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

<u>This class (Lecture 9):</u>

Exoplanets

<u>Next Class:</u>

Nature of Solar Systems

HW 4 is due Sunday!
Exam 1 is next Thursday!

Music: *Planet of Sound*– Pixies

Question

How many multiple choice questions do you want on Exam 1?

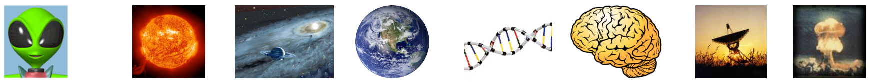
a) 25
b) 30
c) 35
d) 40
e) 45

Outline

- Today we estimate f_p?
- Exoplanets – they are all over the place.
- Getting close to Earth sized planets now!

Drake Equation

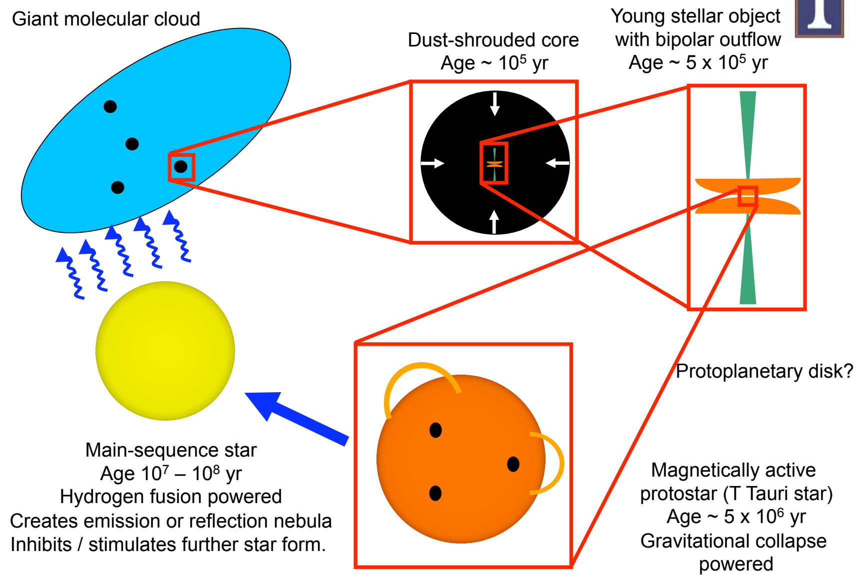
Frank Drake



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

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
	20 stars/ yr	? systems/ star	planets/ system	life/ planet	intel./ life	comm./ intel.	yrs/ comm.

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!

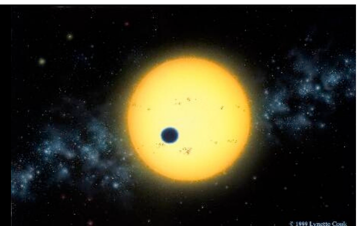
Reflected light from the Earth is 1 billion times fainter than the Sun!!!!!

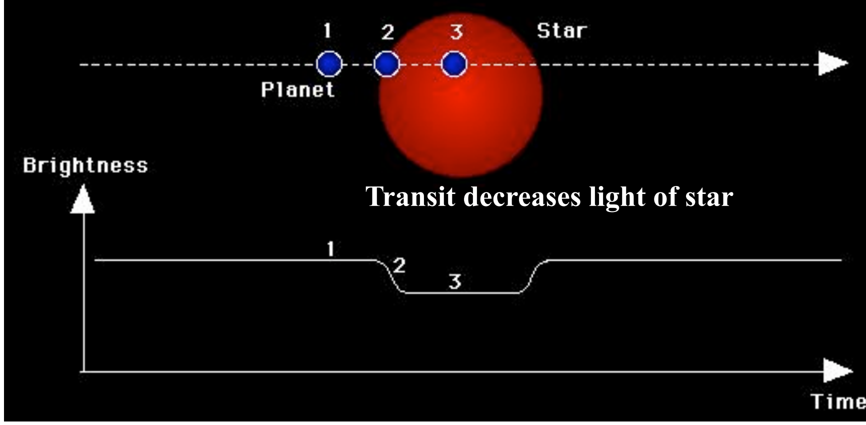
Finding Planets

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.

