ET: Astronomy 230
Section 1– MWF 1400-1450
134 Astronomy Building

HW #2 is due on Friday

This Class (Lecture 9):

Planet Formation

Next Class:

Nature of Solar Systems

Presentations Sept 19
Carl Thomas
Hassan Bhayani
Aaron Bowling

Presentations Sept 23
Andrew Coughlin
Nicolas Jaramillo
Chris Fischetti

Music: *Planet of Sound* – Pixies

Outline

- How did our Solar System form?
- Extrasolar planets: watch them wobble.
- Not exactly what we expected.
- What to expect in the future.
- What is f_p?

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	Rate of star formation	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
	10						

Data: Planet's Dance

http://janus.astro.umd.edu/javadir/orbits/ssv.html

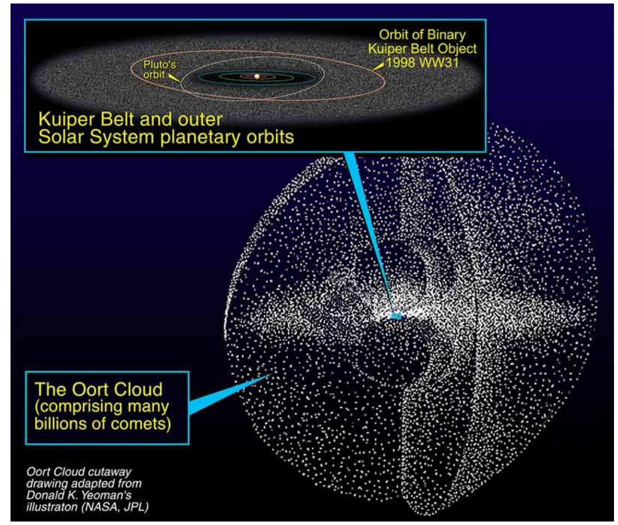
Data:
The Structure of the Solar System

- What are the furthermost solar system objects from the sun and what is their distribution?

Icy objects or long period comets

Furthermost objects form the Oort cloud! So…Spherical Geometry.

Data: Kuiper Belt



Data:
What is the age of the Solar System?

- Earth: oldest rocks are 4.4 billion yrs
- Moon: oldest rocks are 4.5 billion yrs
- Mars: oldest rocks are 4.5 billion yrs
- Meteorites: oldest are 4.6 billion yrs
- Sun: models estimate an age of 4.5 billion yrs

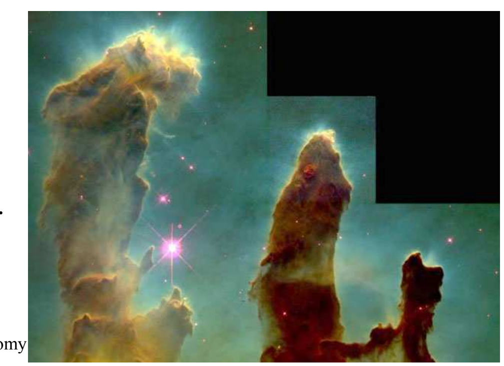
Age of Solar System is probably around 4.6 billion years old

Origin of Solar System: Solar Nebula Theory

"*nebula*" = cloud

Gravitational Collapse

- The basic idea was put forth by Immanuel Kant (the philosopher)– Solar System came from a Gas Nebula.
- 4.6 billion years ago: a slowly spinning ball of gas, dust, and ice with a composition of mostly hydrogen and helium formed the early Solar System.
- This matches nearly exactly with the idea of star formation developed last class.



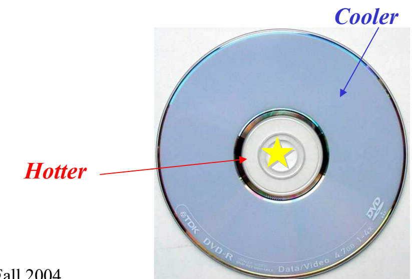
The Early Solar System

- A massive cloud of gas and dust
  - Seeded with elements from
    - Big Bang (hydrogen, helium, etc.)
    - Elements from planetary nebula pushed into space by red giant.
    - Elements blown from across galaxy by supernovae.

The cloud collapsed under its gravity and formed the circumstellar disk from which our solar system formed. Most theories for solar system formation require disks with masses of 0.01 to 1 solar masses.

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.



