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Beyond Our Solar System: The Search for Extrasolar Planetary Systems

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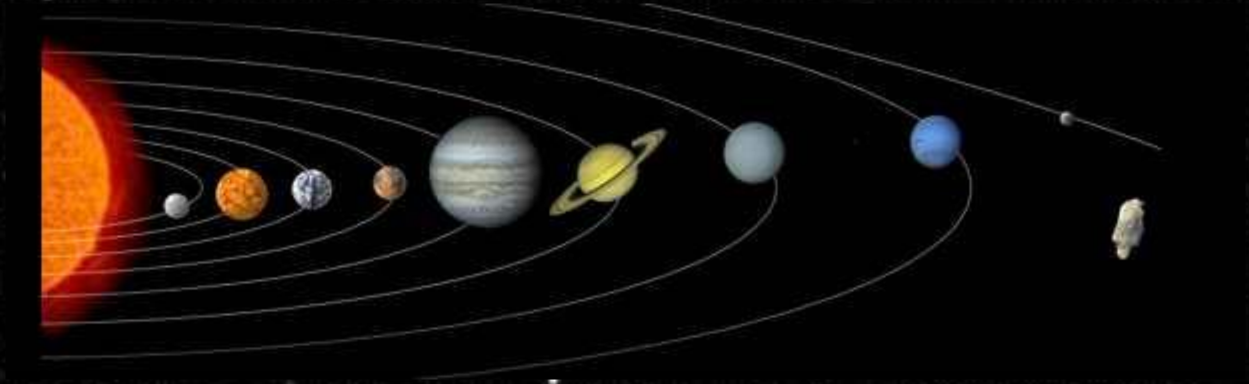
Beyond Our Solar System:

The Search for Extrasolar Planetary Systems



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Beyond Our Solar System

- Our Solar System
- What *is* a **planet**?
- How do we search for planets?
- How many have we found?
- Our recent discovery
- Expectations vs. Reality

Introduction

- In trying to understand the formation of our Solar System, we have made elaborate observations of the planets and other aspects of our Solar System.

- We have used the observations as constraints for elaborate and coherent models to explain its formation.

- These models were developed using a single example - *our own Solar System*.

Is our Solar System the proper paradigm for models of planet formation and planet evolution in general?

- Is planetary system formation:
  - a common natural result of star formation, or
  - are planets rare around stars like our Sun?

- How do the characteristics of a planetary system depend on properties of the central star, such as its mass, rotation, magnetic field, abundance of heavy elements, etc?

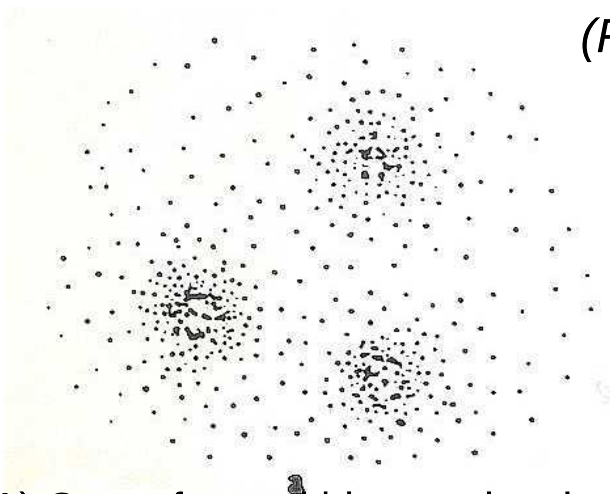
- How do planetary properties change and evolve during the life of the star?

- What is the diversity of habitats for life in the Universe?

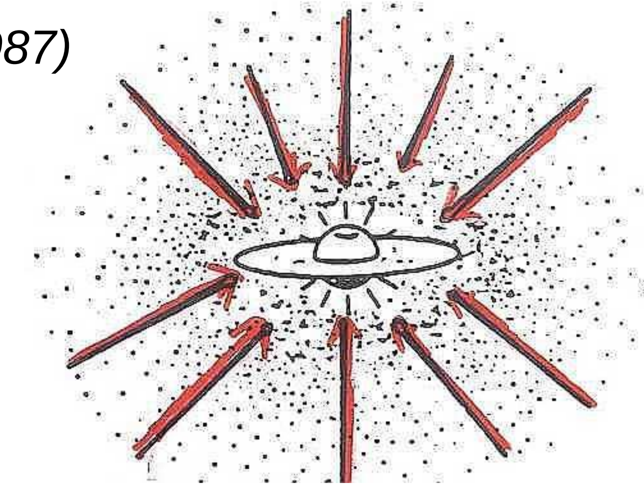
These kinds of questions were unanswerable as long as the *only* planetary system we knew was our own. However, beginning in 1995, with the discovery of the first planet orbiting a star other than our Sun, we have received many new insights into these questions and many new surprises!

Our Current Theory of Star and Planet Formation

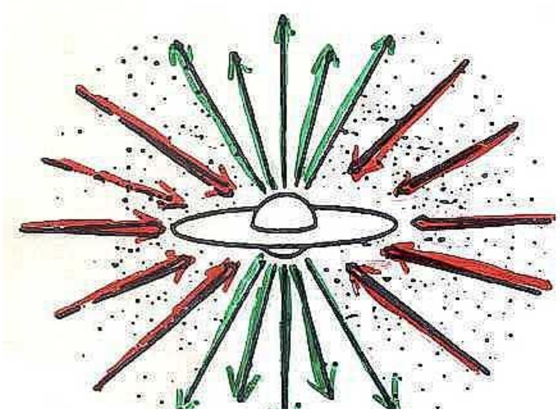
(From Shu et al*. 1987)*



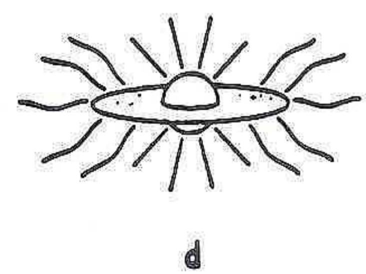
A) Cores form within a molecular cloud



B) A protostar with surrounding nebula and disk forms at the center of a core.



C) A stellar wind starts along the polar axis, and starts to clear out the disk.



D) Infall ends, leaving a newly formed star and disk. Planet formation occurs within the disk.

Young Stellar Disks

Source: STScI, NASA

What do we mean by a planet?

- To answer the previous questions, we want to search for planets orbiting other stars and compare their properties to our own Solar System.
- However, we *cannot* just define a planet as any object orbiting around a star. The following types of objects orbit a star:
  - another star (this is called a *binary* star system)
  - a brown dwarf
  - a planet

Classical Definitions of Stars, Brown Dwarfs, and Planets

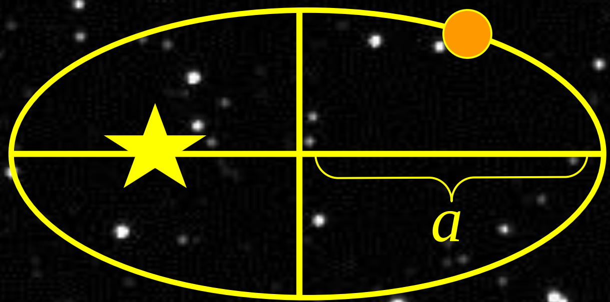
- ***Star:*** an object with sufficient mass that it starts and sustains hydrogen fusion.
- ***Brown Dwarf :*** an object that forms in the same manner as a star but lacks sufficient mass for sustained hydrogen fusion.
  - Brown dwarfs are generally believed to be <0.08 times the mass of the Sun (< 80 times the mass of Jupiter).
- ***Planet:*** an object formed in a circumstellar disk by accretion and/or gravitational instability
  - We do not know if there is a maximum size for a planet but some theorists think they will be < 15 Jupiter masses.

How to Search for Planets?

- Detection of faint planets next to a bright star is extremely difficult.
- There are two approaches to detecting extrasolar planetary systems:
  - ***Direct*** detection attempts to discriminate the light originating from the planet (or reflected from it) from light coming directly from the star.
  - ***Indirect*** detection attempts to detect effects of the planetary system on the light from the star. Usually, this means the detection of orbital motion of the star around the center of mass, or “barycenter” of the star-planet system.

Planetary Orbits

- The orbit of a planet around a star is an *ellipse*. The star is at one focus of the ellipse.   (This is Kepler's first law.)

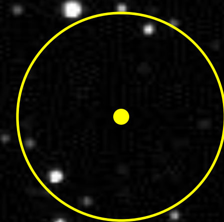


- The size of the ellipse is described by the semi-major axis, "*a*".

Planetary Orbit Shapes

- The shape of the ellipse is described by the eccentricity, "e".