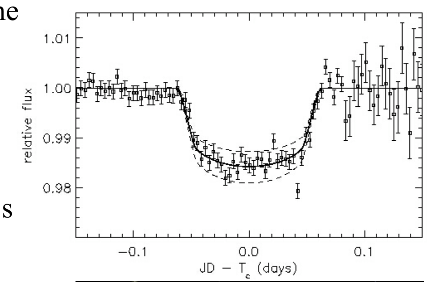
Planet Transits

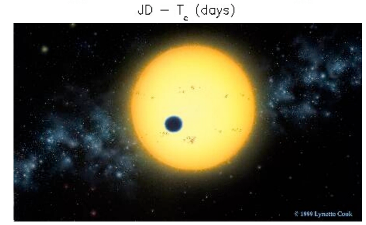




Transits

- The planet passes in front of the star– like Venus 2004.
- 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



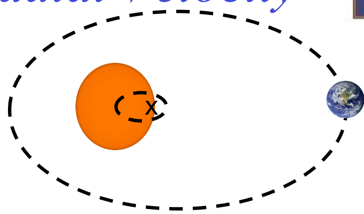


Star Wobble: Radial Velocity

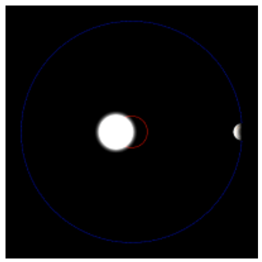
Newton's 3rd Law:

- *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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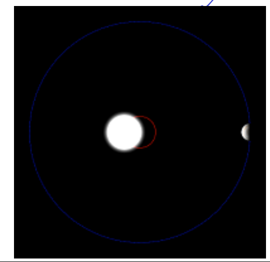
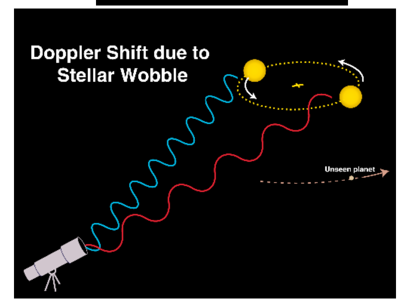
Star Wobble: Radial Velocity



- 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.

