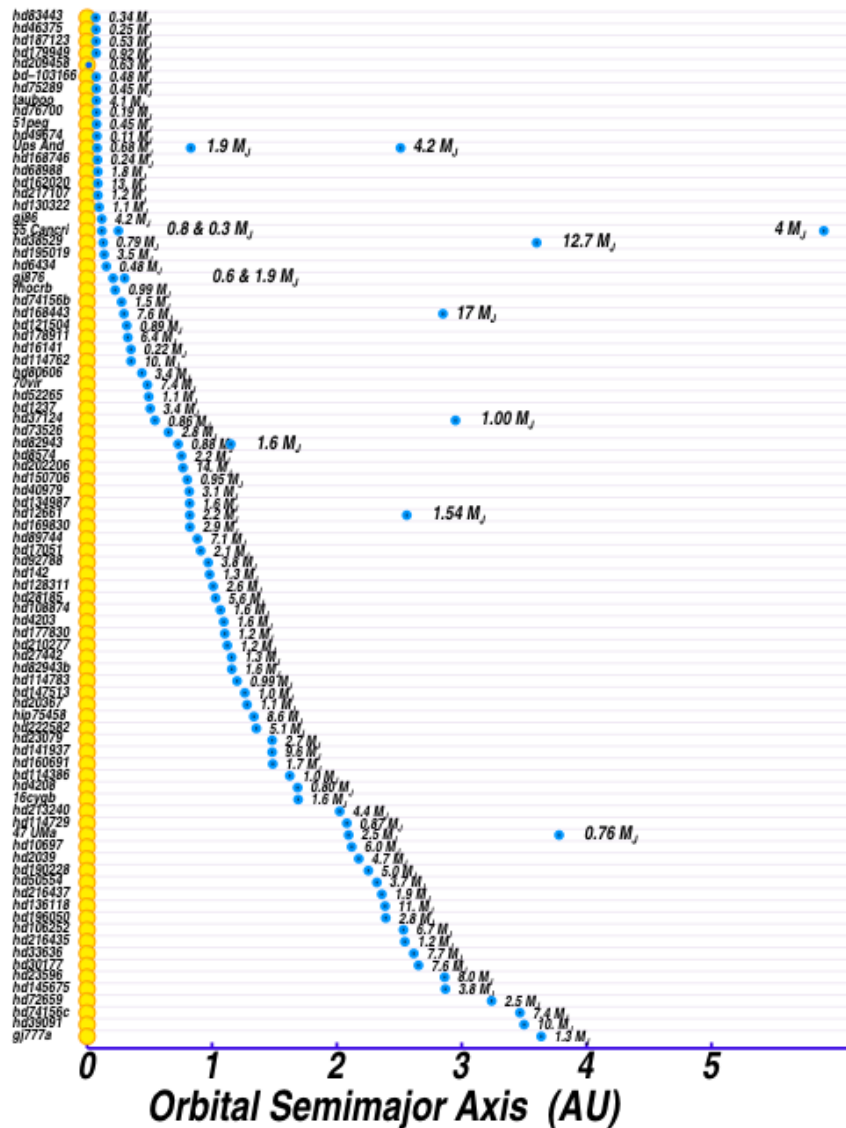


Web list of all planets, searchable



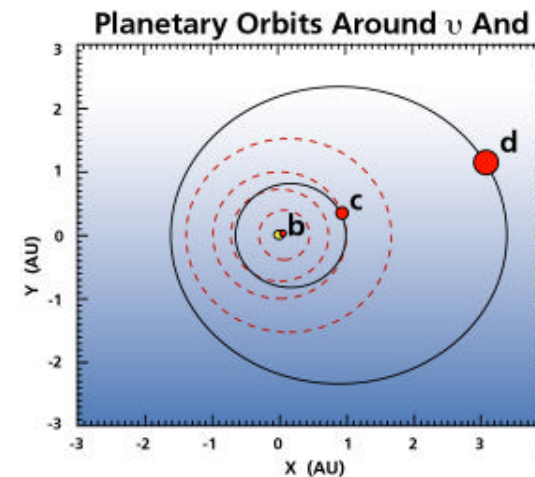
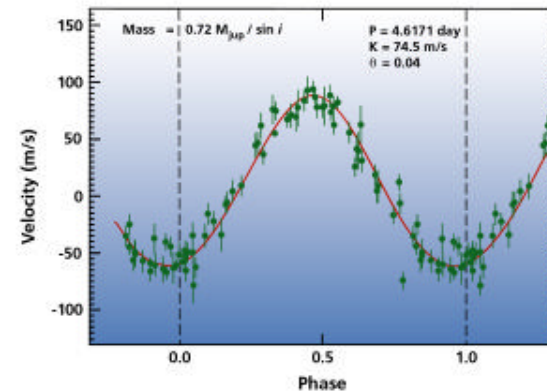
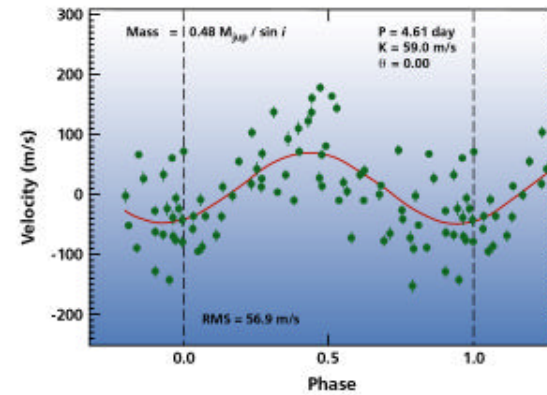
- http://planetquest1.jpl.nasa.gov/atlas/atlas_index.cfm

