The History of the Universe in 200 Words or Less

Quantum fluctuation. Inflation. Expansion. Strong nuclear interaction. Particle-antiparticle annihilation. Deuterium and helium production. Density perturbations. Recombination. Blackbody radiation. Local contraction. Cluster formation. Reionization? Violent relaxation. Virialization. Biased galaxy formation? Turbulent fragmentation. Contraction. Ionization. Compression. Opaque hydrogen. Massive star formation. Deuterium ignition. Hydrogen fusion. Hydrogen depletion. Core contraction. Envelope expansion. Helium fusion. Carbon, oxygen, and silicon fusion. Iron production. Implosion. Supernova explosion. Metals injection. Star formation. Supernova explosions. Star formation. Condensation. Planetesimal accretion. Planetary differentiation. Crust solidification. Volatile gas expulsion. Water condensation. Water dissociation. Ozone production. Ultraviolet absorption. Photosynthetic unicellular organisms. Oxidation. Mutation. Natural selection and evolution. Respiration. Cell differentiation. Sexual reproduction. Fossilization. Land exploration. Dinosaur extinction. Mammal expansion. Glaciation. Homo sapiens manifestation. Animal domestication. Food surplus production. Civilization! Innovation. Exploration. Religion. Warring nations. Empire creation and destruction. Exploration. Colonization. Taxation without representation. Revolution. Constitution. Election. Expansion. Industrialization. Rebellion. Emancipation Proclamation. Invention. Mass production. Urbanization. Immigration. World conflagration. League of Nations. Suffrage extension. Depression. World conflagration. Fission explosions. United Nations. Space exploration. Assassinations. Lunar excursions. Resignation. Computerization. World Trade Organization. Terrorism. Internet expansion. Reunification. Dissolution. World-Wide Web creation. Composition. Extrapolation?

Astronomy 330

This class (Lecture 11):

Exoplanets

Next Class:

Exam 1

Music: *Planet of Sound*– Pixies

Exam 1

- Thursday in this room!!!!
- Class decided on 35 MC questions, plus two extra credit questions.
  - Maximum score is 105 counted out of 100 points.
- You can bring 1 sheet of paper with notes
  - Printed, scribbled, whatever, I don’t care.
- Will cover material up to and including Thursday’s lecture.
- Major resources are lectures, in-class questions and homework.

Outline

- Why are the planets different?
- Exoplanets are common!

Drake Equation

Frank Drake

$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

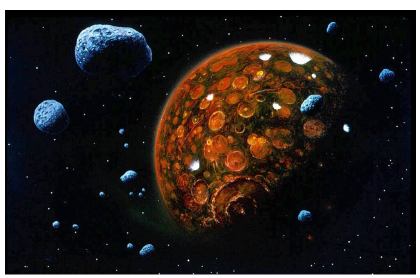
N	R_*	f_p	n_e	f_l	f_i	f_c	L
# of advanced civilizations we can contact in our Galaxy today	Star formation rate	Fraction of stars with planets	# of Earthlike planets per system	Fraction on which life arises	Fraction that evolve intelligence	Fraction that commun-icate	Lifetime of advanced civilizations
	9 stars/ yr	? systems/ star	planets/ system	life/ planet	intel./ life	comm./ intel.	yrs/ comm.

Planet Formation in the Disk

Heavy elements clump

1. *Dust grains* collide, stick, and form planetesimals– about 10^{12} of them, sort of like asteroids! All orbit in the same direction and in the same plane.
2. Gravity Effects: Big planetesimals attract the smaller planetesimals. So, fewer and fewer of large objects (100's). Collisions build-up inner planets and outer planet cores.
3. Collisions can also account for odd motions of Venus (backwards), Uranus (rotates on its side), and Pluto (high inclination of orbit). Proof of period of high collision evident on moon

Heavy Bombardment



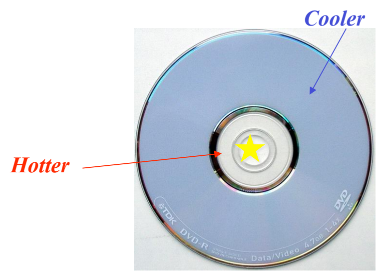
- There were billions of planetesimals in the early solar system
- Many collided with the young planets
  - Look at the Moon & Mercury!
  - Period of **heavy bombardment**
  - Lasted for about the first 800 million years of the Solar System
- Others were ejected from the solar system…