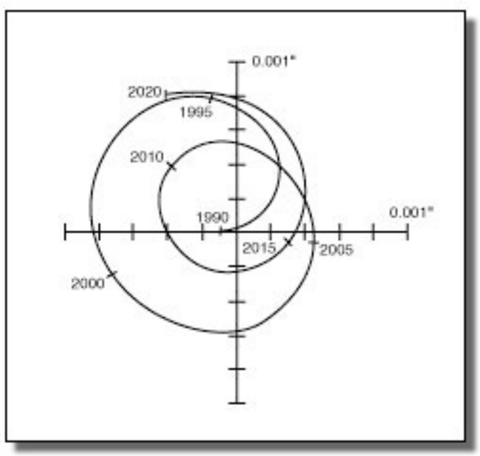


http://www.howstuffworks.com/planet-hunting2.htm

The Sun's Wobble

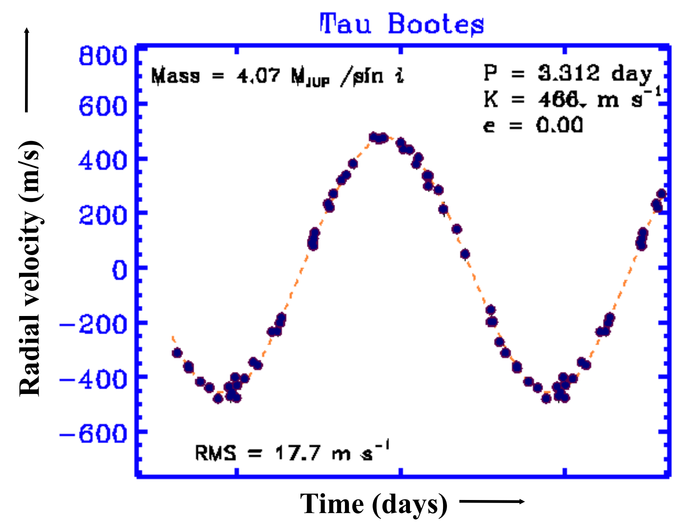
Astrometric displacement of the Sun due to Jupiter (and other planets) as at it would be observed from 10 parsecs, or about 33 light-years.

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



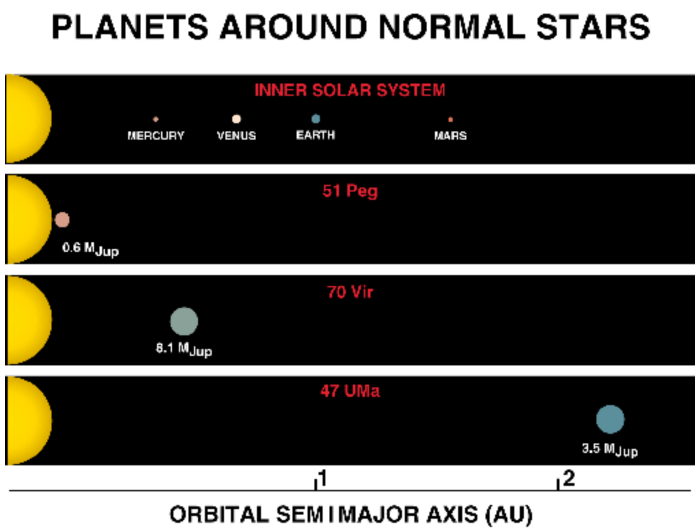
http://planetquest.jpl.nasa.gov/Keck/astro_tech.html

Radial Velocity Shifts: Planets around other Stars?

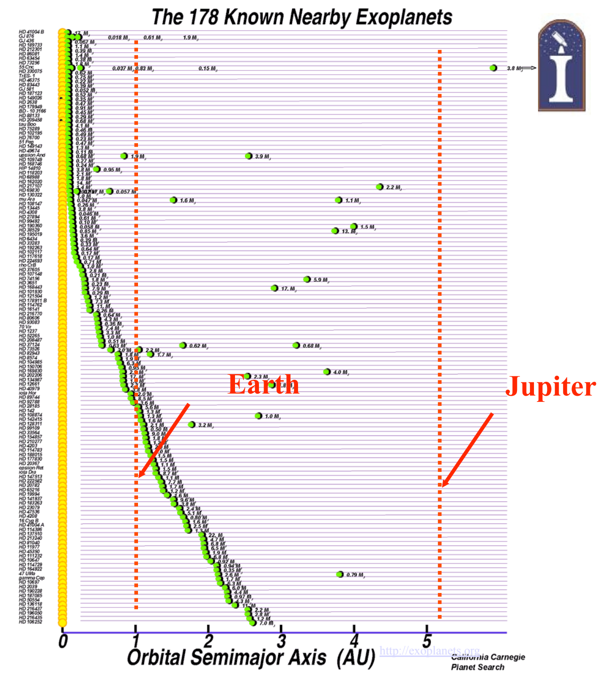


Early Discovery-- 1996

Hear all about it.



As of today, there are 321 planets known around nearby stars.