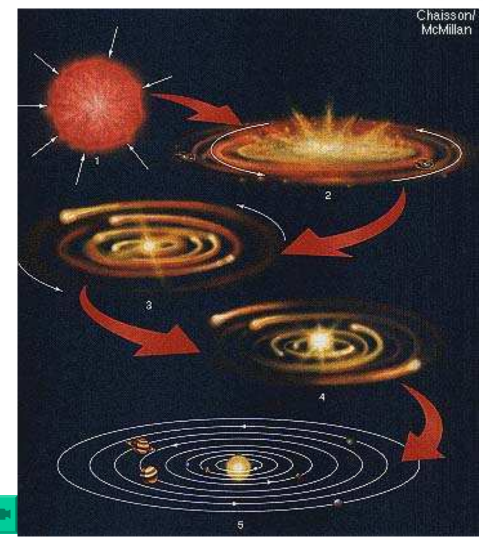
Planet Formation in the Disk

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

What it might have looked like.

http://eeyore.astro.uiuc.edu/~lwl/classes/astro100/fall03/Lectures/solarsystemform.mov

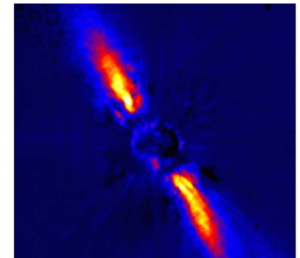


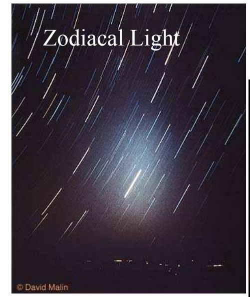
What Are We Looking For?
General Predictions of Solar Nebula Theory

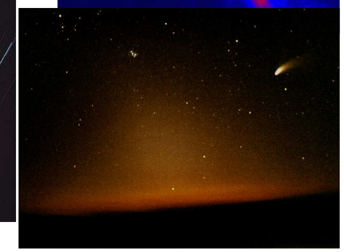
☺ Are interstellar dust clouds common? ***Yes!***
☺ Do young stars have disks? ***Yes!***
? Are the smaller planets near the star?
? Are massive planets farther away?

Fossil Disks Exist around other Stars?

- We see old disks around other stars (e.g. Vega and Beta Pictoris) as well as our own.
- Many (more than half!) of newborn stars surrounded by a disk of material!
- Disks are thick and dusty
  - Enough material to make planets
  - Agrees with the Solar Nebula theory!







http://www.eso.org/outreach/press-rel/pr-1997/phot-16-97.html
http://antwrp.gsfc.nasa.gov/apod/ap970826.html

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?

Test Of Exoplanets

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

<u>Hard to find!</u>

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. Optical Detection: Direct.

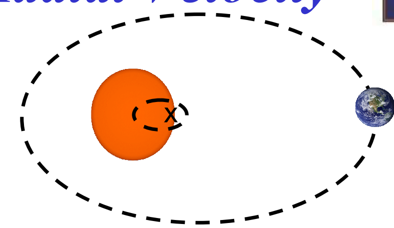
Arguable 2 extrasolar planet have been detected directly in the IR. Remember that planets in our Solar System seem bright because they reflect light from the Sun in the visible.

Star Wobble: Radial Velocity

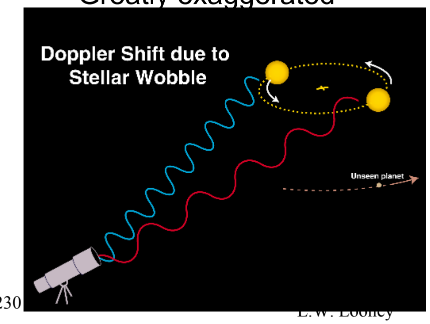
Newton's 3[rd] Law:
- *Both* planet *and star* move
- Both orbits fixed around the "center of gravity"

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

- Star movement too small to see
  - Moves in small, tight circle
  - But "wobble" in star speed detected!