Master list of other solar systems

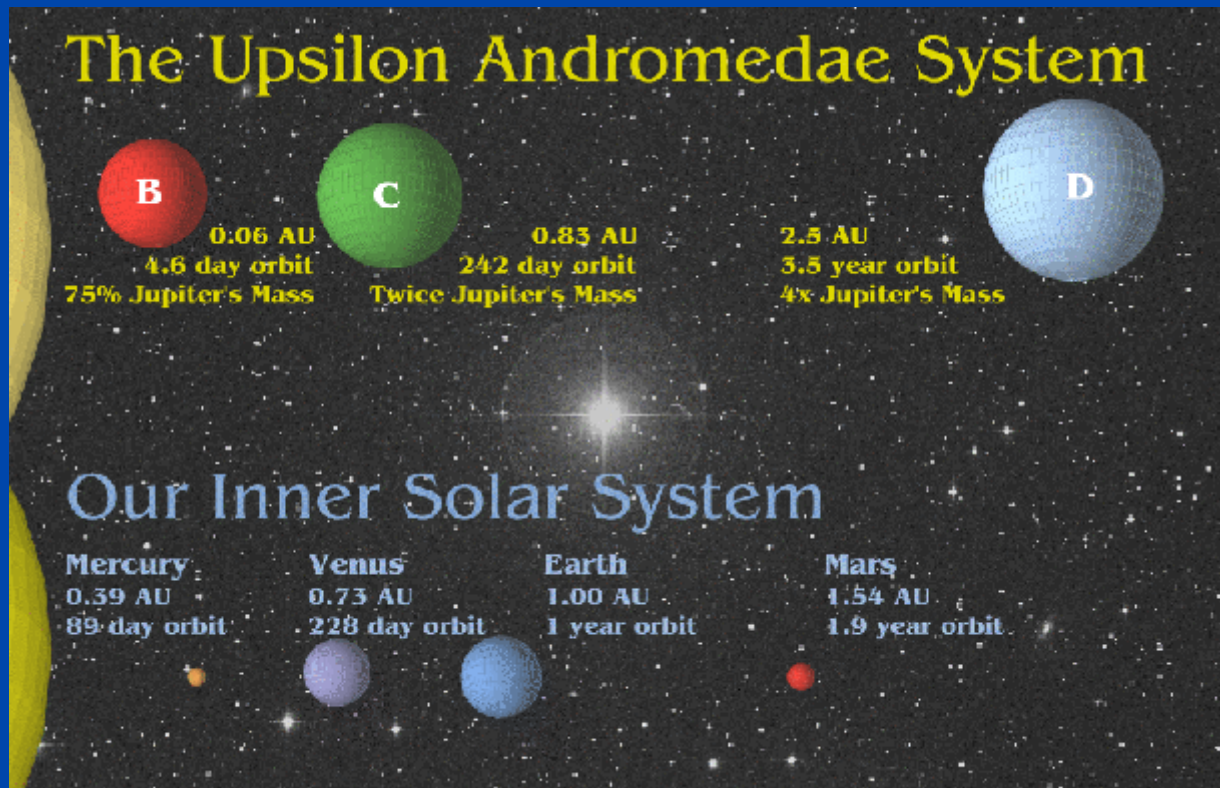


One Example

- 50 multi-planet systems to date
- Upsilon Andromedae
- Three-planet system

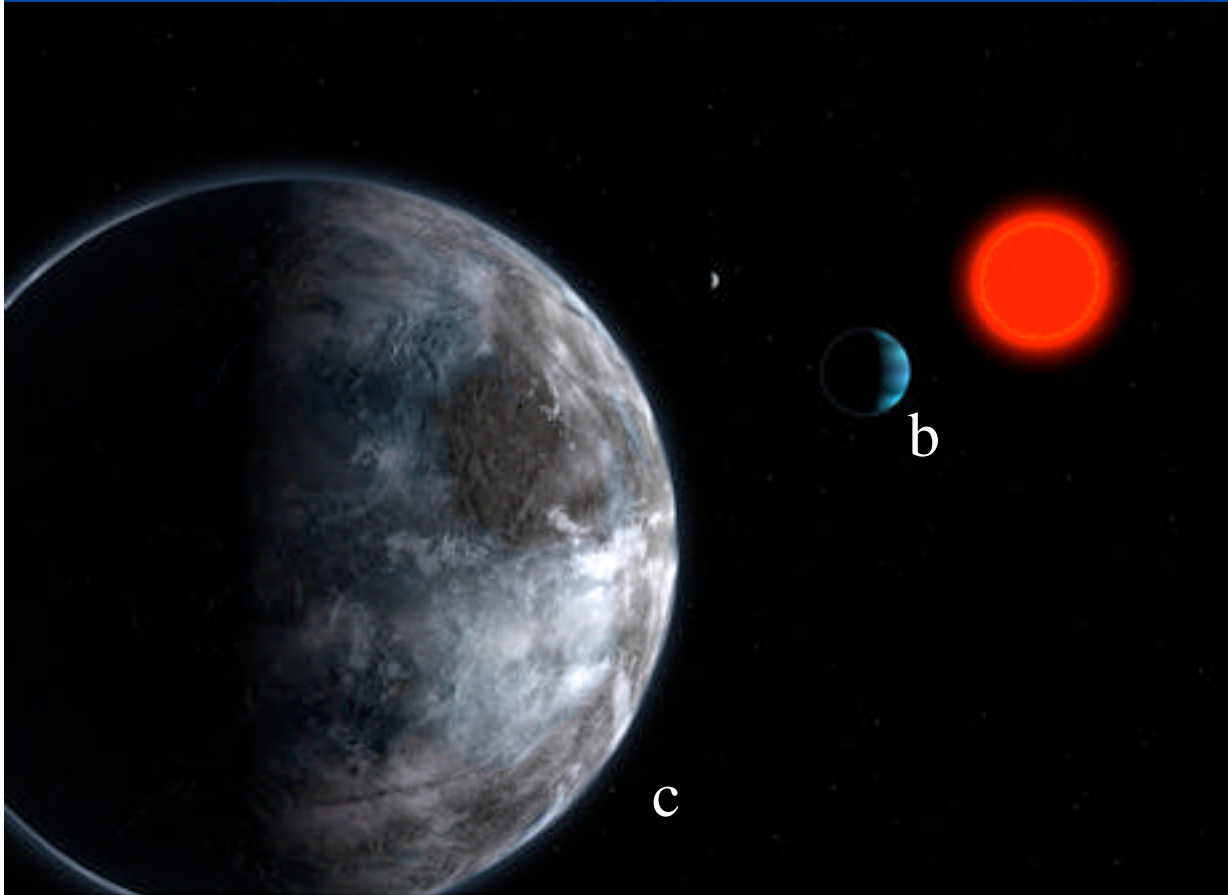


Upsilon Andromedae



- 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

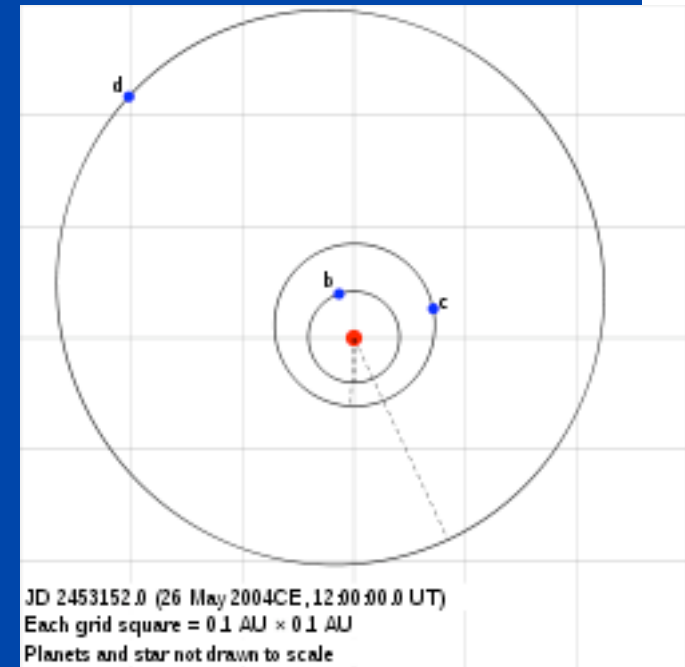
The GJ581 system



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

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

This image is copyright © ESO. It is released in connection with an ESO press release and may be used by the press on the condition that the source is clearly indicated in the caption.