- A circle has e = 0.0 :



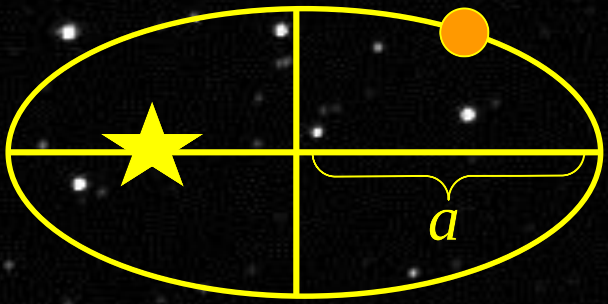
- As the eccentricity increases from 0.0 to 1.0, the ellipse becomes more and more elongated:

e =0.6

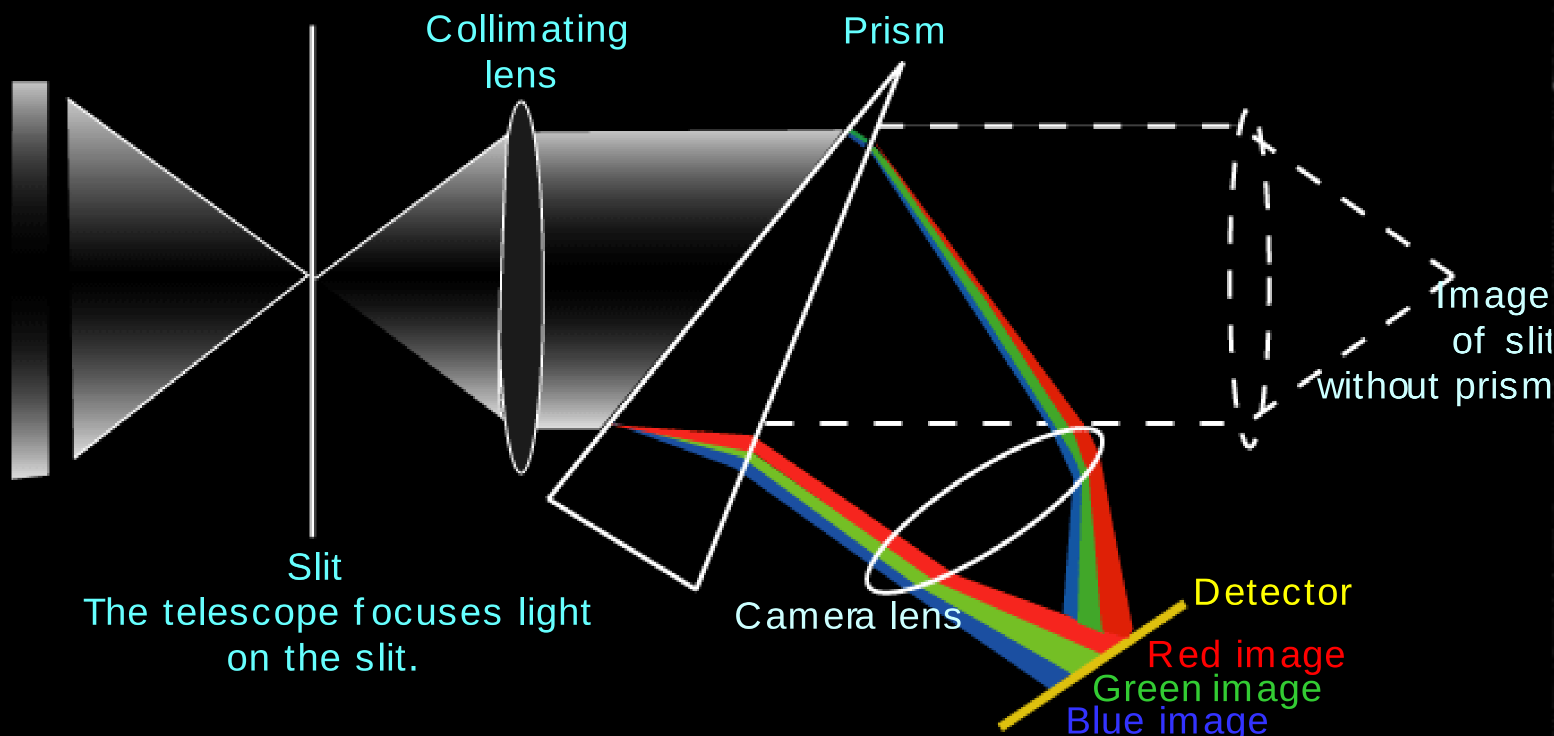
e = 0.99

Direct Detection

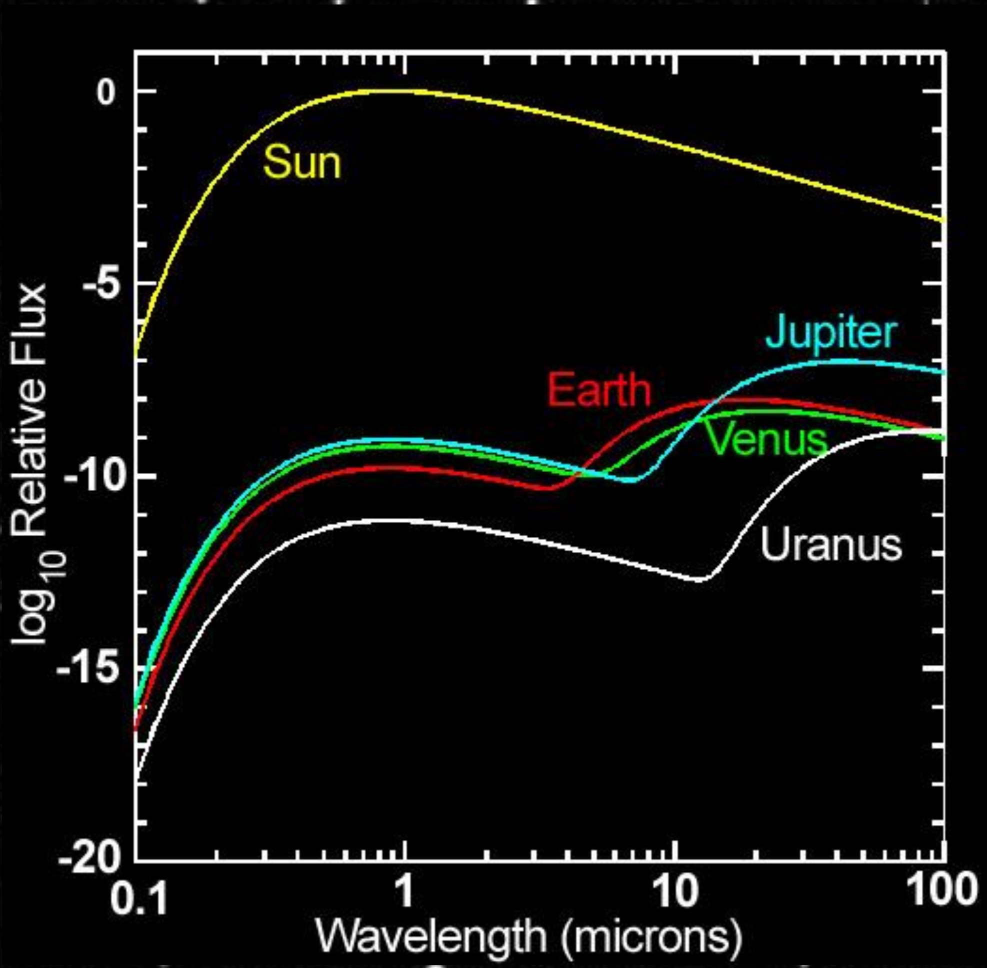
- In theory, planets around other stars can be detected by imaging in either visible or infrared light.
- With a series of images and spectra, you can measure:
  - semimajor axis: *a*
  - eccentricity: *e*
  - inclination (the tilt of the planet's orbit with respect to the plane of the sky)
  - planet size
  - temperature
  - composition



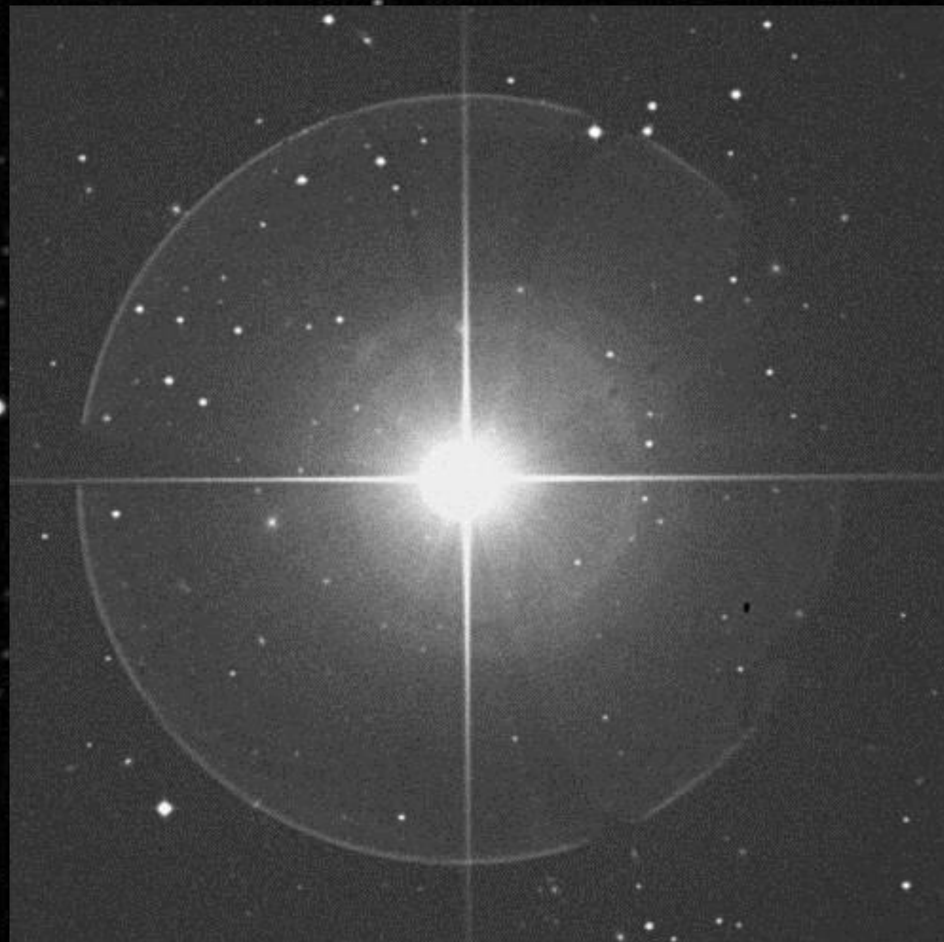
Simple Spectrograph



An isolated planet might be bright enough to observe on its own. However, we are trying to image a relatively faint object very close to a bright star (like observing a candle near a search light)!