Greatly exaggerated

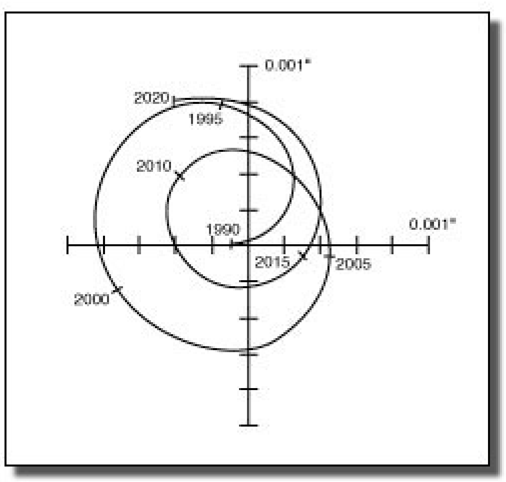


http://www.howstuffworks.com/planet-hunting2.htm

The Sun's Wobble

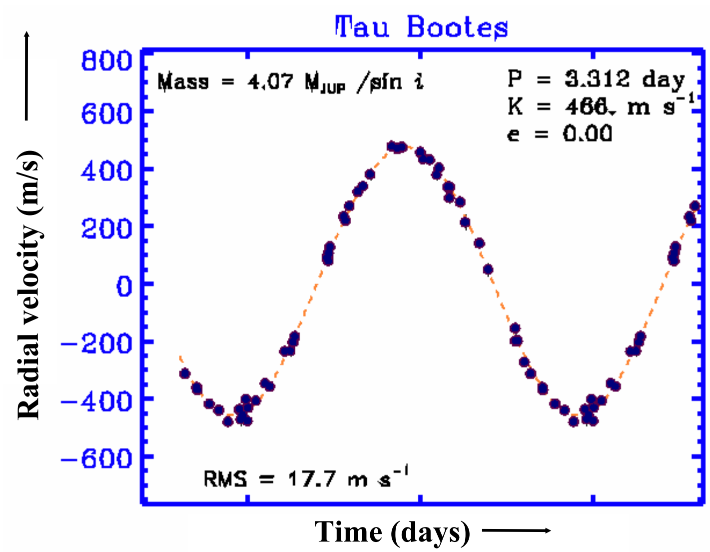
Astrometric displacement of the Sun due to Jupiter (and other planets) as at it would be observed from 10 parsecs, or about 33 light-years.

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

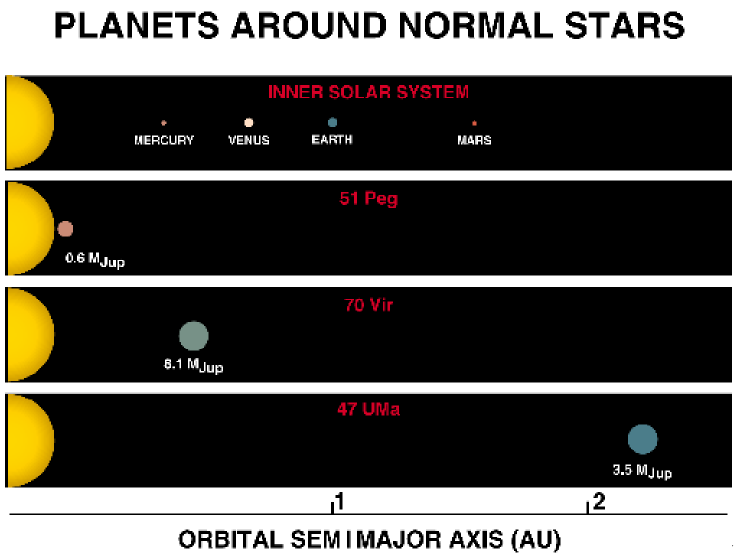


http://planetquest.jpl.nasa.gov/Keck/astro_tech.html

Radial Velocity Shifts: Planets around other Stars?

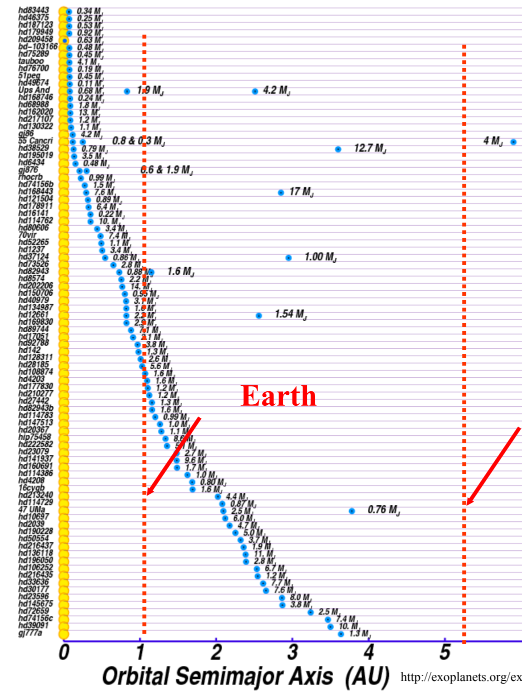


Early Discovery-- 1996



Hear all about it.