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

Planet Hunters Discover a World That Could Harbor Life

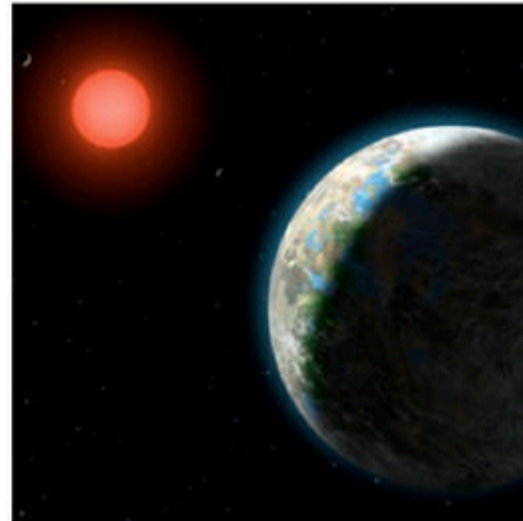
A newfound "super-Earth" just 20 light-years away appears to reside in the habitable zone of its host star

By John Matson | September 30, 2010 | 30

[Share](#) [Email](#) [Print](#)

After more than a decade of telescopic monitoring, astronomers have added two newfound worlds to a nearby planetary system [already known to harbor four other planets](#), and one of the new discoveries looks to be the kind of place where life might be able to take hold.

"Since the beginning of this hunt we've tried to find planets at about the size of the Earth with temperatures so that [water](#) can exist," said one of the researchers, [Steven Vogt](#) of the University of California, Santa Cruz, in a Webcast press briefing on September 29. "This is the first exoplanet that really has the right conditions for water to exist in liquid form on its surface." Vogt and his colleagues are [set to publish their findings in a future issue of *The Astrophysical Journal*](#).



A LAND NOT SO FAR AWAY: Twenty light-years away, astronomers have located what might be the most hospitable world yet discovered outside our solar system. This artist's conception depicts the Gliese 581 planetary system, with the potentially habitable Gliese 581g in the foreground. *Image: Lynette Cook/NSF*

Questions



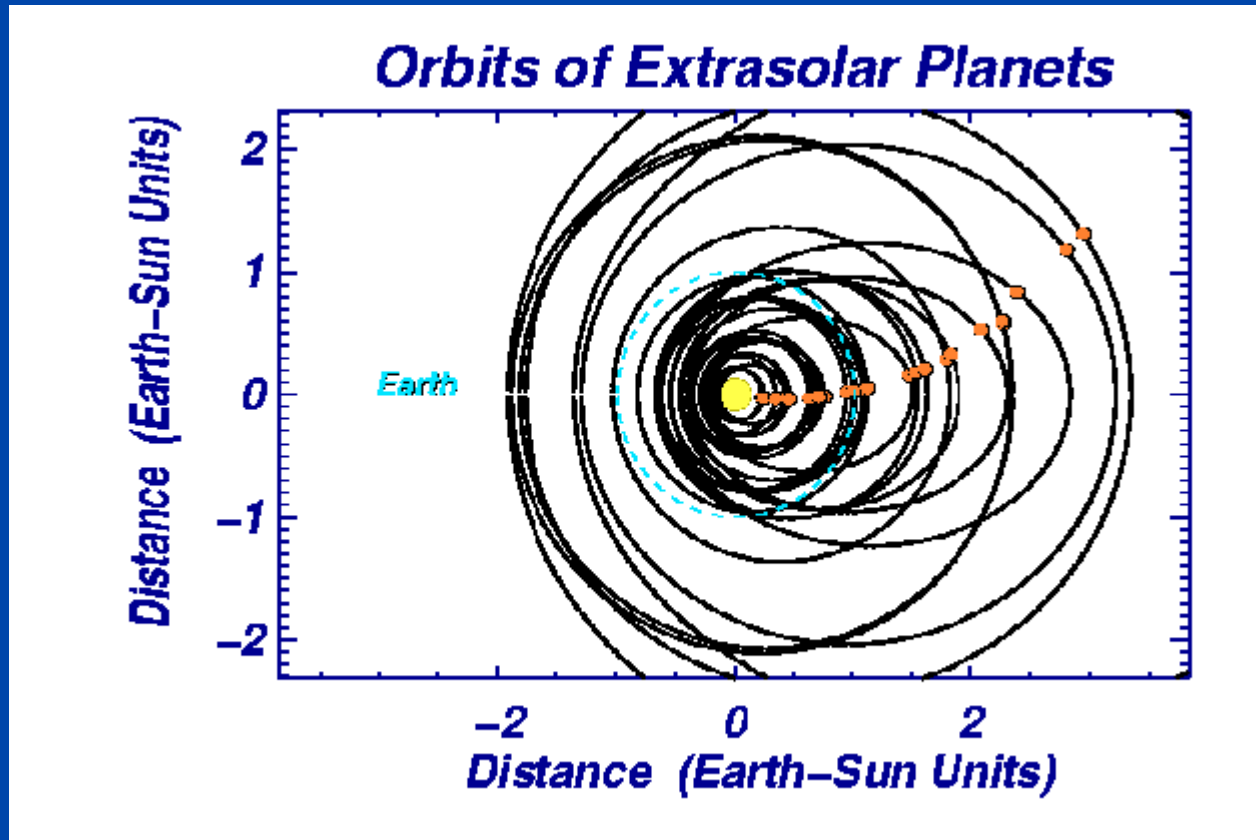
- Has the discovery of other solar systems changed your own feelings about the universe?
- Are you comfortable or uncomfortable with the idea that they are so different from our own?