This star has a planet around it!



Can you find it?

Indirect Detection

- We are left with using the light from the *star* to infer the presence of the *planet*. To do so, we must find something the planet is doing to the star to make its presence known.
  - The most obvious thing any planet does is to orbit the star.
  - More correctly, *both* the planet and the star orbit the *center-of-mass* (barycenter*)* of the system.
  - Since the star is much more massive than the planet, the star moves in a smaller and slower orbit.

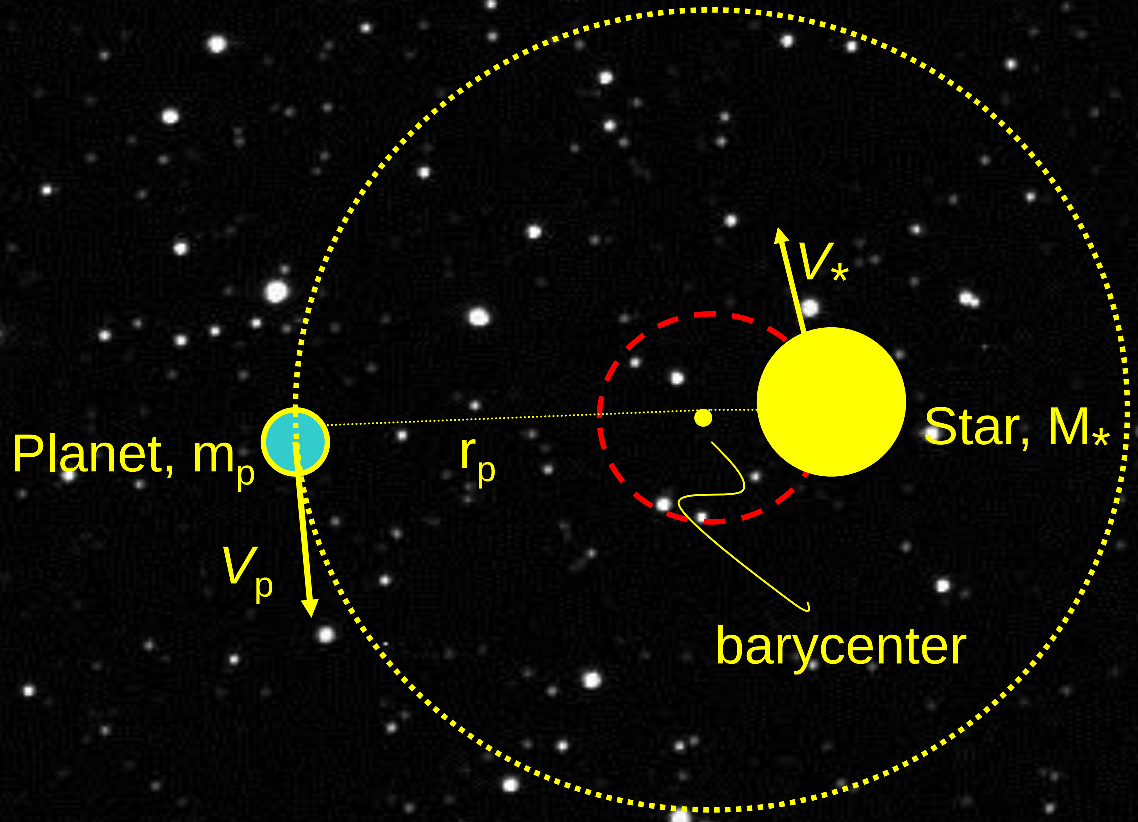
- How can we detect the orbital motion of the star and use it to determine the presence of planets?
  - Radial velocities
  - Astrometry
  - Transit photometry
- Additional indirect methods (not to be discussed today) include micro-lensing and very accurate pulse timings of pulsars and white dwarf stars.

Star and Planet Orbit

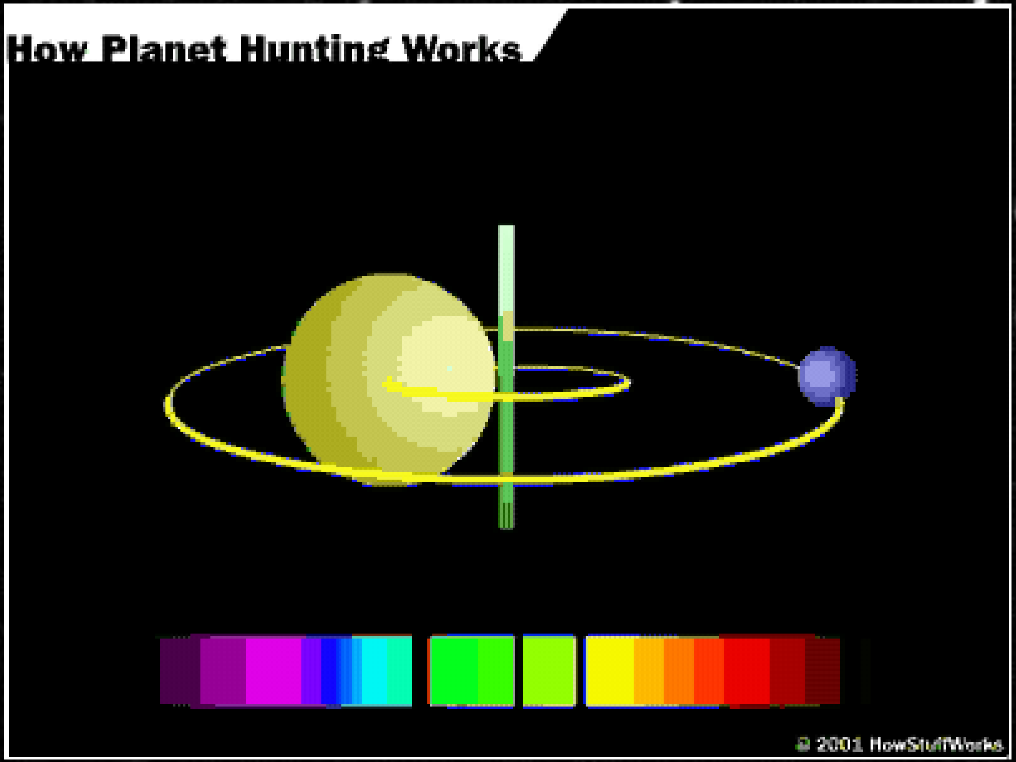
Source: STScI, NASA

Radial Velocities

We want to measure the changes in the line-of-sight (radial) component of the star as it orbits the system barycenter (center of mass).



Spectroscopic Technique



What do radial velocity measurements tell us?

- We measure the how long it takes the planet to orbit the star.
  - ⇒This tells us the orbital semi-major axis (how far the planet is from the star).
- We measure the speed of the star in its orbit.
  - ⇒This tells us the minimum mass of the planet.
  - ⇒The mass might be higher than this minimum value, if we are looking nearly pole-on to the system.
- We measure the shape of the radial velocity curve.
  - ⇒This tells us the shape of the orbit -- its eccentricity.