As of June, there are at least 155 planets around nearby stars.



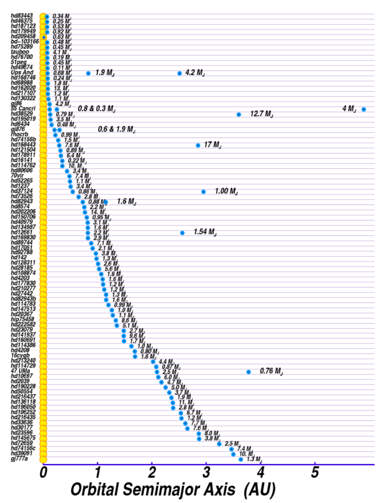
http://exoplanets.org/exoplanets_pub.html

Exoplanets: Results to Date

Over 155 planets detected so far

- More than 15 times the number in our Solar System!

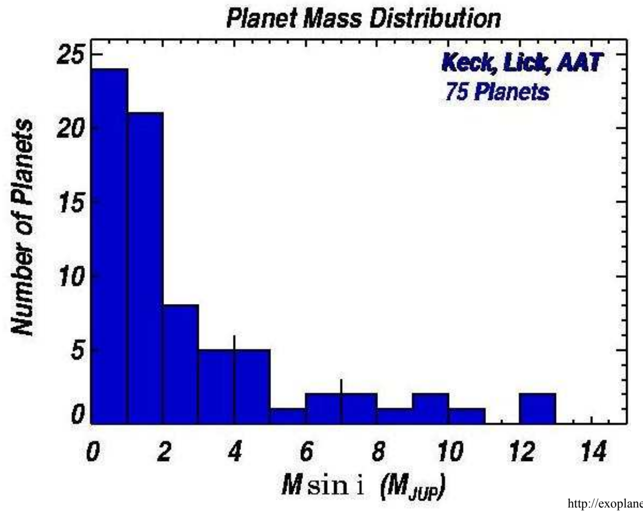
- By measuring the wobble variation:
  - With time, gives the planet distance: Kepler's 3rd law
  - The orbital speed of the star gives masses: the bigger the wobble amplitude, the heavier the planet
- At least 13 are multi-planet systems



List

http://exoplanets.org/planet_table.shtml

Masses of Extrasolar Planets



http://exoplanets.org

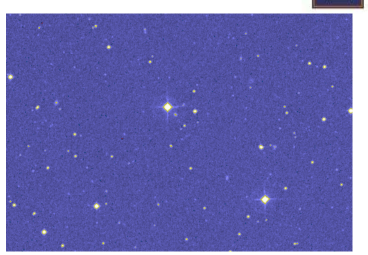
Other Planets, Other Stars

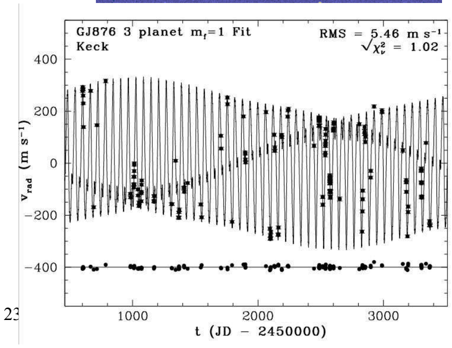
47 Ursae Majoris System– 51 light years away (near the Big Dipper). 13 years of data has shown 2 planets– 1 Jupiter like and 1 Saturn like.

Wow! Among the most similar to our own system

The Lowest Mass to Date

GJ 876 – a Red Dwarf that is 15 light years away (in Aquarius). Has three planets! 2 Jupiter-like and one that is 6-8 Earth masses! But all our inside 1 AU!





The Lowest Mass to Date

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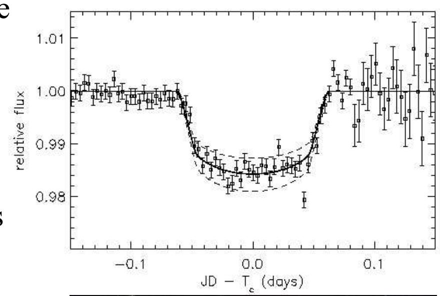
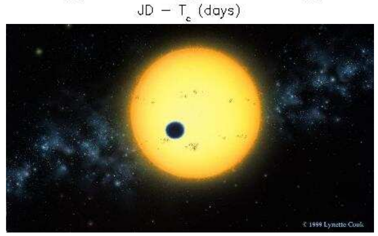
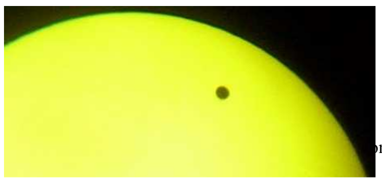
Transits