Unanticipated characteristics of extra-solar planets



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

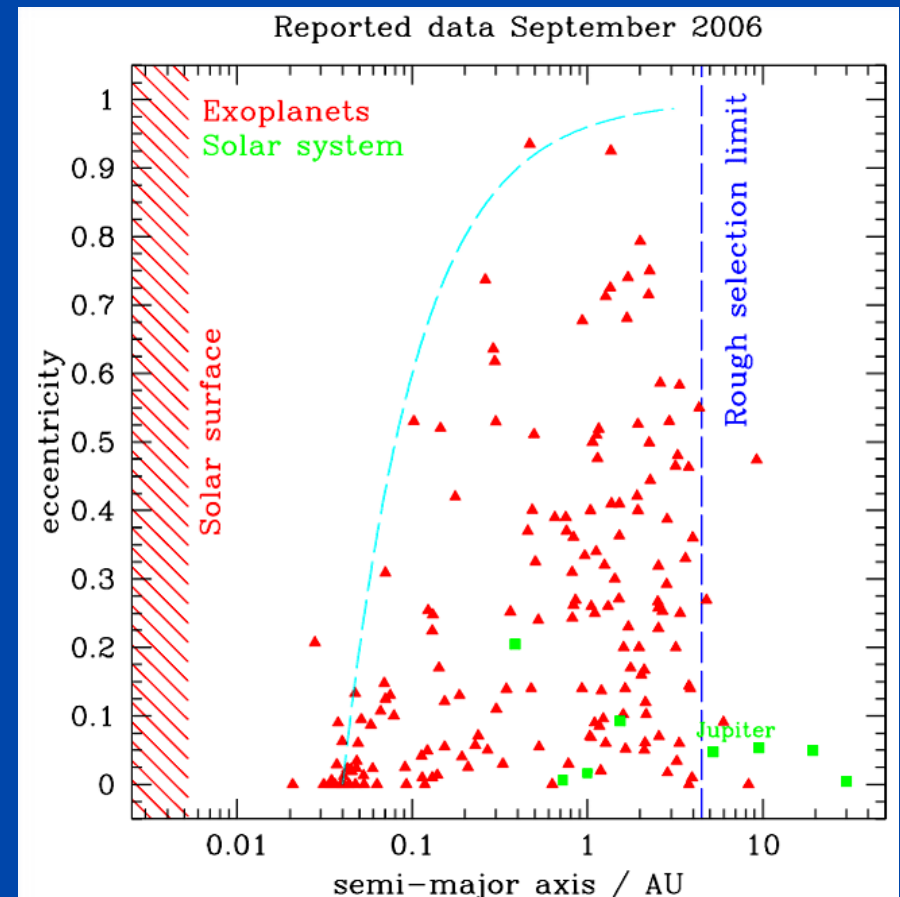
Eccentric Orbits



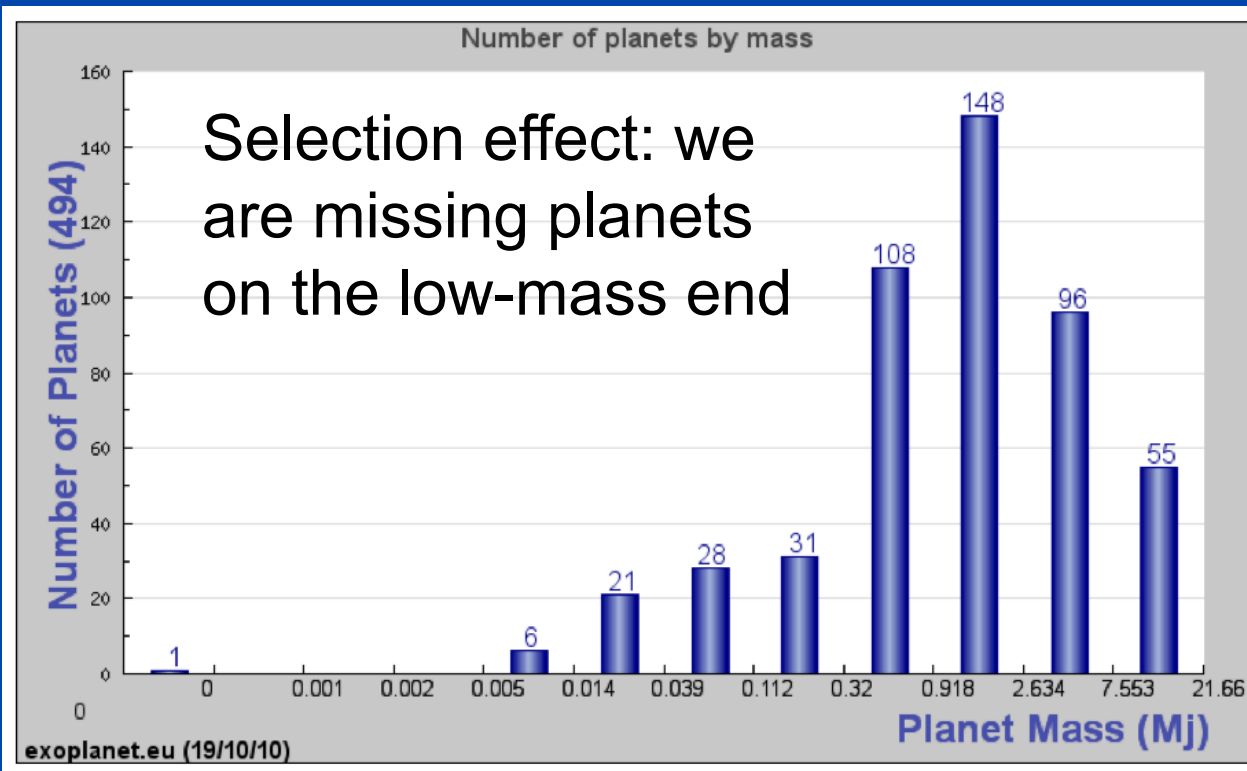
Many extrasolar planets are very close to parent stars



- *This is a selection effect* (caused by detection method)
- But it does show that such planets exist!
- Our Solar System is very different (green points) - Mercury is farther away from Sun than many of the extra-solar planets are from their stars