Fates of the Planetesimals

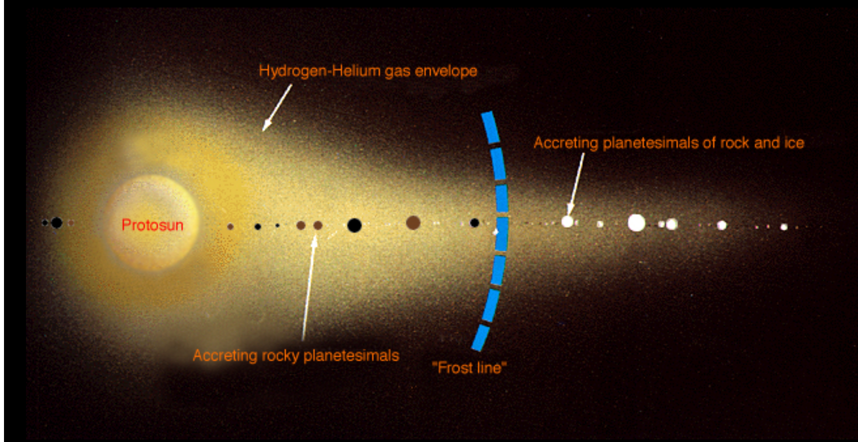
- Between Mars and Jupiter
  - Remain as the asteroids
- Near Jupiter & Saturn
  - Ejected from the solar system
- Near Uranus & Neptune
  - Ejected to the Oort Cloud
- Beyond Neptune
  - Remain in the Kuiper Belt

Everyone Loves Disks

- As the star forms, the inner region of the disk gets much hotter than the outer regions, creating a temperature gradient.
- The inner part of the disk had a higher density than the outer regions.
- Icy mantles of dust grains (NH_3, CH_4, etc.) evaporated at varying distances.



Why are the Planets so Different?



Temperature is the key factor!

Why are the Planets so Different?

- Temperature is the key factor
- Inner Solar System: Hot
  - Light gasses (H, He) and "ices" vaporized
  - Blown out of the inner solar system by the solar wind
  - Only heavy elements (iron & rock) left
- Outer Solar System: Cold
  - Too cold to evaporate ices to space
  - Rock & ice "seeds" grew large enough to pull gasses (H, He) onto themselves

Question

How can we explain the differences between planets in our Solar System?

a) Unlikely to be any systematic difference in their formation.

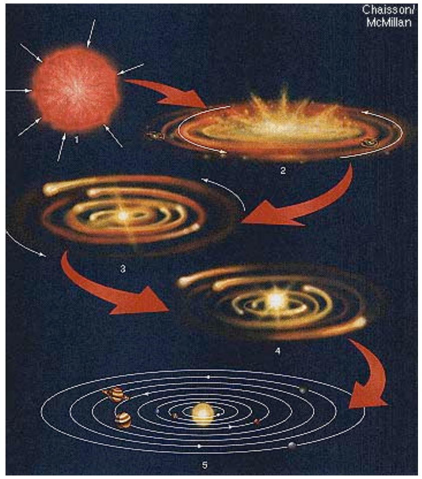
b) Due to the mass of the planet only.

c) Due to the age of the Sun and what elements were available.