Examples from our Solar System

For a 1 solar mass star:

Planet	Period	Speed
Jupiter	11.9 years	13 m/sec (29 mph)
Uranus	84 years	0.3 m/sec (0.7 mph)
Earth	1 year	0.09 m/sec (0.2 mph)

Astrometry

- Astrometry is the very accurate measurement of the positions of objects (stars, etc.) with respect to a known, fixed reference frame such as distant quasars.
- The orbit of a star around a star-planet barycenter will appear as an ellipse when projected on the plane of the sky.
- The astrometric signal is largest for:
  - nearby stars
  - low mass stars
  - massive planets
  - planets far from their parent stars

Examples

For our solar system viewed from 10 pc away:

Planet	Orbit Size	Angular Size	Period
Jupiter	5.2 AU	0.5 milliarcsec	11.9 yr
Uranus	19.2 AU	84 microarcsec	84 yr
Earth	1 AU	0.3 microarcsec	1 yr

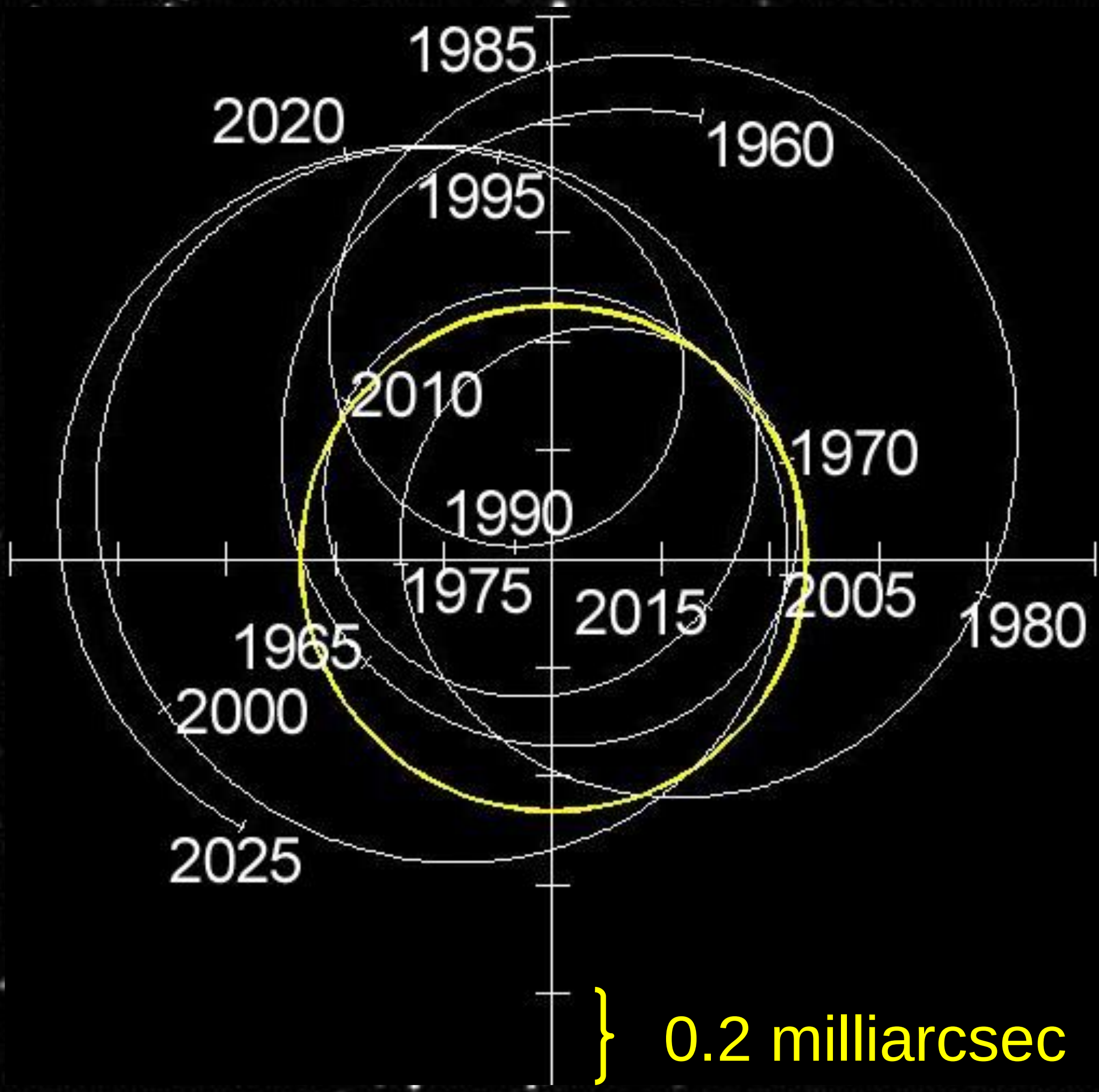
1.0 milliarcsec is 1/3,600,000 degrees!

The current ground-based limits are a few milliarcsec.

To do better, we must use a spacecraft.

So far, there are no good, reliable detections of extrasolar planets via astrometry.

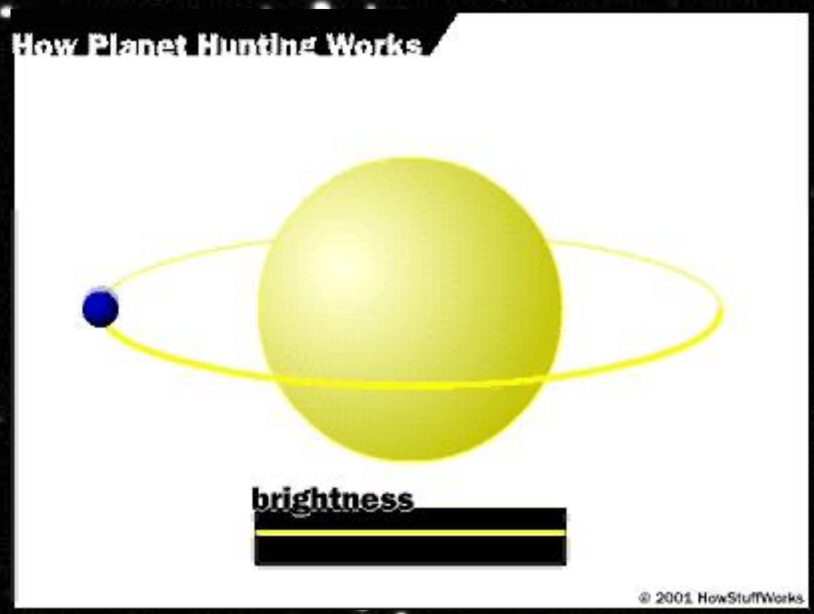
The Motion of Our Sun Around the Barycenter as Seen from 10pc



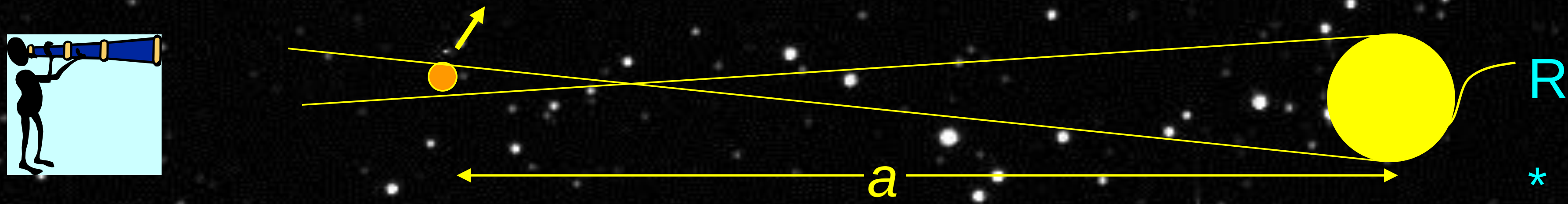
Transit Photometry

- A transit occurs when a small body passes in front of a larger body as viewed from the Earth.
  - In this case, the planet passes in front of the star.
  - If you are viewing the star when this happens, you will see the brightness of the star decrease because the planet is blocking it.
  - This requires that the line-of-sight be very close to the orbital plane of the planet around the star.

Transit Technique



How often does this happen?



- The probability of a transit = R_*/a
  - For a Jupiter-mass body at 0.05AU, this is 10%
  - For an Earth-mass body at 1AU 0.5%
  - For a Jupiter-mass body at 5AU 0.1%
- The maximum transit duration = $(P\ R_*)/(\pi a)$

  (P = orbital period)
  - For a Jupiter-mass body at 0.05AU, this is ~3 hours
  - For an Earth-mass body at 1AU ~13 hours
  - For a Jupiter-mass body at 5AU ~29 hours
- The transit depth $=(R_p/R_*)^2$
  - For a Jupiter-mass body (any distance) 1-2%
  - For an Earth-mass body ~0.008%

Extrasolar Planet Detection Results

(as of November 2002)

- There have been over 100 planets found orbiting other stars.
- For 11 of the stars, more than 1 planet has been detected.
  - For all other stars with planets, we so far only know of 1 planet orbiting the star.
  - This may be a *selection effect* since it is harder to find smaller planets or planets far from the star

We now have many examples to compare to our Solar System and we find that <u>none</u> have the same properties as our system!

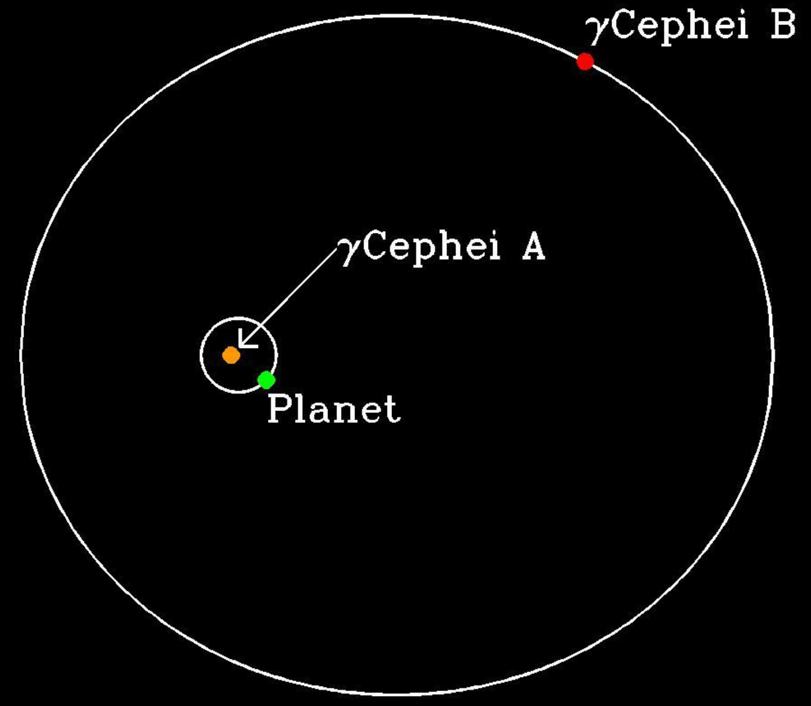
Caveat!