Characteristics of Extra-Solar Planets: Mass

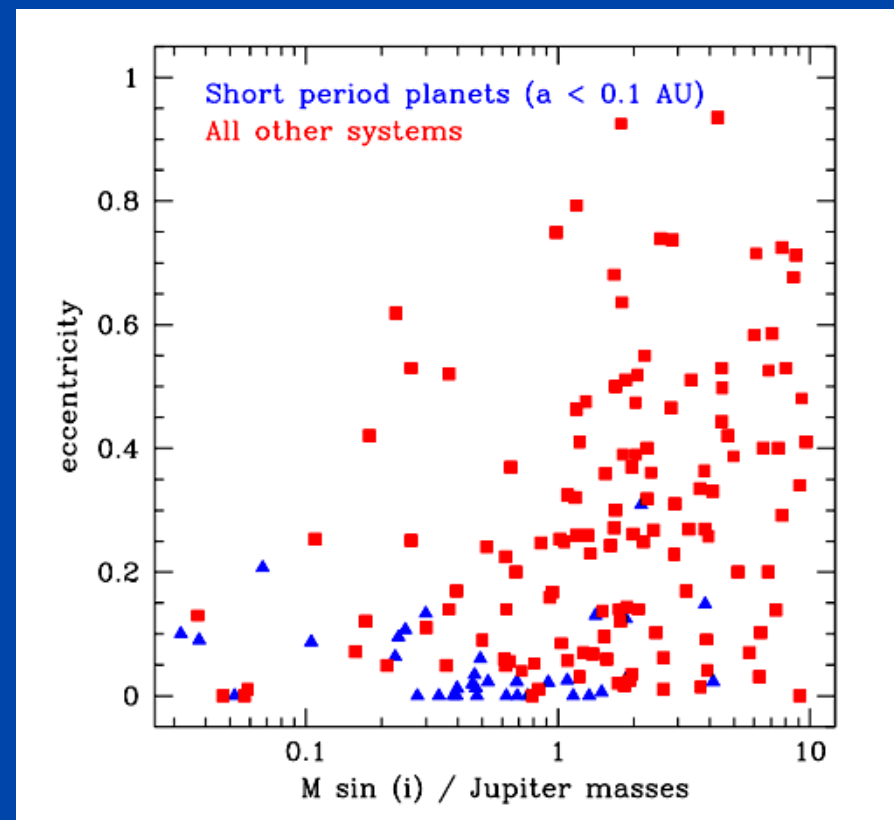


- Many planets much more massive than Jupiter



Patterns in eccentricity

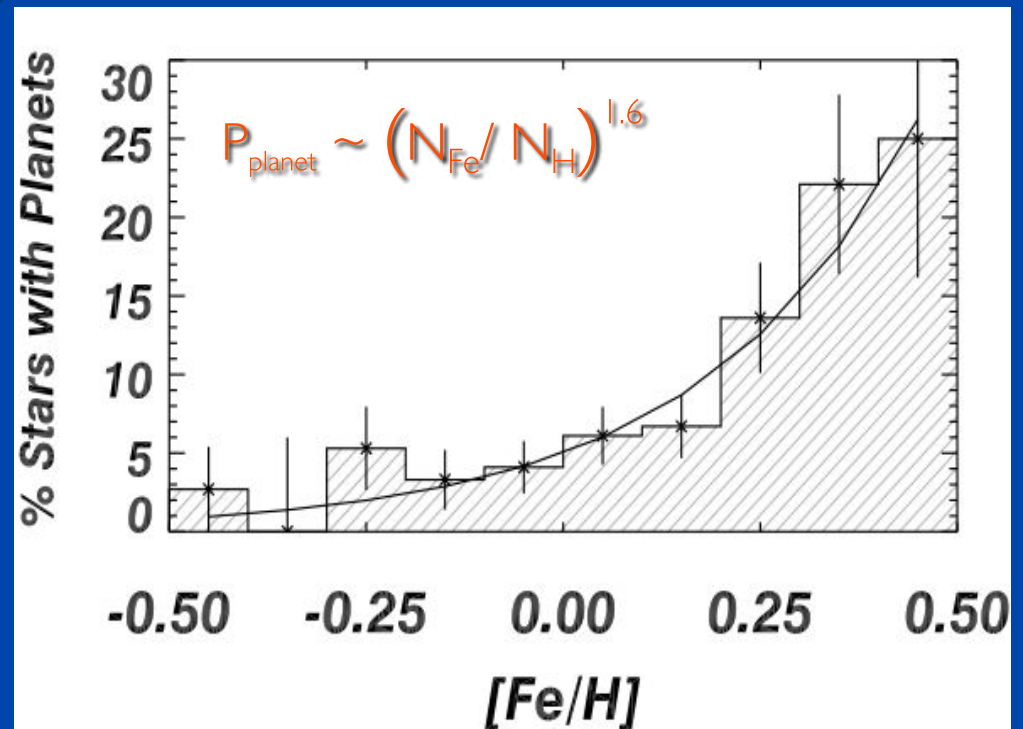
- Most new planets are in elliptical orbits
- Short period planets:
 - Very close to parent stars, very low eccentricity
 - Same process that moved planets close to star circularized their orbits



Parent stars of extrasolar planets



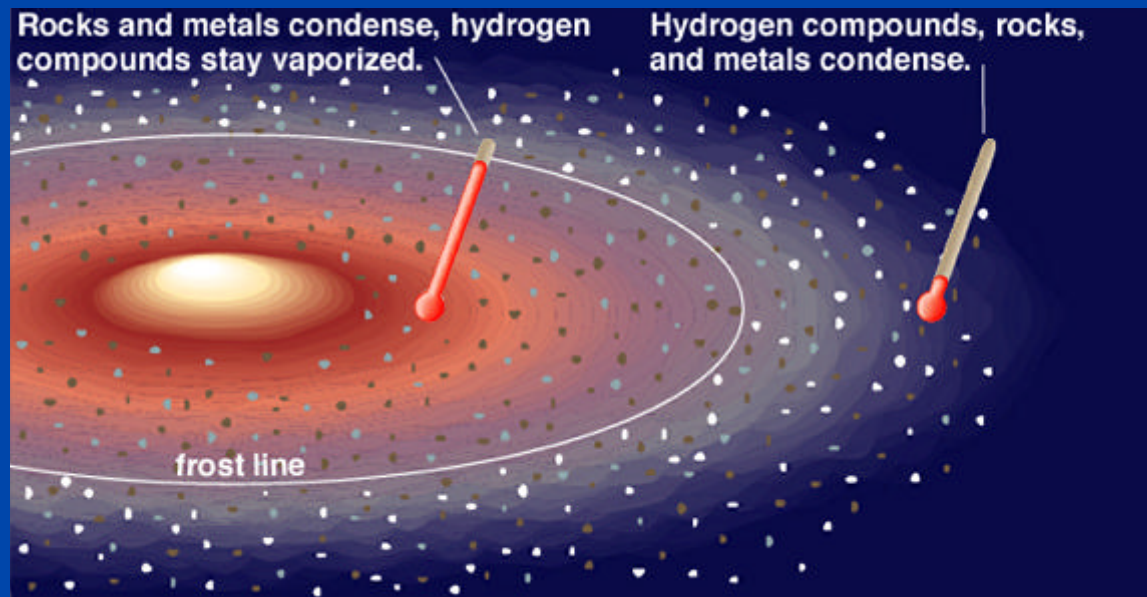
- High in elements heavier than hydrogen and helium (usually $>$ Sun)
 - reasonable: planets form from dust
- Probability of finding a planet increases as heavy element content of parent star increases



What are these planets?



- Our Solar System has small rocky planets close to star, large gas giants further away
 - no experience of large massive planets close to sun in our Solar System
- Theory of giant planet formation says they have to form outside “frost line”



Hot Jupiters



Jupiter

Composed primarily of hydrogen and helium
5 AU from the Sun
Orbit takes 12 Earth years
Cloudtop temperatures ≈ 130 K
Clouds of various hydrogen compounds
Radius = 1 Jupiter radius
Mass = 1 Jupiter mass
Average density = 1.33 g/cm^3
Moons, rings, magnetosphere



Hot Jupiters orbiting other stars

Composed primarily of hydrogen and helium
As close as 0.03 AU to their stars
Orbit as short as 1.2 Earth days
Cloudtop temperatures up to 1300 K
Clouds of "rock dust"
Radius up to 1.3 Jupiter radii
Mass from 0.2 to 2 Jupiter masses
Average density as low as 0.2 g/cm^3
Moons, rings, magnetospheres: unknown

How are giant extrasolar planets formed?



- Theory for our Solar System:
 - Stellar wind from young Sun blew volatiles outwards
 - “Snowstorm” at 5 AU where water-ice solidified
 - Fast accretion of large icy planet ($\sim 10 M_{\text{Earth}}$) which then collected H/He atmosphere
 - » Gas giants Jupiter, Saturn just outside “frost line”
 - » Small rocky planets inside
 - » Slowly accreting icy planets in outer system (Uranus, Neptune)
- Extrasolar giant planets:
 - Do they form in situ?
 - » looks impossible: too hot for ices, too little material for rock
 - Do they form outside frost line and migrate inwards?
 - » planet forms in gas/dust disc around star
 - » drag from remaining gas/dust causes it to spiral inwards
 - » or scattering from other giant planets causes migration
 - » why does it stop?

This is the “paradigm shift”