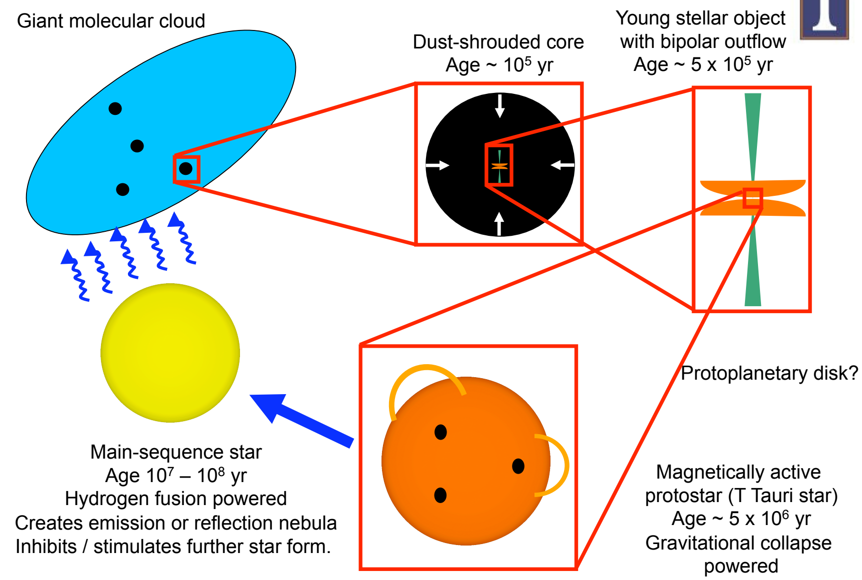
d) Due to the temperature in the disk at the time.

e) We don't know. One of the biggest questions in modern astronomy.

Formation of the Solar System 4.6 billion years ago



Star Formation - Summary



Question

A star is born. Which of the following did not happen?

a) the nuclear strong force created gravitational instabilities.
b) a gas cloud clumped because of gravity and began to collapse.
c) a protoplanetary or circumstellar disk formed due to conservation of momentum.
d) an outflow or jet of material was ejected from the system.
e) fusion began due to heat and pressure.

What Are We Looking For?

General Predictions of Solar Nebula Theory

- ☺ Are interstellar dust clouds common? ***Yes!***
- ☺ Do young stars have disks? ***Yes!***
- ? Are the smaller planets near the star?
- ? Are massive planets farther away?

Test Of Exoplanets

Planets around other stars
 = extrasolar planets = ***"exoplanets"***

Would our solar system nebula formation theory account for other solar systems around other stars?

Hard to find!

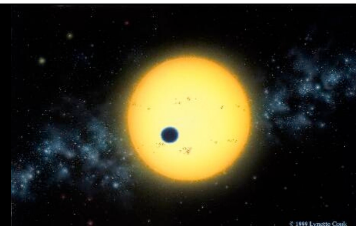
Reflected light from the Earth is 1 billion times fainter than the Sun!!!!!

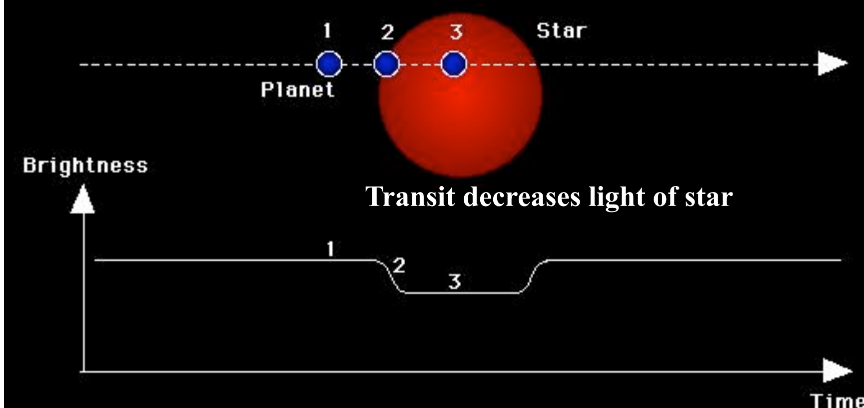
Finding Planets

1. **Radial Velocity: Stars will wobble.**
2. Astrometry: See the stars move.
3. Transit Method: Occultation.
4. Direct Detection: Direct imaging.

Only a few planets have been detected directly in the optical and IR. Remember that planets in our Solar System seem bright because they reflect light from the Sun in the visible.