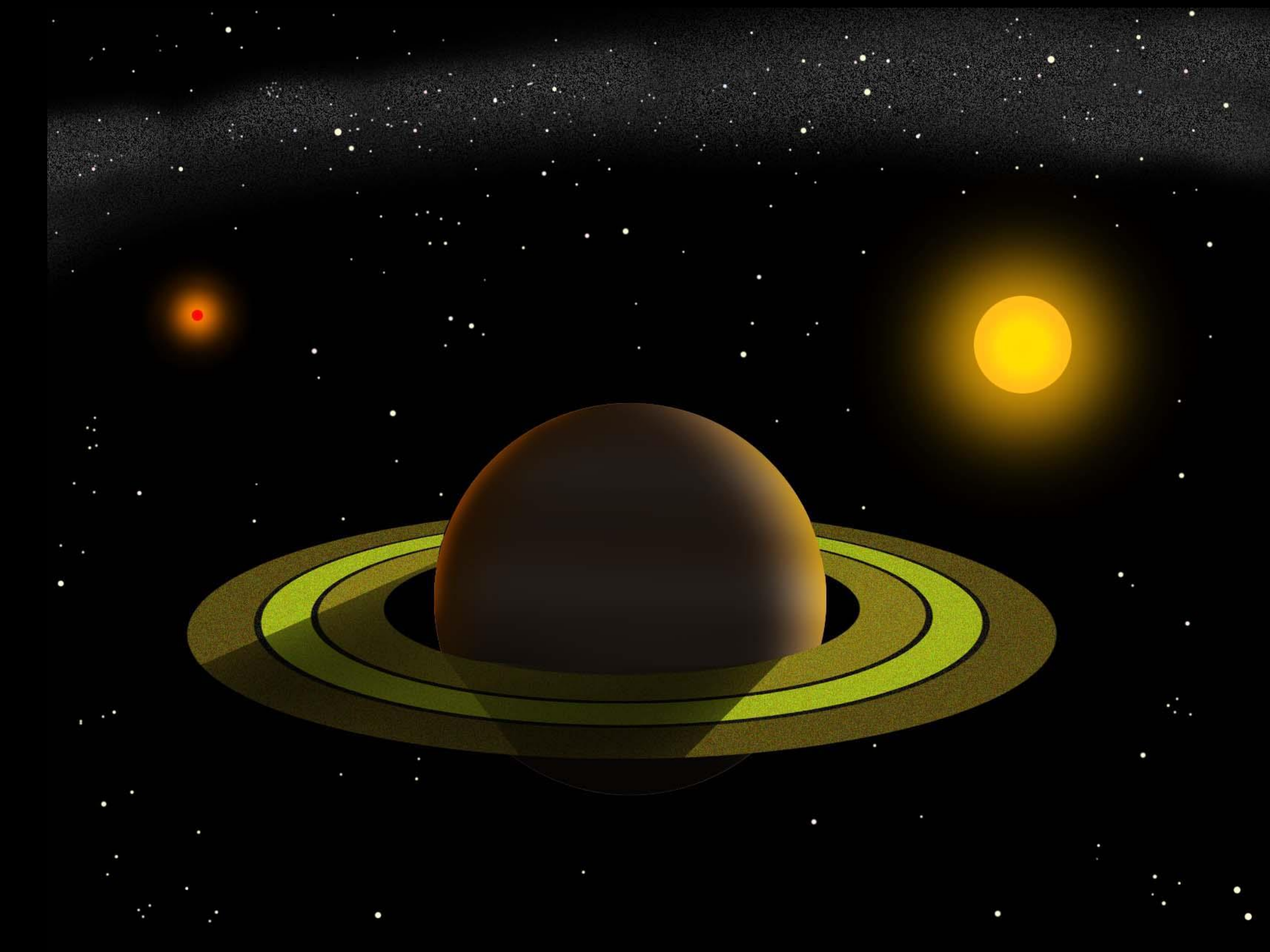
All of our conclusions about the types of planets that exist are biased by the methods we use to find planets and the properties of those planets to which these methods are most sensitive.

These are called “selection effects”.

Latest Results from McDonald Observatory: The planet around γ Cephei A A planet in a close Binary Star System

- γ Cephei A is the third brightest star in the constellation Cepheus
- It is a close binary star (the 2 stars can not be separated by eye
- We have found a planet in a 2.5 year period orbit around γ Cephei A.
- Other planets have been found in *wide* binary star systems, but never in one with the stars so close together.





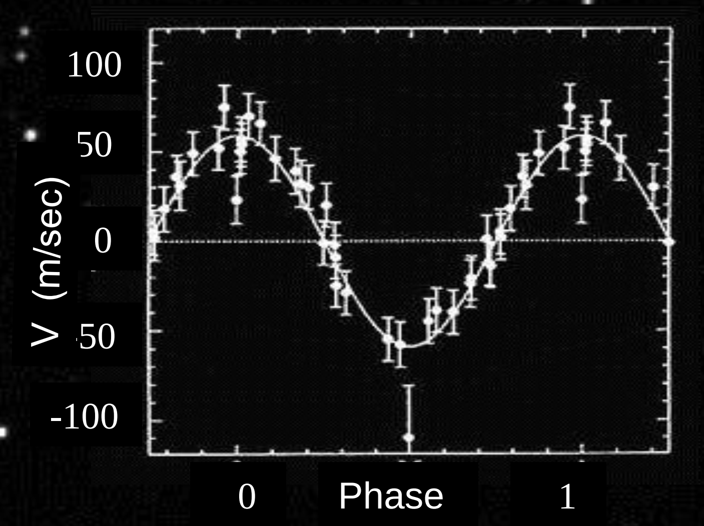
“Hot” Jupiters or 51 Peg-Type Stars

- The first extrasolar planet detected was orbiting 51 Peg. The first few planets found had properties similar to the planet around 51 Peg (called 51 Peg b).
  - These objects are in *very* short-period orbits
  - They are planets of about the same mass as Jupiter.

51 Peg

P = 4.2293 days

(Mayor and Queloz 1995)

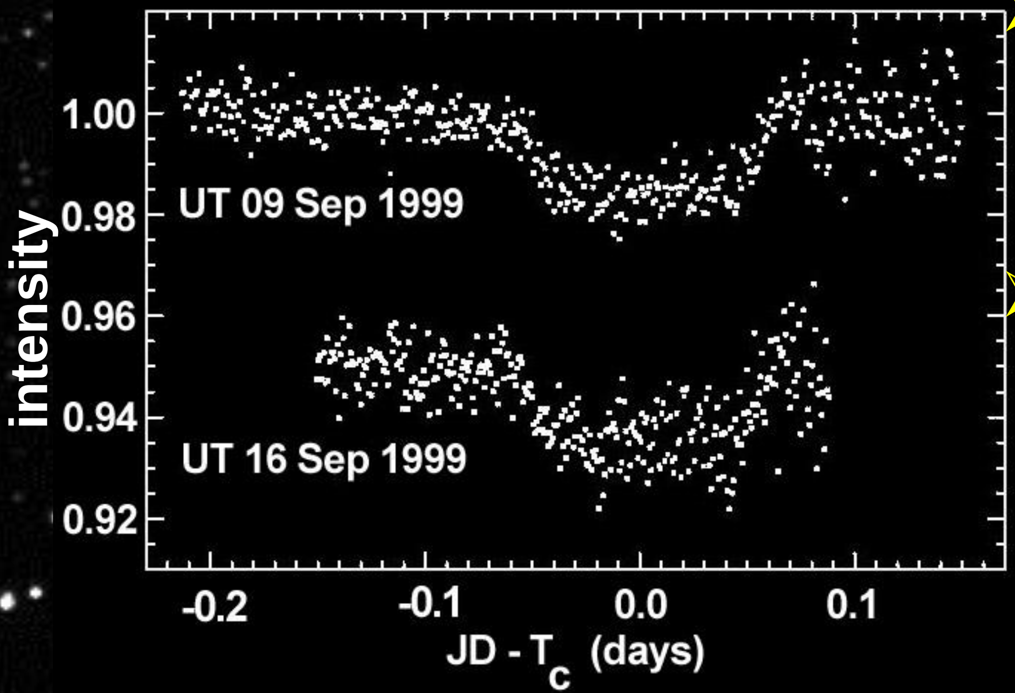


- We see the orbital speed is alternately increasing and decreasing every 4.2293 days.

- Are these “hot” Jupiters really gas giant planets, or can we have super-massive terrestrial planets?