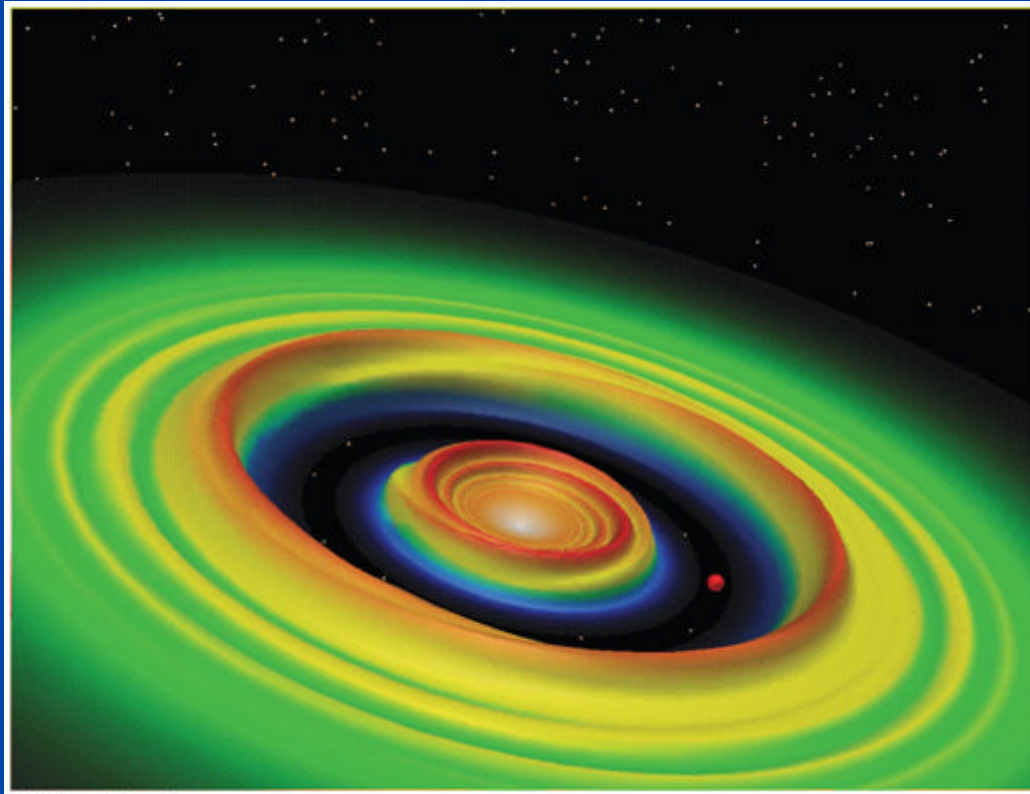
- Original theories of solar system formation developed when our own Solar System was the only one
 - Mostly circular orbits
 - Giant planets in outer solar system, terrestrial planets inside
- New Solar Systems are (in general) not like ours
- Needs a new theory
- How to arrive at a new paradigm?
 - Mostly use computer simulations to develop ideas, test hypotheses, make predictions
 - Test predictions against observed young solar systems, disks

Theories for how giant planets got so close to their stars



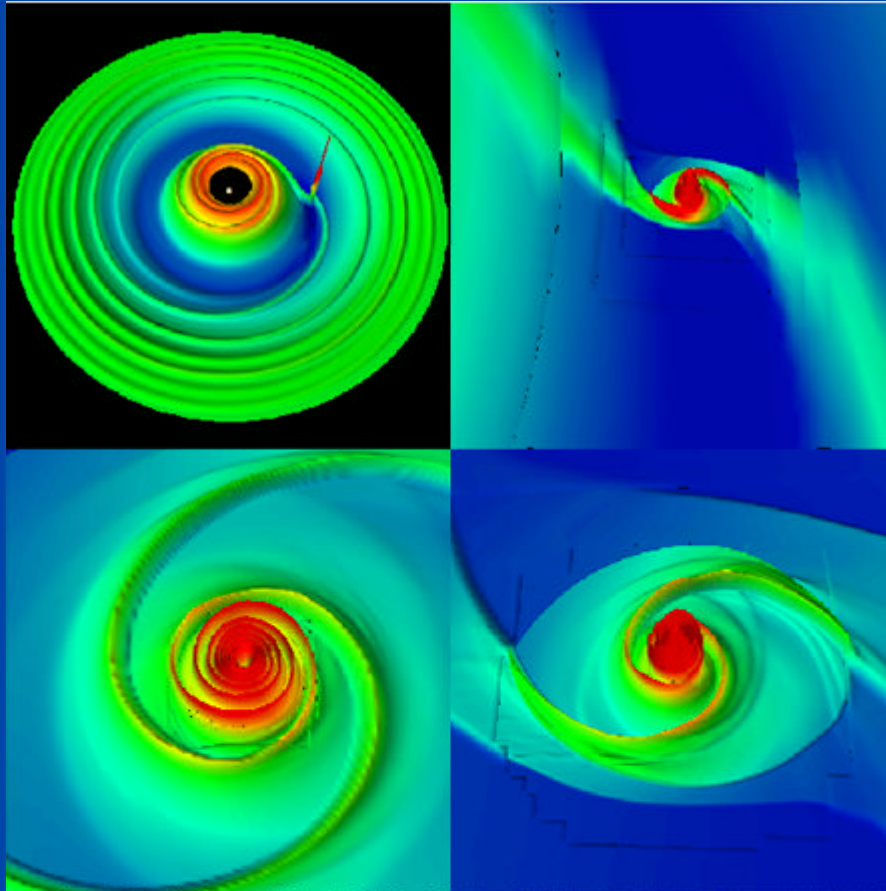
1. Interactions between individual new planets and gaseous disk. “*Migration*”
 2. After gas disk cleared away, several giant planets in outer parts of solar system were left
 - Three-body gravitational interactions between them
 - One giant planet got slung outwards, a second was slung inwards and got “captured” by the star in a close orbit
 - But why isn’t the close orbit very elliptical?
- Why didn’t Jupiter migrate inwards close to Sun?

Planetary Migration in a massive disk



- A young planet's motion can create waves in a planet-forming disk.
- Models show that matter in these waves can tug on a planet, causing its orbit to migrate inward.

I. Planet formation in gaseous disk

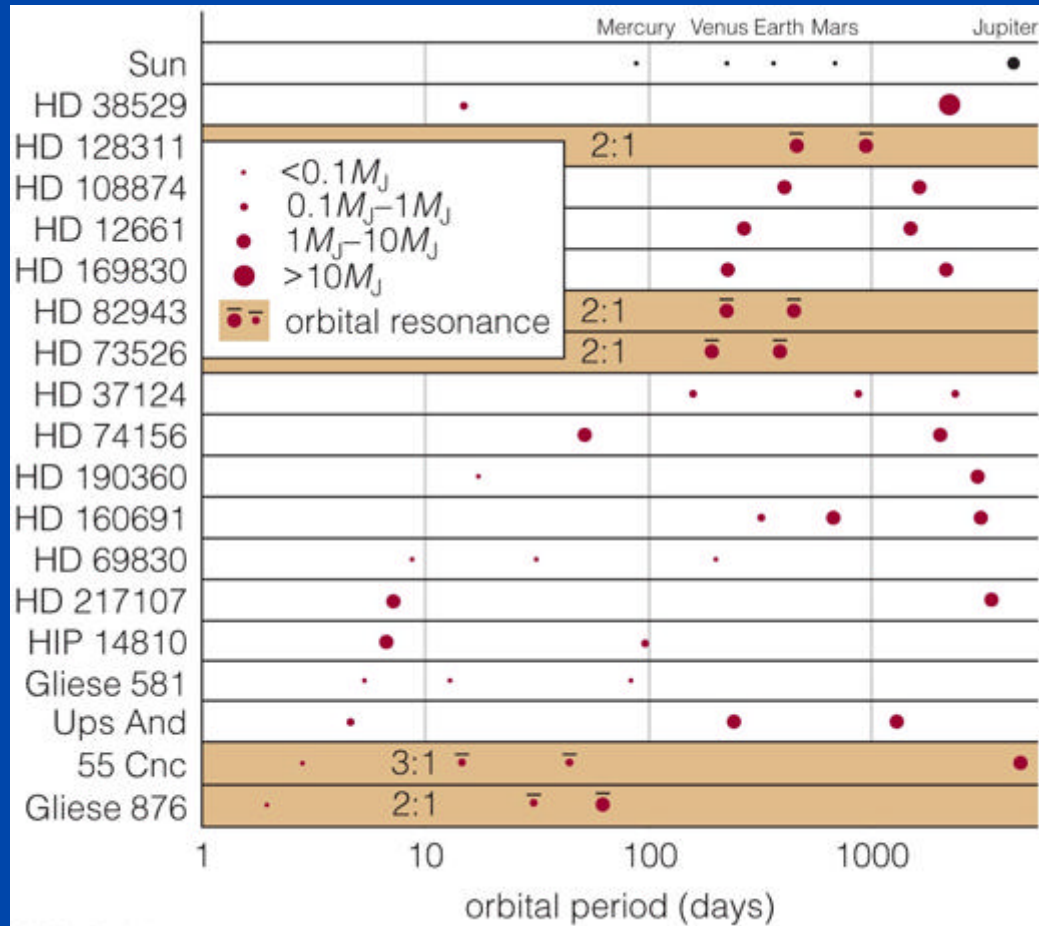


- One planet in a gaseous disk
- Accretion begins, gap starts to form
- Planet can continue to accrete mass even after a “gap” in disk has formed
- From computer simulation by Pawel Ciecielag