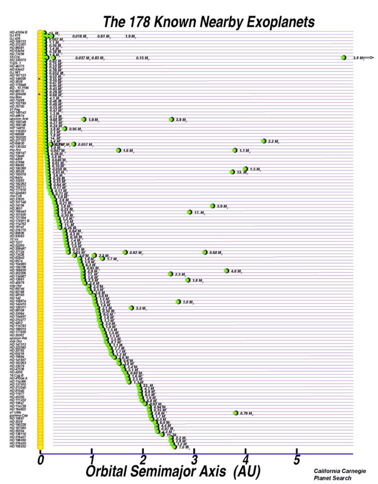


Exoplanets: Results to Date

Over 321 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

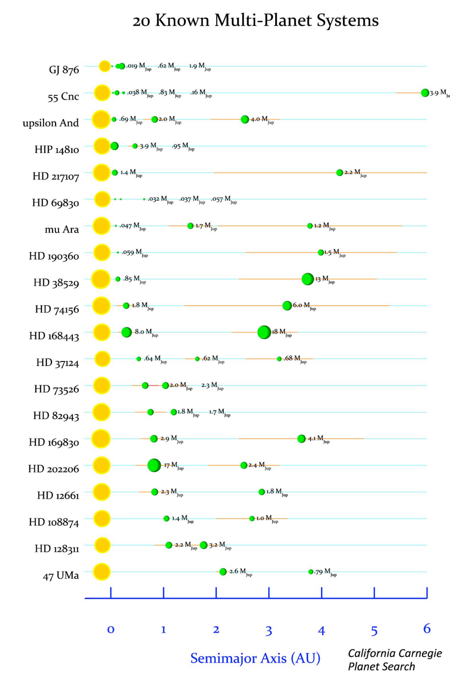
$M_E = 0.003\ M_J$

$M_J = 0.001\ M_{Sun}$

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

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

$Period_J = 12$ years



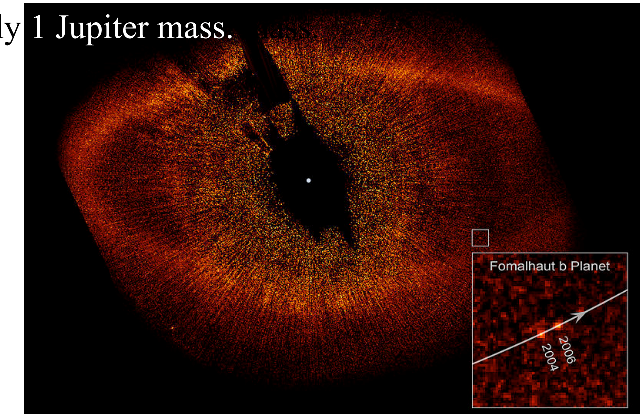
Lists

http://exoplanets.org/

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

Fomalhaut

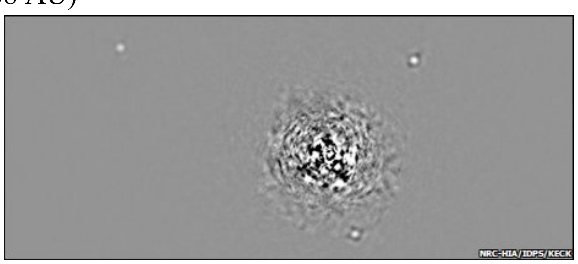
- First planet imaged in visible light
- Orbits at 115 AU!
- Probably 1 Jupiter mass.



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)



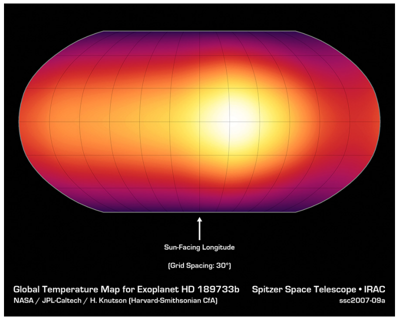
COROT-Exo-7b

- Discovered this 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.