The Planet Around Star HD 209458

Charbonneau *et al.* 2000

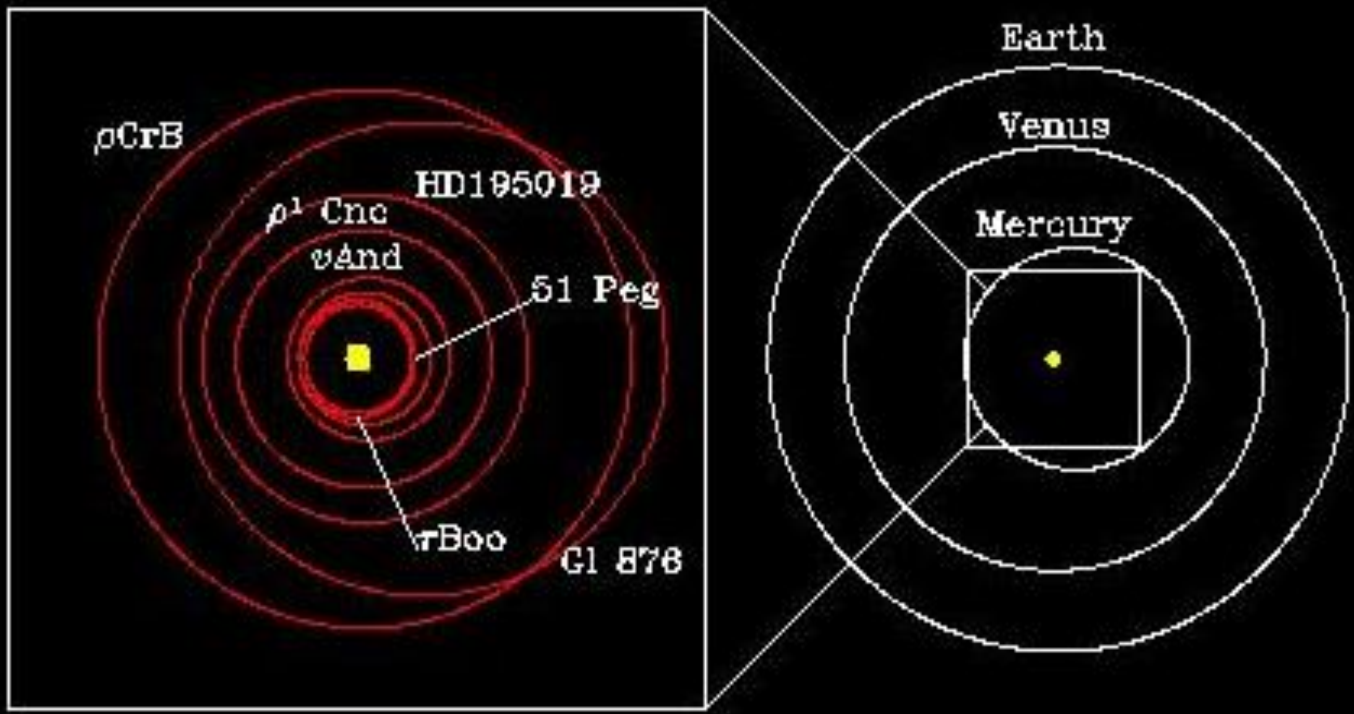


Definitely a gas giant planet like Jupiter!

- The planet around HD209458 was discovered by the radial velocity signal.
- After discovery, a transit was observed $\Rightarrow$ this gives a good measure of the *inclination*. From M sin *i*, we can then derive M.

  - $M_P = 0.69 \pm 0.05\ M_{JUP}$
  - $R_P = 1.40 \pm 0.17\ R_{JUP}$
  - density = $\rho = 0.31 \pm 0.07$ g/cm^3

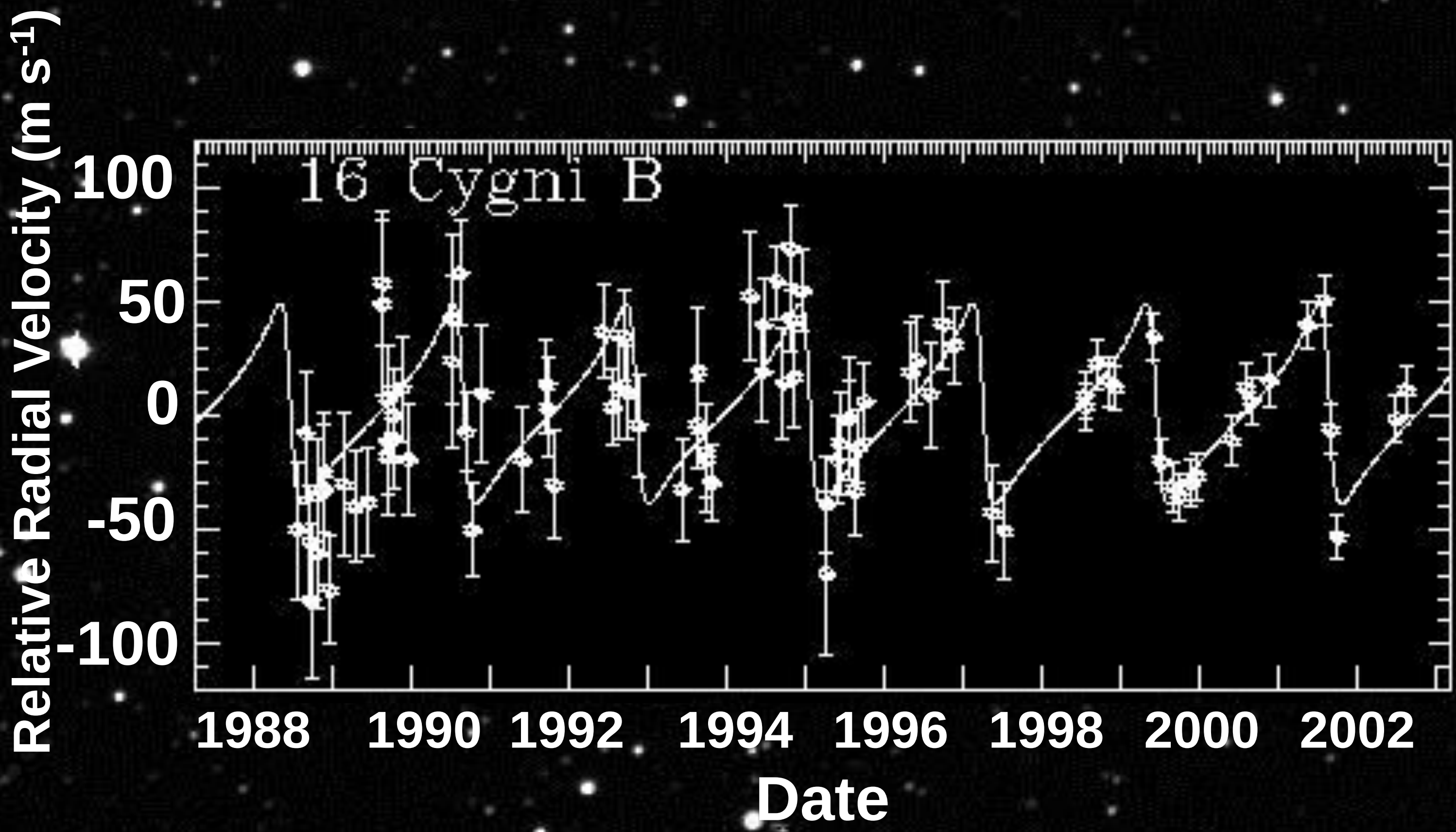
The 51 Peg-Type Planets



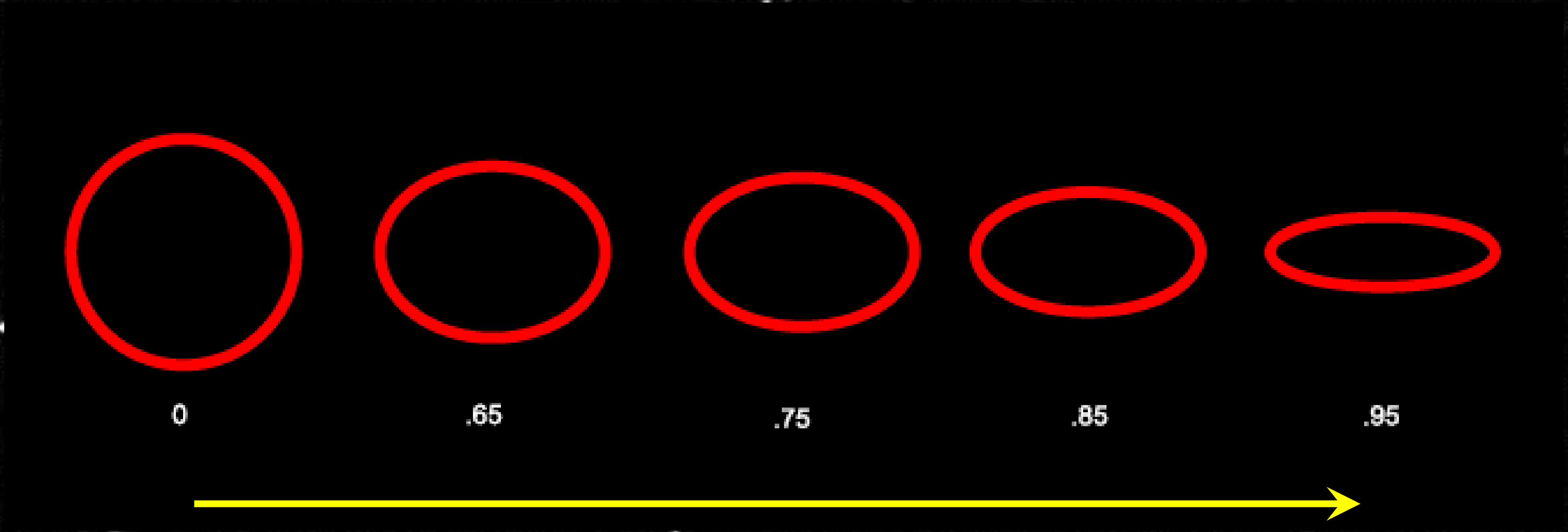
Sun to scale **Sun NOT to scale**

Massive Eccentric Planets

- In our Solar System, the planetary orbits have *low eccentricities* (with the exception of Pluto).
  - This is a natural consequence of planet formation.
  - This is what we expected for other planetary systems.