Hypothesis 2: Gravitational Encounters

- Close gravitational encounters between two massive planets can eject one planet while flinging the other into a highly elliptical orbit.
 - Orbit would later have to be circularized (drag?)
- Multiple close encounters with smaller planetesimals can also cause inward migration.

Orbital Resonances



- Resonances between planets can also cause their orbits to become more elliptical.

Thought Question

What happens in a gravitational encounter that allows a planet's orbit to move inward?

- A. It transfers energy and angular momentum to another object.
- B. The gravity of the other object forces the planet to move inward.
- C. It gains mass from the other object, causing its gravitational pull to become stronger.

Thought Question

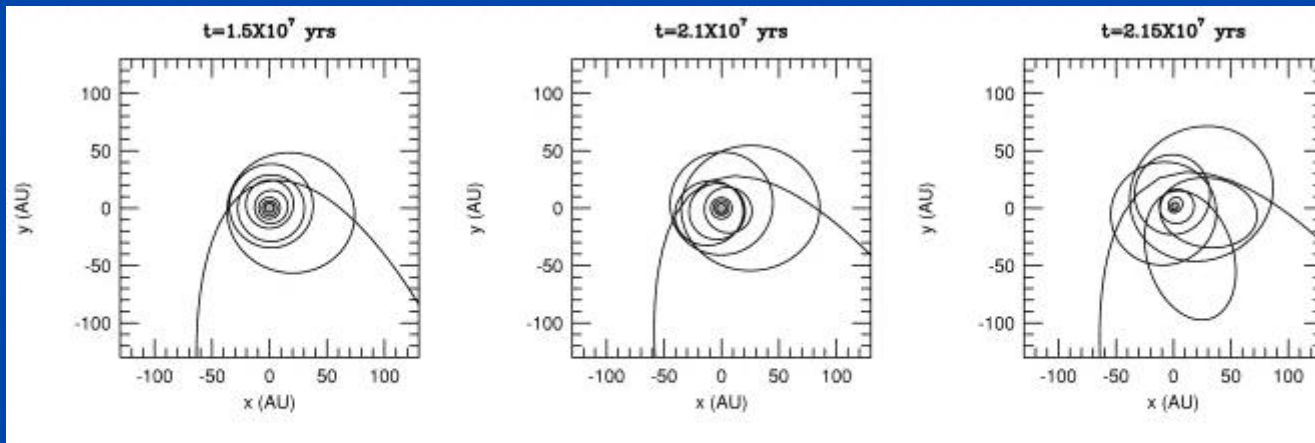
What happens in a gravitational encounter that allows a planet's orbit to move inward?

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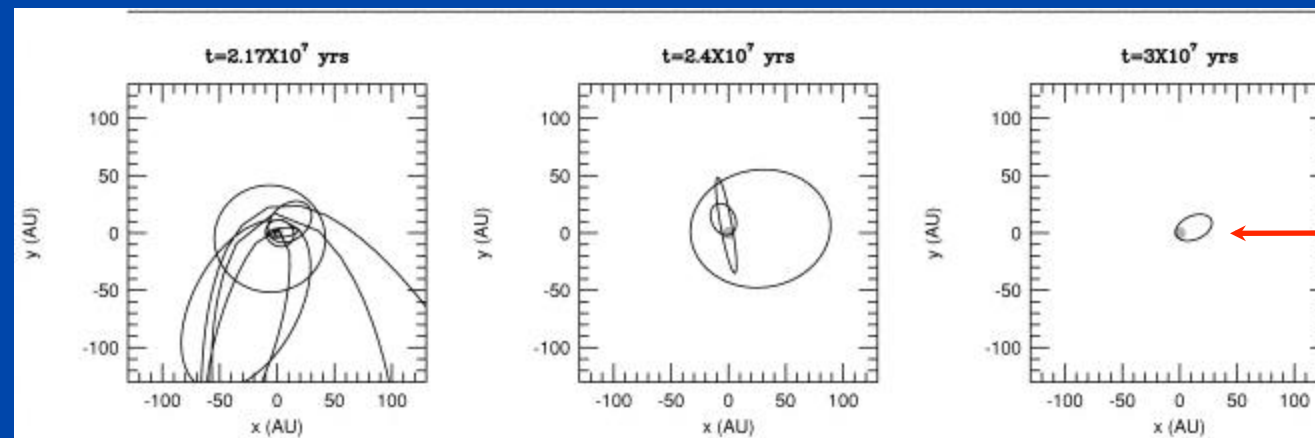
Multi-Planet Interactions as Cause of Planetary Migration



- Simulation: start with 100 Planet “Embryos”
- Scatter, Collide, Stick, Accrete Gas



After 21.5 Myr:
Chaos



After 30 Myr:
Lone Close-in
Jupiter in
Eccentric Orbit.

A bright star with a prominent diffraction pattern is centered in a field of numerous smaller, distant stars. The background is black, and the stars are scattered across the frame.

Simulation Time: 00.0 years

What have we learned?



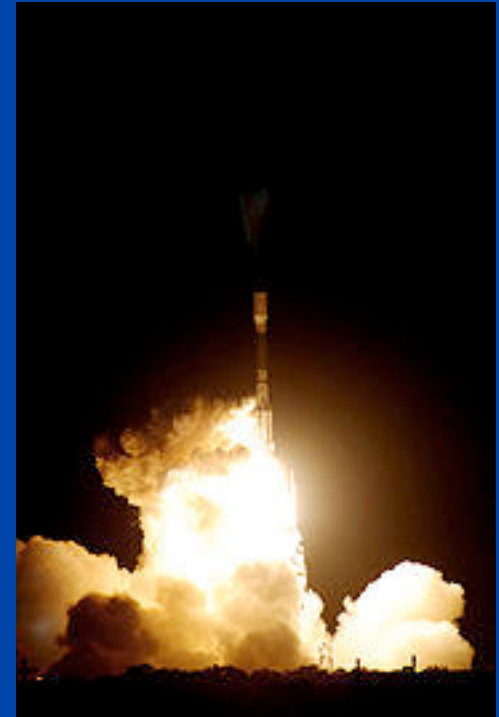
- Using Doppler shift measurements we have detected ~ 500 planets around nearby stars
 - massive planets close to stars, often in eccentric orbits
 - » not what was expected
 - » may arise when Jupiter-like planets migrate inwards after formation
 - more likely to find planets around stars that have more heavy elements

- What does this imply?
 - does not imply that such systems are typical
 - » detection method is biased
 - does imply that they are possible!
 - does not imply that systems like ours are uncommon
 - » Jupiter is barely detectable
 - but does not provide evidence that they are common!
- No “other Earths” yet but we’re getting much closer

Ambitious space missions to detect Earth-like planets



- COROT (French) In orbit now
- Kepler (NASA) Launched in March, 2009



COROT mission is in orbit now



- Planetary transits
- Will look at 10,000 stars for 150 days
- Earth-like planets but far away
- 7 planets found so far
- COROT-7-b: ~ 5-10 Earth masses, 1.7 times Earth diameter



What is a Habitable Planet?