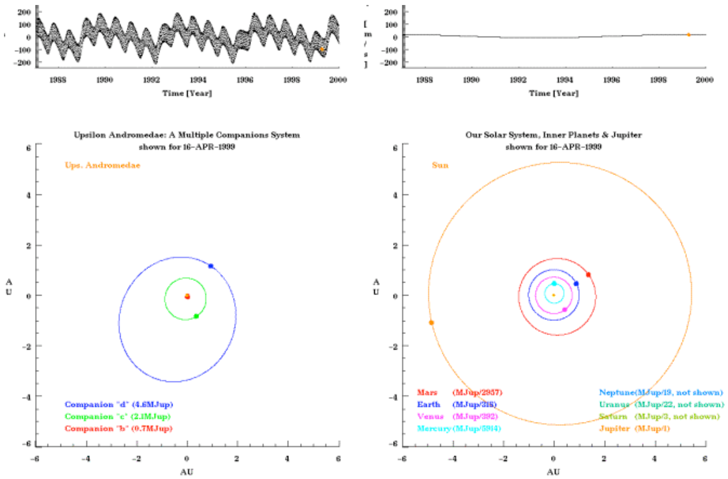


Other Planets, Other Stars

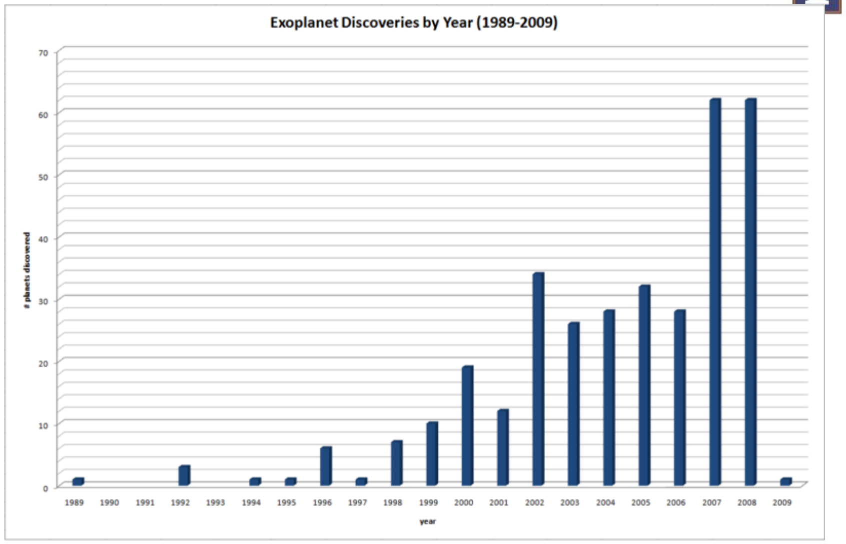
47 Ursae Majoris System– 51 light years away (near the Big Dipper). 13 years of data has shown 2 planets– 1 Jupiter like and 1 Saturn like.

Wow! Among the most similar to our own system

Detecting the Solar System



Discover!

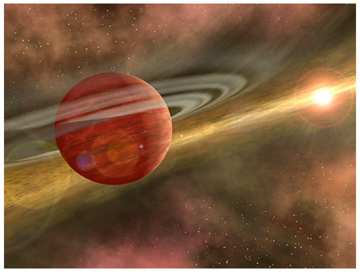


http://en.wikipedia.org/wiki/File:Exoplanet_Discoveries_by_Year_2009.png

Results to Date

No surprise

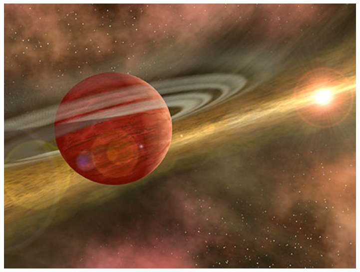
- ✓ New planets are massive
- ✓ Why? Big planets make a big wobble
- ✓ If not massive, we could not have found them
- ✓ About 3-5% of all stars have some type of planet.