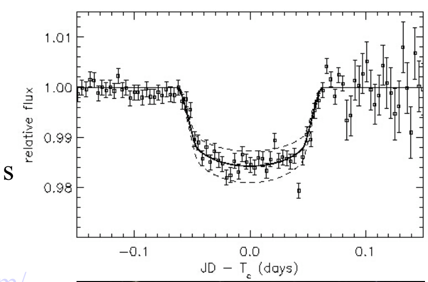
Planet Transits

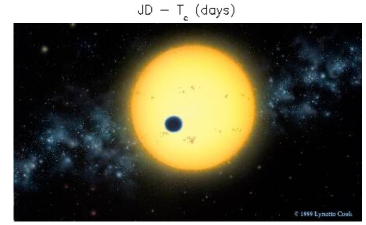


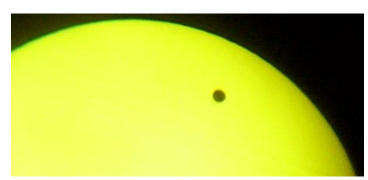


Transits

- The planet passes in front of the star– like Venus 2004.
  - Again 6 June 2012
- Can find planet radius
- Best chance of finding Earth-like planets
- Requires the extrasolar planet's orbital plane to be pointed at Earth
- http://www.howstuffworks.com/planet-hunting2.htm





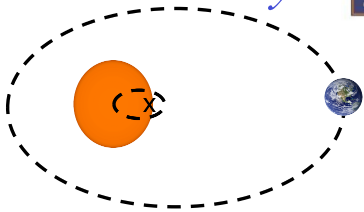


Star Wobble: Radial Velocity

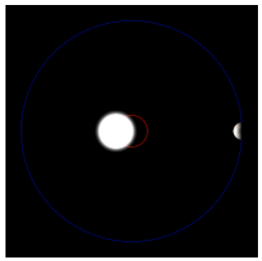
Newton's 3rd Law:

- *Both* planet *and star* move
- Both orbits fixed around the "center of gravity"

- Star's period? Place your bets…
  - Same as planet



Greatly exaggerated



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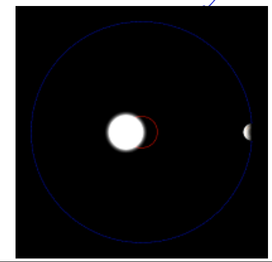
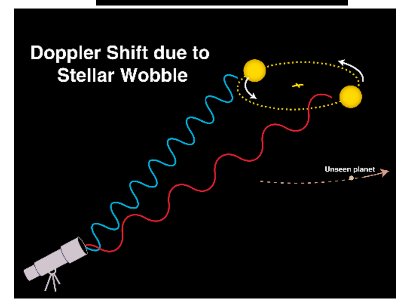
Star Wobble: Radial Velocity



- Star movement too small to see
  - Moves in small, tight circle
  - But "wobble" in star speed detected!
  - The stellar spectrum is shifted red and blue as it moves towards us and away from us.

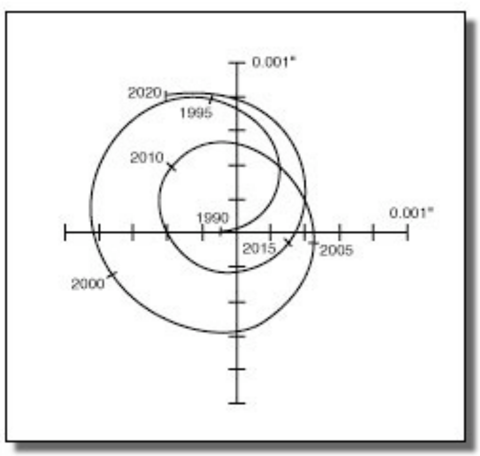


http://www.howstuffworks.com/planet-hunting2.htm

The Sun's Wobble

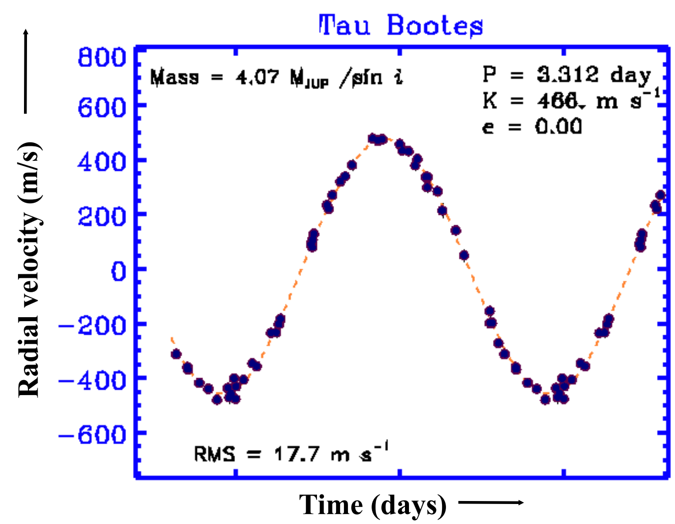
Astrometric displacement of the Sun due to Jupiter (and other planets) as at it would be observed from 10 parsecs, or about 33 light-years.