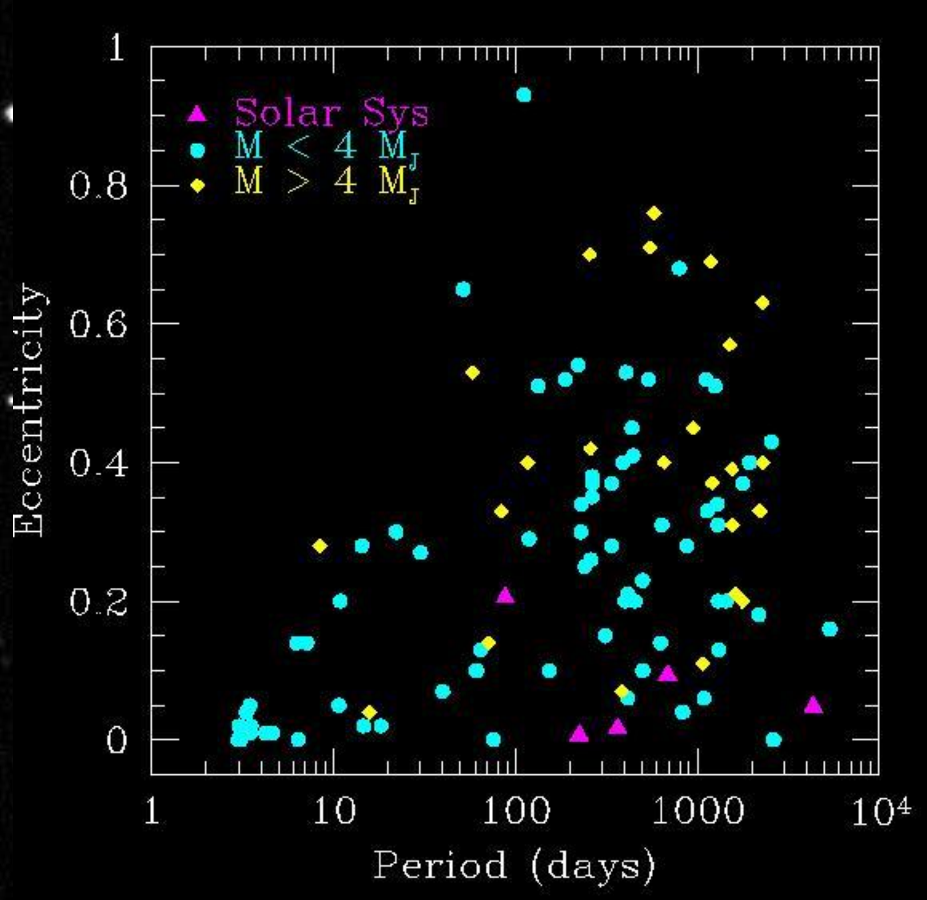


- When we look at the list of planets which have been discovered so far, we see that *low eccentricities are not common.*



Increasing eccentricity

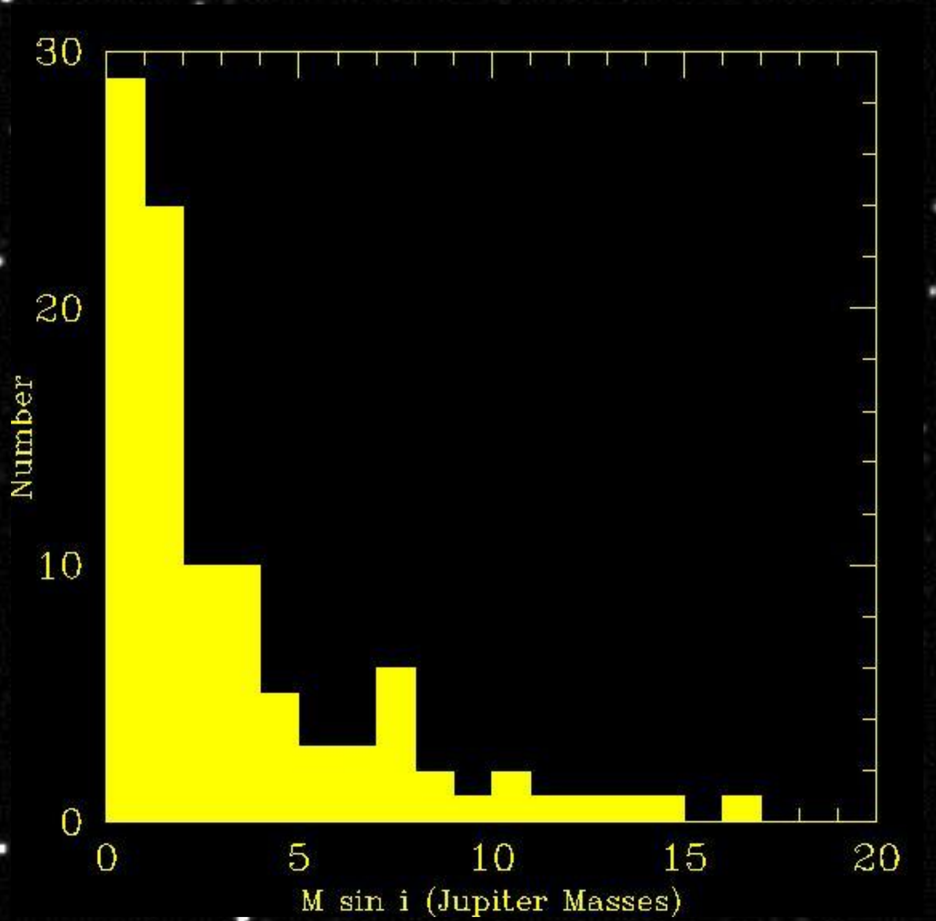
- When we look at the list of planets which have been discovered so far, we see that *low eccentricities are not common.*
- Except for the 51 Peg-type systems, the eccentricities are relatively large, independent of mass.



How massive are the planets we have found?

If we look at a histogram of masses, we see that we have preferentially found objects with *small* masses.

- The radial velocity technique is sensitive to *larger* masses.
- Therefore, there appears to be very few brown dwarfs orbiting these stars.



How do we get planets into very close orbits around the stars?

- Maybe they form at large distances from the star, and then are moved to their present locations by some process. This is called orbital migration.
  - There is an elaborate theory that uses tidal forces raised by the planet in the disk of material from which it was formed to cause the inward migration.
  - Of course, the migration must stop before the planet plunges into the star!
- Perhaps the planets formed where we find them today, but by some different process than we think formed our solar system.

How do we account for the very large orbital eccentricities?

- Interactions with any remaining planetesimals:
  - A slow inward migration can still occur once the gas disk is gone if there are still a lot of planetesimals remaining.
- Gravitational interactions among planets:
  - A system of multiple planets can become dynamically unstable once the gas disk dissipates. Planets can collide, be ejected, or be put into eccentric orbits.
- Dynamical interactions with other stars:
  - If most stars form in dense star clusters, then the gravity of nearby stars could disrupt newly formed planetary systems.