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

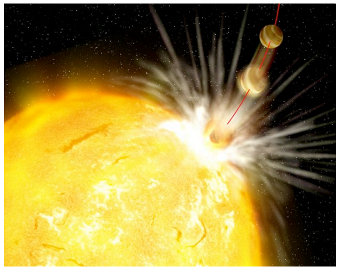
- Our current observations of extrasolar planets do **not** exclude planetary systems like our solar system
- Current instruments are most sensitive to large planets close to their stars
  - Big planet - big wobble
  - Close planet - fast wobble
- We only have a little over 10 years of data – 1 orbit's 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"!?!

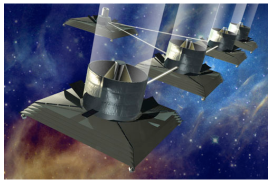
Anyway: Planets are common!
✓ Good news in search for life elsewhere...maybe

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?

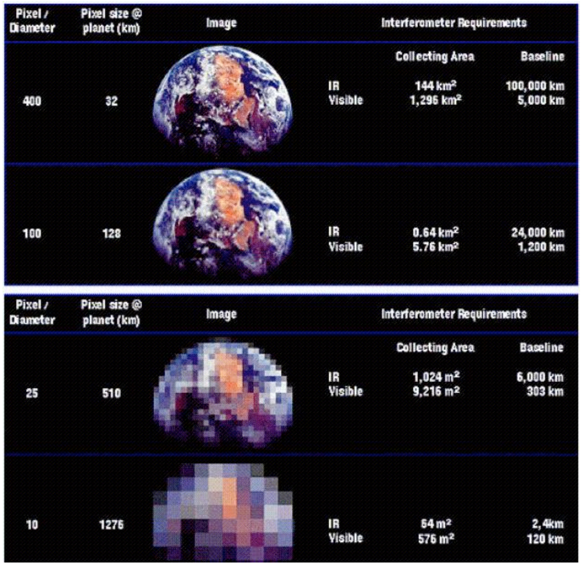


The goal of imaging an Earth-like planet.

5 platforms of 4 eight meter interferometer in space.

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

A Future Mission



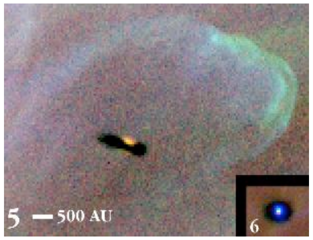
Pixel / Diameter	Pixel size @ planet (km)	Image		Interferometer Requirements: Collecting Area	Interferometer Requirements: Baseline
400	32		IR Visible	144 km² 1,296 km²	100,000 km 5,000 km
100	128		IR Visible	0.64 km² 5.76 km²	24,000 km 1,200 km
25	510		IR Visible	1,024 m² 9,216 m²	6,000 km 303 km
10	1276		IR Visible	64 m² 576 m²	2,4km 120 km

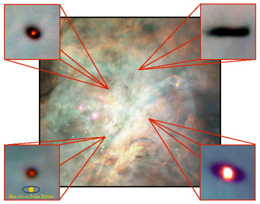
Disks in Binary Systems

- >60% of all stars are in binary or multiple systems.
- We do see circumstellar disks in binary systems
- We do see exoplanets in binary systems.
- But we also see effects of the binary on the disk.
  - Still unclear how large of an effect.

Now, for f_p

- About 2/3 of all stars are in multiple systems.
  - Is this good or bad?
- Disks around stars are very common, even most binary systems have them.
- Hard to think of a formation scenario without a disk at some point– single or binary system.
- Disk formation matches our solar system parameters.
- We know of many brown dwarves, so maybe some planets do not form around stars.
  - There might be free-floating planets, but…





Now, for f_p

- Extrasolar planet searches so far give about $f_p \sim 0.03$, but not sensitive to lower mass systems.
- Maximum is 1 and lower limit is probably around 0.01.
- A high fraction assumes that the disks often form a planet or planets of some kind.
- A low fraction assumes that even if there are disks, planets do not form.
- This is not Earth-like planets, just a planet or many planets.