If we could observe this, we could derive the planetary systems– also called astrometry.

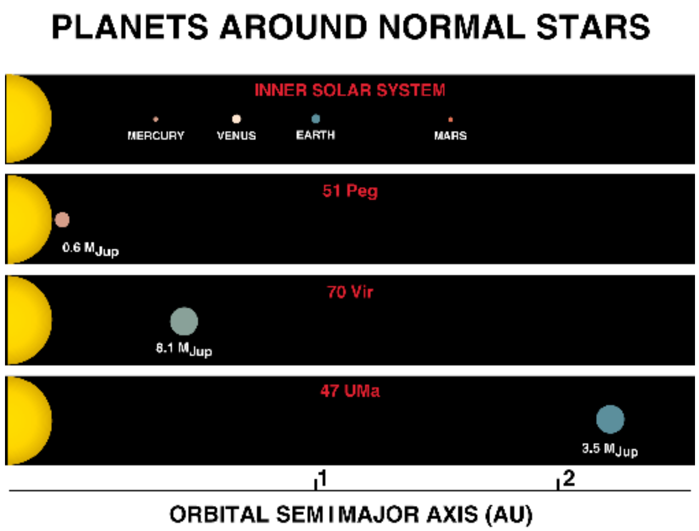


http://planetquest.jpl.nasa.gov/Keck/astro_tech.html

Radial Velocity Shifts: Planets around other Stars?

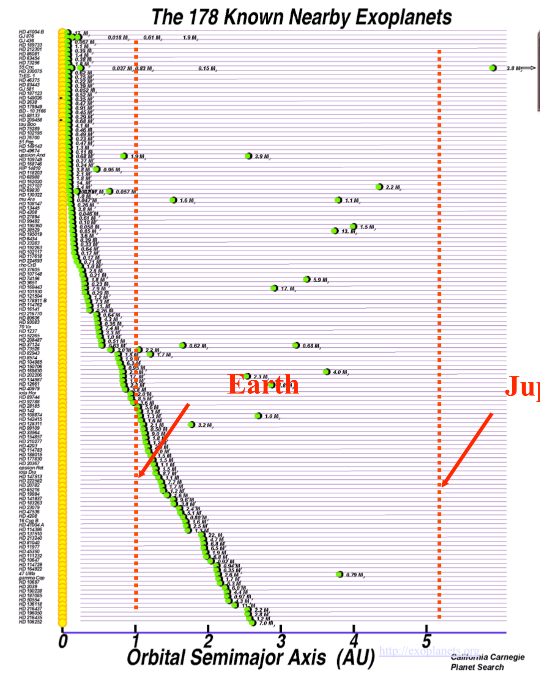


Early Discovery-- 1996



Hear all about it.

As of today, there are 349 planets known around nearby stars.

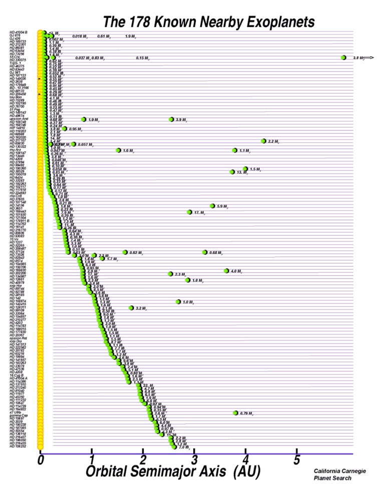


Exoplanets: Results to Date

Over 349 planets detected so far

- More than 25 times the number in our Solar System!

- By measuring the wobble variation:
  - With time, gives the planet distance: Kepler's 3rd law
  - The orbital speed of the star gives masses: the bigger the wobble amplitude, the heavier the planet



Exoplanets: Results to Date

More than 20 multi-planet systems!