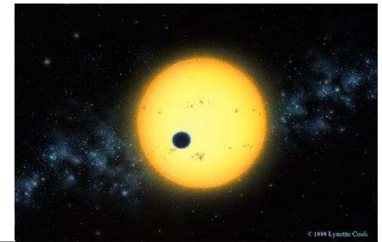
- The planet passes in front of the star– like Venus last year.
- Can find planet radius
- Best chance of finding Earth-like planets
- Requires the extrasolar planet's orbital plane to be pointed at Earth
- http://www.howstuffworks.com/planet-hunting2.htm

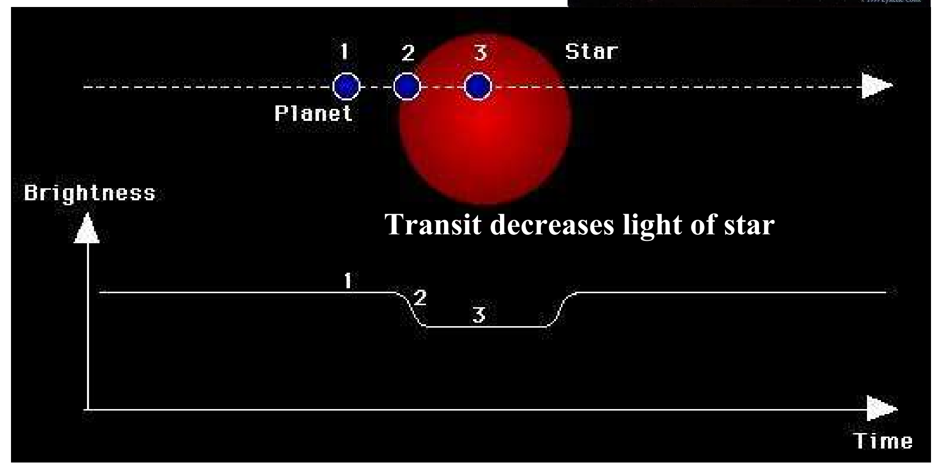




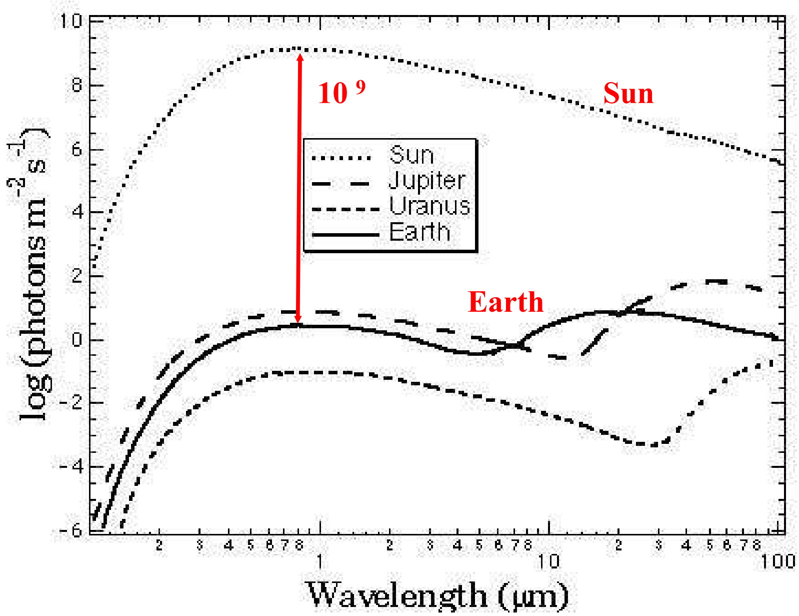


Planet Transits



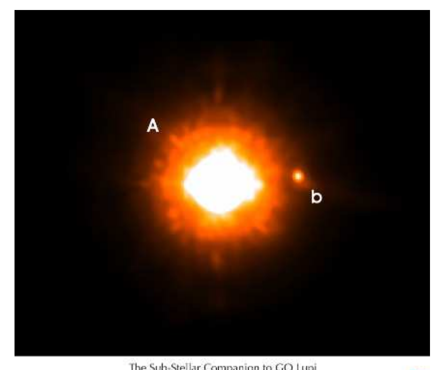


Direct Detection is a Hard Business

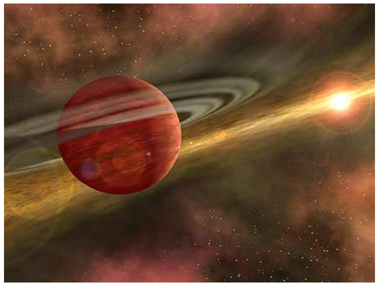


Direct Detection?