A good planet is:

- Not too big
- Not too small
- Not too hot or too cold

What does “habitable” mean to you?



- Right temperature
- Liquid water
- Free oxygen to breath
- Light to keep you warm and to see by
- Radiation shield
- Asteroid protection from atmosphere and Jupiter



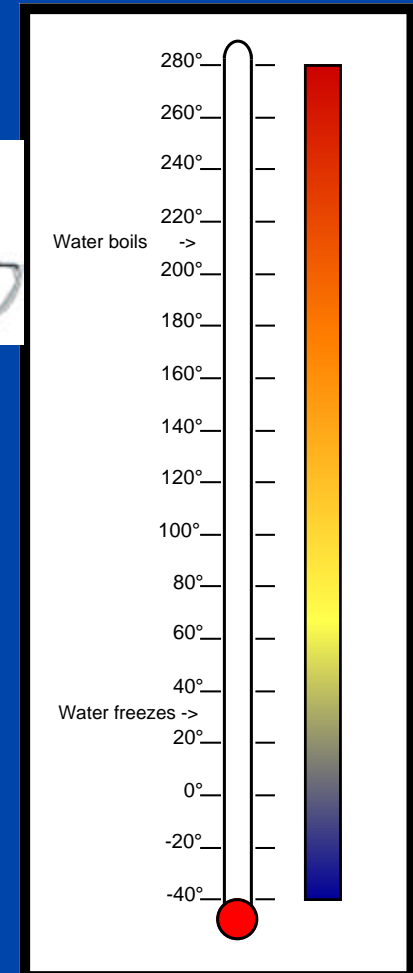
Next few slides courtesy of Stephen Kane

Things That Affect Temperature

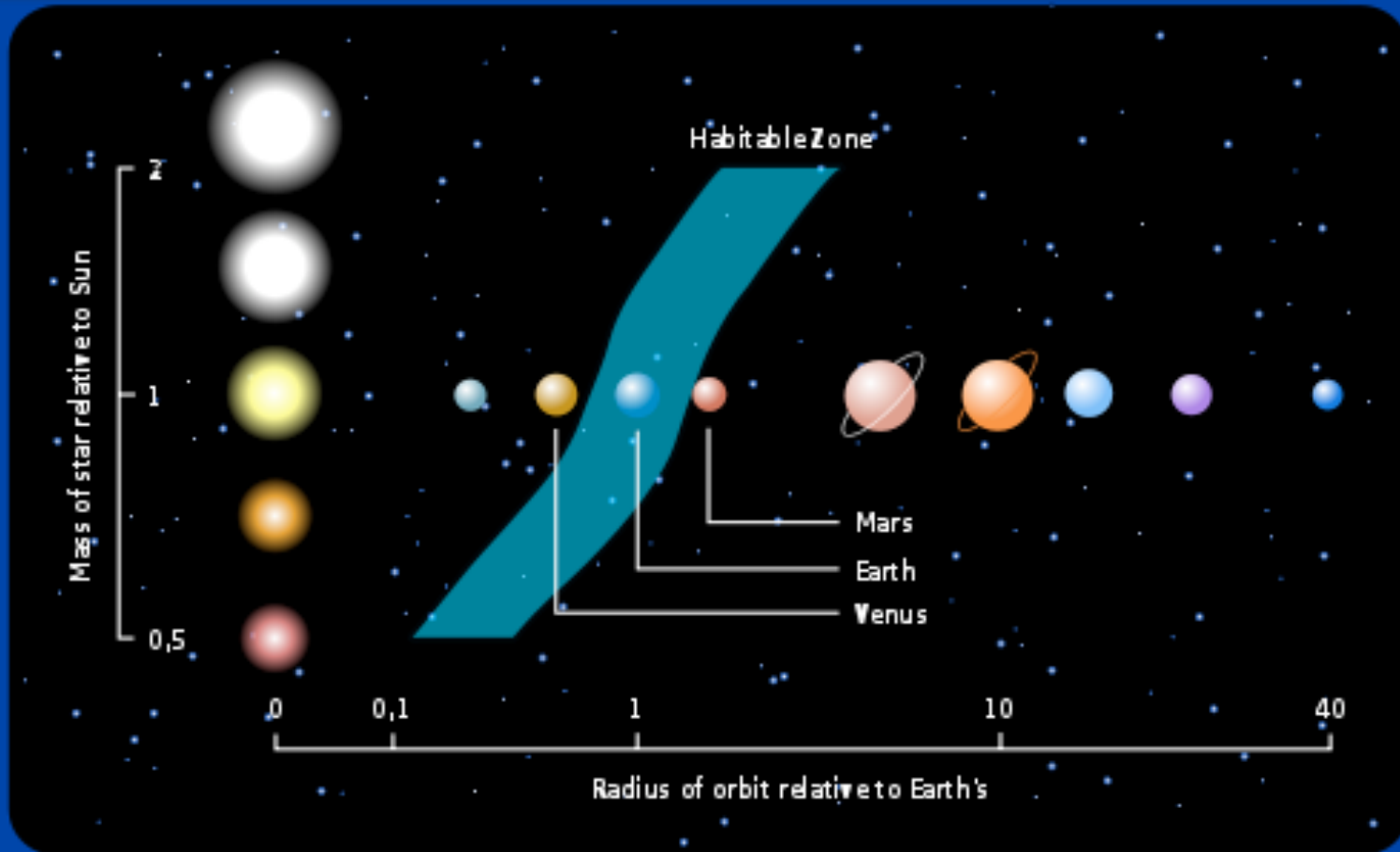


- Want temperature so you can have liquid water on the surface of the planet

1. Temperature of star
2. Distance from the star
3. Shape of planet's orbit: circular or elliptical
4. Planet's atmosphere: greenhouse gases



The Habitable Zone for Stars of Various Masses



- The Habitable Zone (HZ) in green is the distance from a star where liquid water is expected to exist on the planets surface.

Question



- NASA has made its goal to find habitable planets. (Gas giants don't "matter" as much....)
 - Do you agree that this should be the main priority?

The Main Points



- The ~ 500 planets we have detected to date are only a sub-set of potential planets out there
- These new solar systems have raised big questions about how our own Solar System formed
- Migration and planet-planet interactions play a role in reshaping a planetary system
- Future search methods have high probability of finding more (and more varied) planets
- It's hard to find Earth-like planets
 - But prospect of finding Earth-like planets is thrilling!

Main Points, continued



- Planet formation and solar system evolution are in midst of a “paradigm shift”
 - Prevailing ideas of 10 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!**