DOCTOR FUN

17 Jan 2002

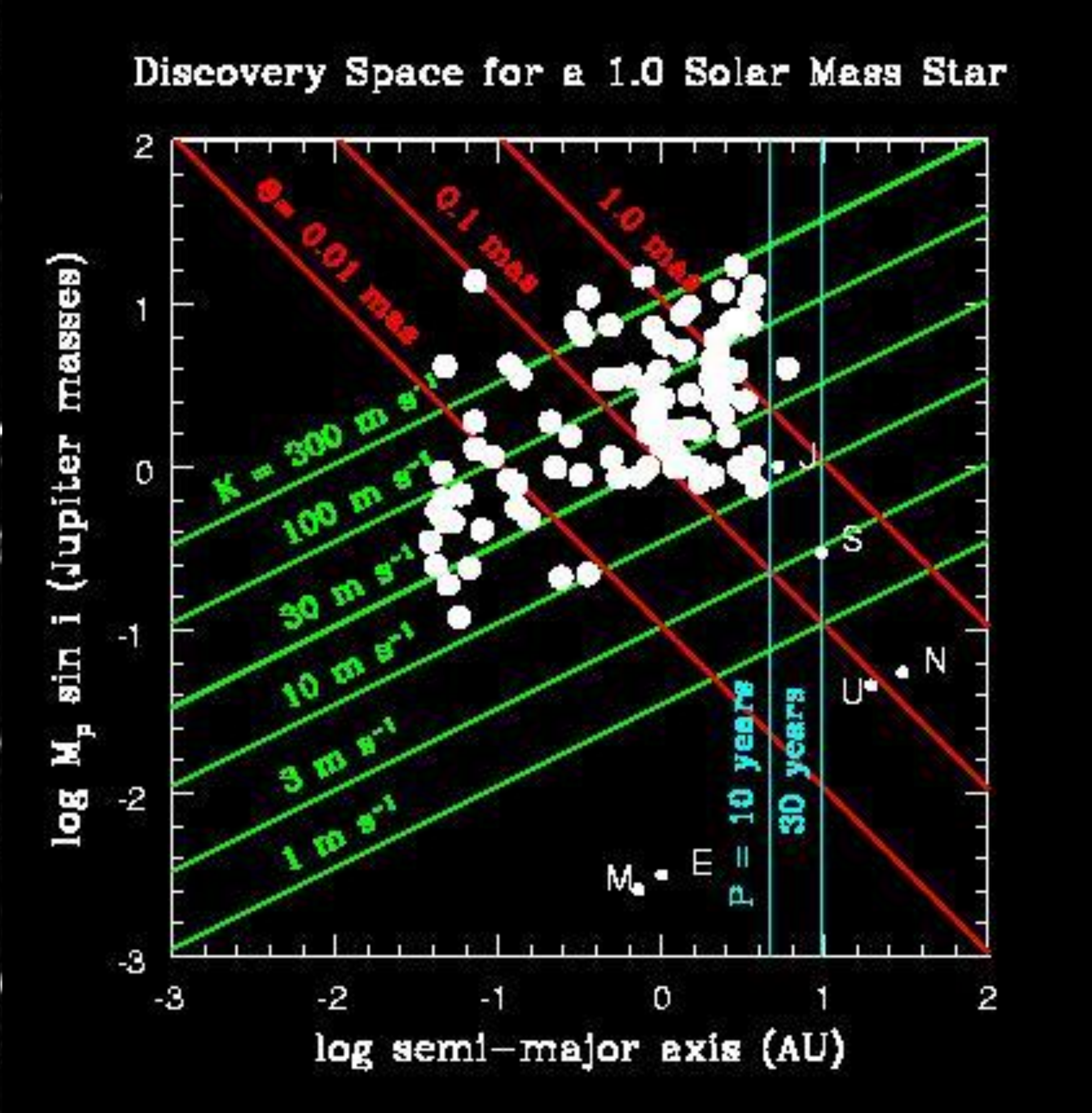
Interplanetary Worlds In Collision Bumpercars

Multi-planet systems around other stars

- Our Solar System has many planets, all orbiting the Sun.
- Multiple *star* systems form in hierarchical systems (e.g. a pair of stars orbit another star *as a pair*).
- Thus, a true test for if objects are in a *planetary system* is to find multiple objects orbiting the same star.

Star	M sin i (M_{JUP})	Period (days)	a (AU)	e
HD 83443	0.35	2.986	0.038	0.08
	0.17	29.83	0.174	0.42
Ups And	0.71	4.617	0.059	0.02
	2.05	241.3	0.828	0.24
	4.29	1308.5	2.56	0.31
55 Cnc	0.93	14.66	0.118	0.03
	>5?	>2920		
HD 82943	0.88	221.6	0.728	0.54
	1.63	444.6	1.16	0.41
HD 74156	1.55	51.60	0.276	0.65
	7.46	2300	3.47	0.40
Gliese 876	0.56	30.12	0.130	0.27
	1.89	61.02	0.207	0.10
47 U Ma	2.56	1090.5	2.09	0.06
	0.76	2640	3.78	0.0
HD 168443	7.64	58.1	0.295	0.53
	16.96	1770	2.87	0.2

Selection Effects in the discovery of extrasolar planets



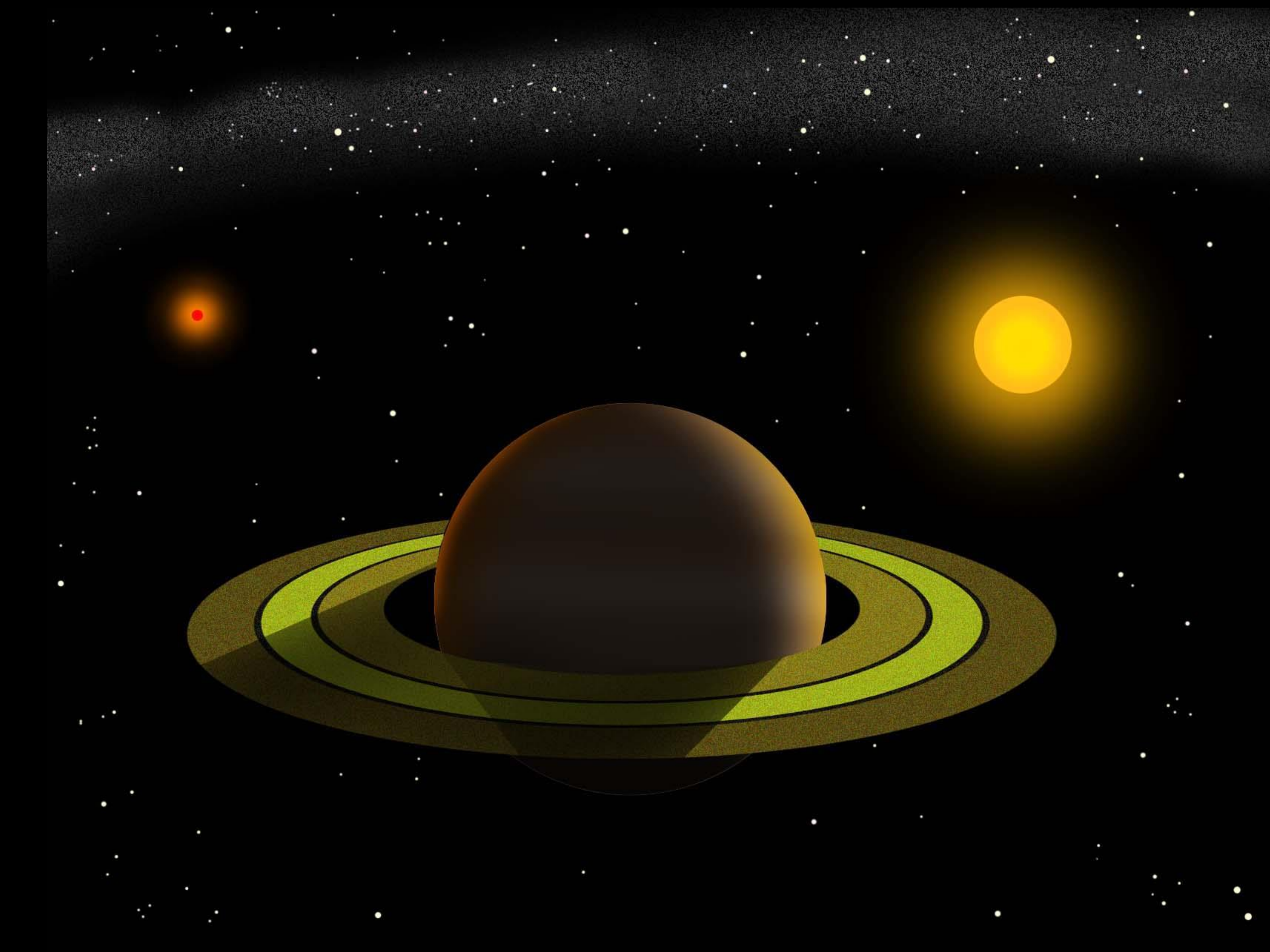
Selection effects are important! We are most sensitive to the short period systems.

Expectations	***Reality***
Planetary Systems are common	So far, about 4% of main-sequence stars have detectable planets.
There are many planets per system.	Only a few systems of multiple planets have been found *so far*.
Jupiter is the prototype giant planet.	Many objects are more massive than Jupiter. Radii, composition, and structure are unknown.
All planets are in prograde orbits near the stellar equatorial plane.	Orbital inclinations are unknown.

Expectations	Reality
a > 5AU for gas giants.	There is a very wide range of semimajor axes. How did “hot” Jupiters get so close to their parents?
Nearly circular orbits.	Many highly eccentric orbits.
Terrestrial planets in the inner regions.	Terrestrial planets not yet detectable.
Configurations are dynamically stable.	Dynamical evolution is probably very important.

Summary

- As we get longer time baselines and better precision, we will be able to detect systems which look more like our own.
- We need larger surveys of more stars to really understand the diversity of planetary systems.
- We need to keep modifying our formation models to account for what we have found.



Dr. William Cochran
Senior Research Scientist

Dr. William Cochran received his Ph.D. from Princeton University in 1976. His research interests include extrasolar planetary systems, high-precision measurements of stellar radial velocity variations, variable stars, planetary atmospheres, comets, and asteroids.