- Two groups have detected a slight change in the brightness of two systems were the planet transits in the mid-infrared. But they were known transit systems.
- The race is on to directly image a planet in the IR, it is still difficult to determine the stellar mass.
- Best example so far is an adaptive optic image from April, so planet or brown dwarf?



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.

Big surprises

- ? Some 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?

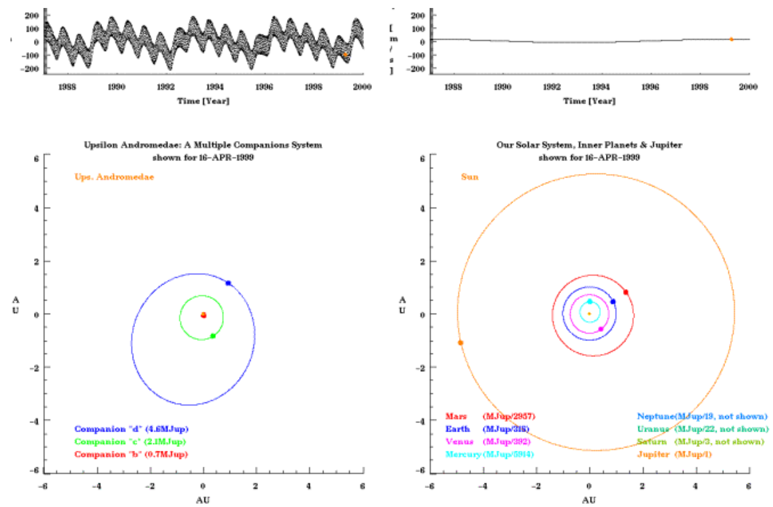
  Not the ones found so far! Haven't found smaller planets yet!
- ? Are massive planets farther away?

  Not most of the ones found so far!

Important Caveat

- Our current observations of extrasolar planets do **<u>not</u>** 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

Detecting the Solar System

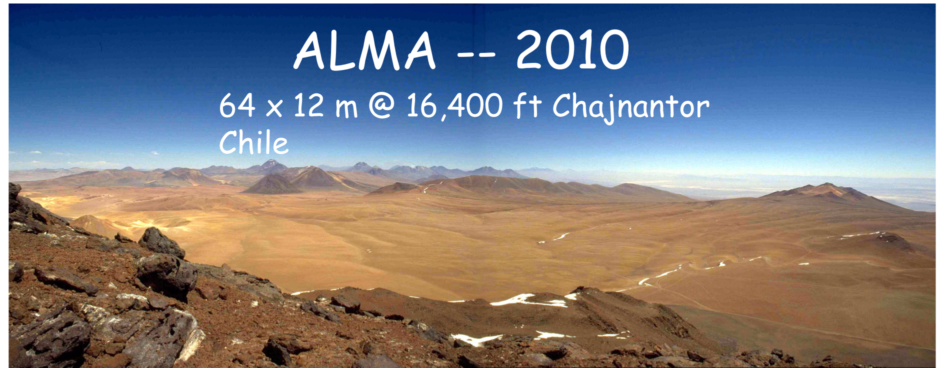


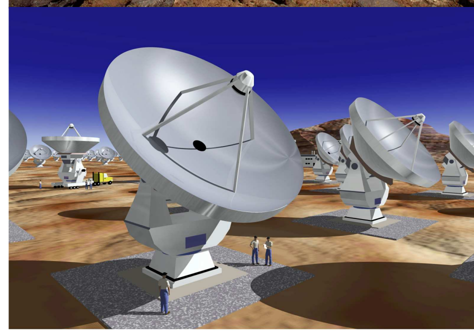
Future Projects

- Atacama Large Millimeter Array (ALMA): 2010
  - mm interferometer: direct detection of young gas giants
- Kepler: 2007
  - Planet Transits
- Next Generation Space Telescope
  James Webb Space Telescope (JWST): 2011
  - Direct imaging of forming gas giants?
- Space Interferometry Mission (SIM): 2009?
  - Astrometry
- Terrestrial Planet Finder (TPF): 2012?
  - Coronagraph
  - IR interferometer
- Terrestrial Planet Imager (TPI): 2015?
  - Either a visible band coronagraph or a large-baseline infrared interferometer. Imaging extrasolar Earths!!!!