Note: Jupiter is 318 times the mass of Earth or

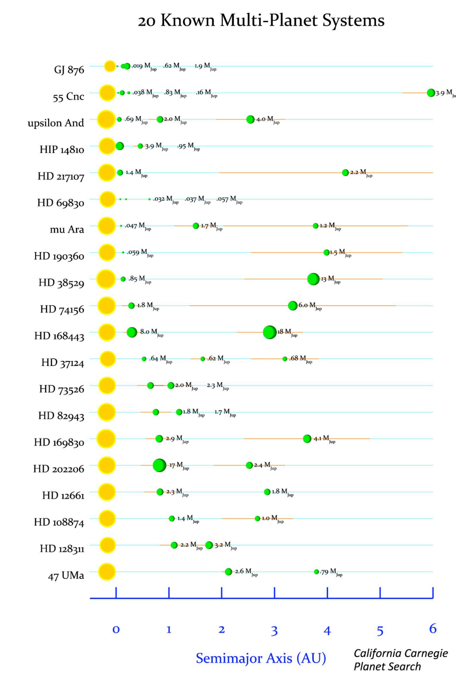
$M_E = 0.003\ M_J$

$M_J = 0.001\ M_{Sun}$

$M_{red\ dwarf} = 80\ M_J$

$M_{brown\ dwarf} = 18\ M_J$

$Period_J = 12$ years



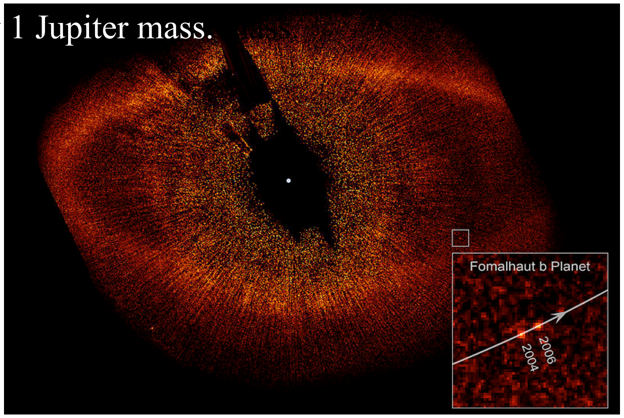
Lists

http://exoplanets.org/

http://en.wikipedia.org/wiki /List_of_extrasolar_planets

Fomalhaut

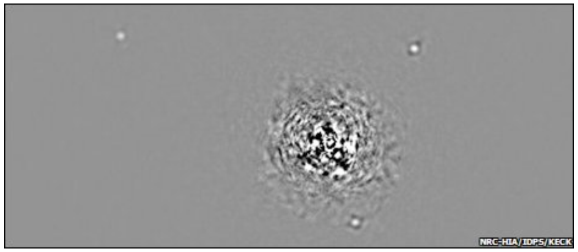
- First planet imaged in visible light
- Orbits at 115 AU!
- Probably 1 Jupiter mass.



http://hubblesite.org/newscenter/archive/releases/2008/39/image/

HR 8799

- First detection of exoplanet in IR.
- Three planet system
  - 10 M_J (24 AU)
  - 10 M_J (38 AU)
  - 7 M_J (68 AU)



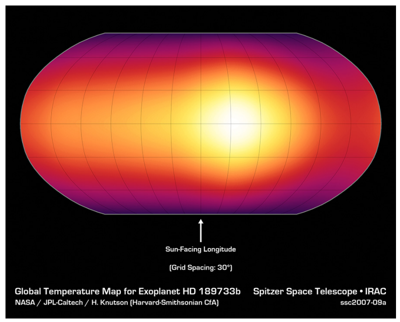
COROT-Exo-7b

- Discovered last year.
- Smallest planet yet, only 1.7 Earth diameters.
- But, probably 5-10 Earth masses
- Orbits freaky close— 20 hours (0.017 AU)!
- Hot! Might even be lava.

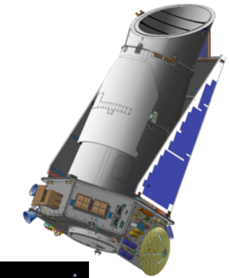
http://turbinaionica.blogspot.com/2009/02/descoberto-o-corot-exo-7b.html

Exoplanet Weather

- Transiting Planet: HD 189733 b (orbit of 0.03AU)
- Surface temp estimated by Spitzer
- Atmosphere has water vapor and methane!
- Surface temp of 1000 K.