ALMA -- 2010

64 x 12 m @ 16,400 ft Chajnantor Chile

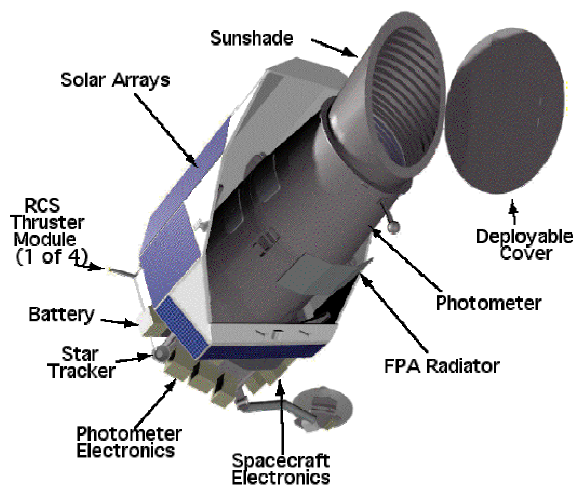




Kepler

1.4 meter mirror, measuring accurate brightness of stars.

A terrestrial-sized Earth-like planet would dim the star's light by 1/10,000th – comparable to watching a gnat fly across the beam of a searchlight.

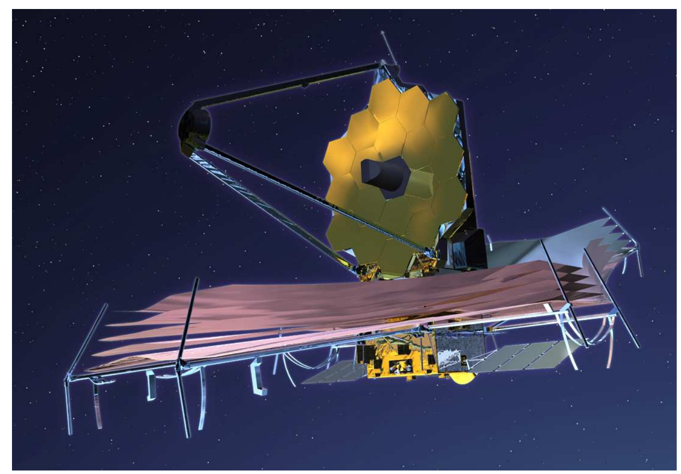


JWST

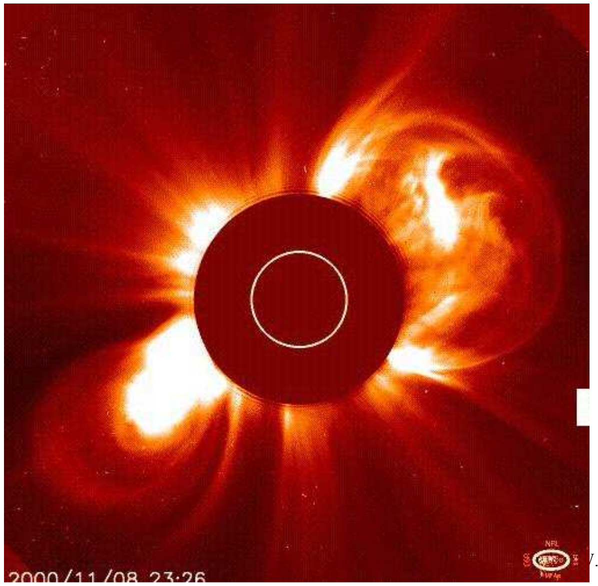
James Webb Space Telescope: Successor to HST

6.5 meter observatory

Working in the infrared with a coronagraph.



The Coronagraph Advantage



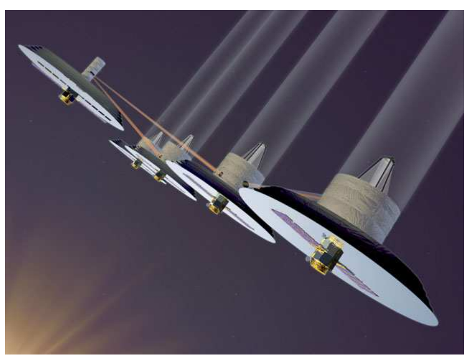
Space Interferometry Mission

Accurately measure location of stars to micro-arcseconds.