Kepler Mission



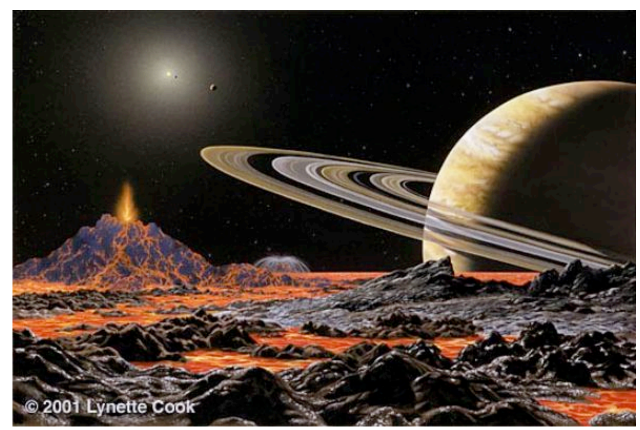
- Launched March 7, 2009
- Meant to find planet transits

Kepler Mission

- First results announced in Jan 2010
- 6 new short-period planets discovered
  - 4 larger than Jupiter
  - 1 similar to Neptune
  - 1 weirdo: 50% lighter but 50% bigger than Jupiter (density between styrofoam and cork)
- And more to come!

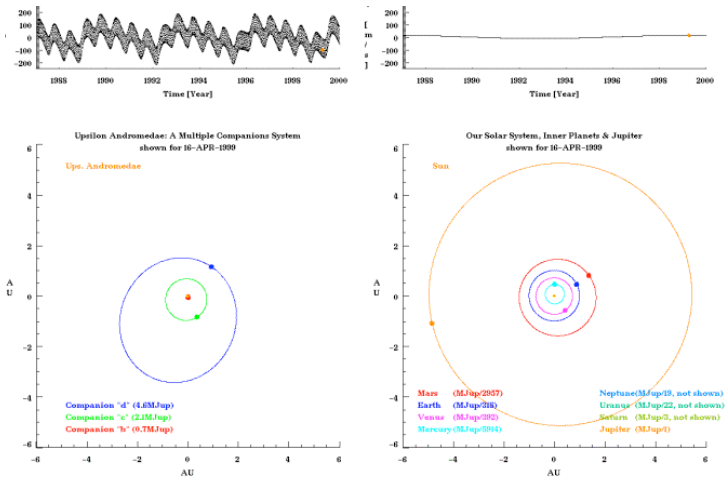
Other Planets, Other Stars

47 Ursae Majoris System– 51 light years away (near the Big Dipper). 13 years of data has shown 2 planets– 1 Jupiter like and 1 Saturn like.

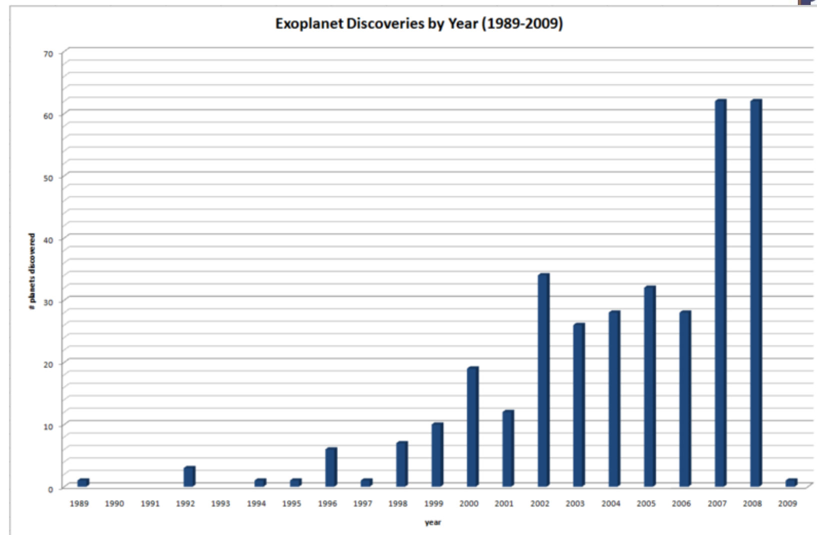


Wow! Among the most similar to our own system

Detecting the Solar System



Discover!