Need to know relative location of components to 50 pm.

http://planetquest.jpl.nasa.gov/SIM/sim_index.html

Terrestrial Planet Finder Mission

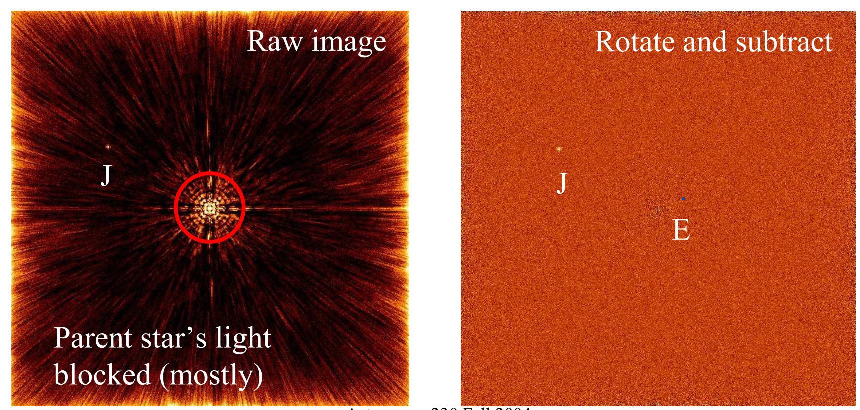


- Survey nearby stars looking for terrestrial-size planets in the "habitable zone"
- Follow up brightest candidates looking for atmospheric signatures, habitability, or life itself
- Launch is anticipated between 2012-2015

TPF

Visual wavelength `coronagraph'

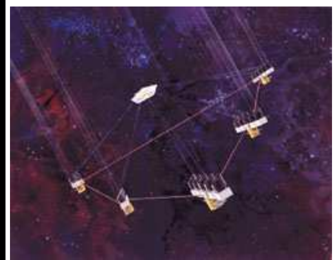
- Find Earth-like planets
- Characterize their atmospheres, surfaces
- Search for bio-signatures of life (O_2, H_2O, etc)



Terrestrial Planet Imager

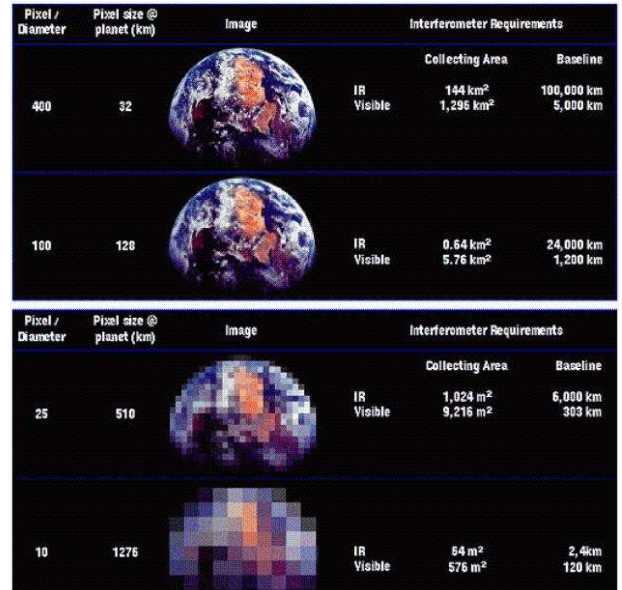
The goal of imaging an Earth-like planet.

5 platforms of 4 eight meter interferometer in space.



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

TPI -- Scales



Pixel / Diameter	Pixel size @ planet (km)	Image	Interferometer Requirements	Collecting Area	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

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	Rate of star formation	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
	10						

f_p

- About 2/3 of all stars are in multiple systems.
  - Is this good or bad?
- But disks around stars are very common, even many of the binary systems have them.
- Hard to think of a formation scenario without a disk at some point– single or binary system.
- Disk formation scenario matches our solar system parameters.

f_p

- Binary or multiple systems.
- We know of many brown dwarfs, so maybe some planets do not form around all stars.
  - There might be free-floating planets, but…
- 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 0.02. A high fraction assumes that the disks often form planets.
- A low fraction assumes that even if there are disks, planets do not form.
- This is not Earth-like planets, just planets.