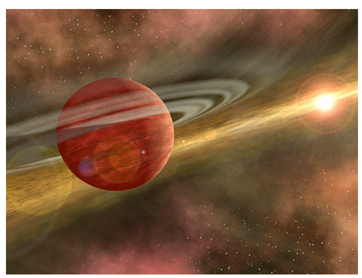


http://en.wikipedia.org/wiki/File:Exoplanet_Discoveries_by_Year_2009.png

Results to Date

No surprise

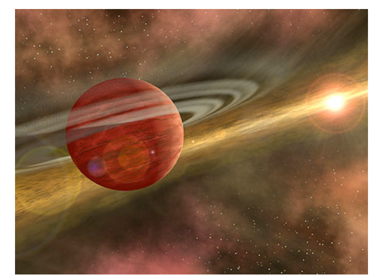
- ✓ New planets are massive
- ✓ Why? Big planets make a big wobble
- ✓ If not massive, we could not have found them
- ✓ About 3-5% of all stars have some type of planet.



Results to Date

Big surprises

- ? Most periods of only *a few days!*
- ? Most planets are very near their stars!
- ? τ Bootes' planet is 3.6 times Jupiter's mass, but it's orbit smaller than Mercury's!
- ? If a Jupiter-like planet formed close in, perhaps that prevents terrestrial planets from forming.



What Are We Looking For?
General Predictions of Solar Nebula Theory

☺ Are interstellar dust clouds common? ***Yes!***

☺ Do young stars have disks? ***Yes!***

? Are the smaller planets near the star?

Not the ones found so far! Haven't found smaller planets yet!

? Are massive planets farther away?

Not most of the ones found so far!

Important Caveat

- Our current observations of extrasolar planets do **not** exclude planetary systems like our solar system
- Current instruments are most sensitive to large planets close to their stars
  - Big planet - big wobble
  - Close planet - fast wobble
- We only have a little over 10 years of data – 1 orbit's worth for Jupiter
- To find solar-type systems, we need more sensitive equipment

Exoplanets: Implications

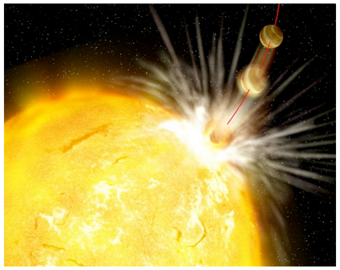
Solar Nebula **Theory**:
- Giant planets born far from star

Exoplanet Data:
- Giant planets found very close

Theory is *incomplete/wrong*!

New questions:
? Who is normal: Them or us?
? Are giant planets born close in?
? Are some giant planets born far out, move in? "planet swallowing"!?!

Anyway: Planets are common!
✓ Good news in search for life elsewhere...maybe

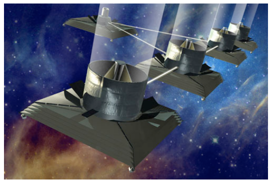


Question

We have only mostly detected Jupiter-sized planets around other stars because

a) lower mass planets collide with the star.
b) Jupiter-type planets are just nicer to look at.
c) the technology of the detection techniques make detecting massive planets easier.
d) they represent burned up corpses of binary star systems.
e) low-mass planets like those in our solar system are freak occurrences

A Future Mission?

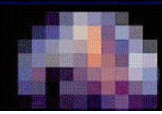


The goal of imaging an Earth-like planet.

5 platforms of 4 eight meter interferometer in space.

http://spider.ipac.caltech.edu/staff/jarrett/talks/LiU/origins/openhouse30.html

A Future Mission

Pixel / Diameter	Pixel size @ planet (km)	Image	Interferometer Requirements		
				Collecting Area	Baseline
400	32		IR	144 km^2	100,000 km
			Visible	1,296 km^2	5,000 km
100	128		IR	0.64 km^2	24,000 km
			Visible	5.76 km^2	1,200 km
25	510		IR	1,024 m^2	6,000 km
			Visible	9,216 m^2	303 km
10	1276		IR	64 m^2	2,4km
			Visible	576 m^2	120 km