Astronomy 230
Section 1– MWF 1400-1450
106 B6 Eng Hall

This Class (Lecture 7):

Planet Formation and

Extrasolar Planets

Oral Presentation Decisions!

Deadline is Feb 6th.

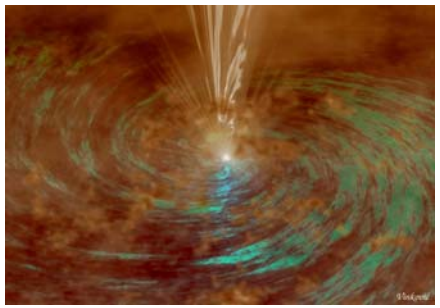
Next Class:

Nature of the Solar System

Outline

- Star formation requires a circumstellar disk that is often seen around young stars.
- The origin of the Solar system also requires a disk of material in which dust clumped, forming planetesimals, then planets.
- Planets are different due to distance away from Sun.
- Extrasolar planets– wobbling into history.
- Future planet searches.

Star Formation

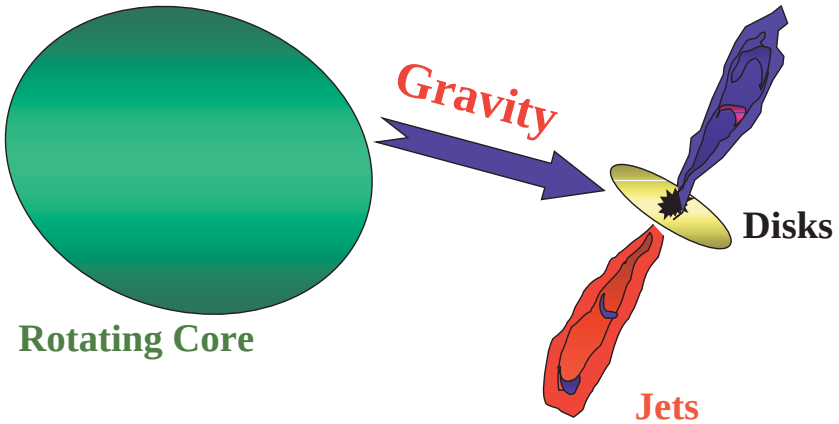


Stars are born in cold, dense interstellar clouds
- Cold gas
- Dust grains

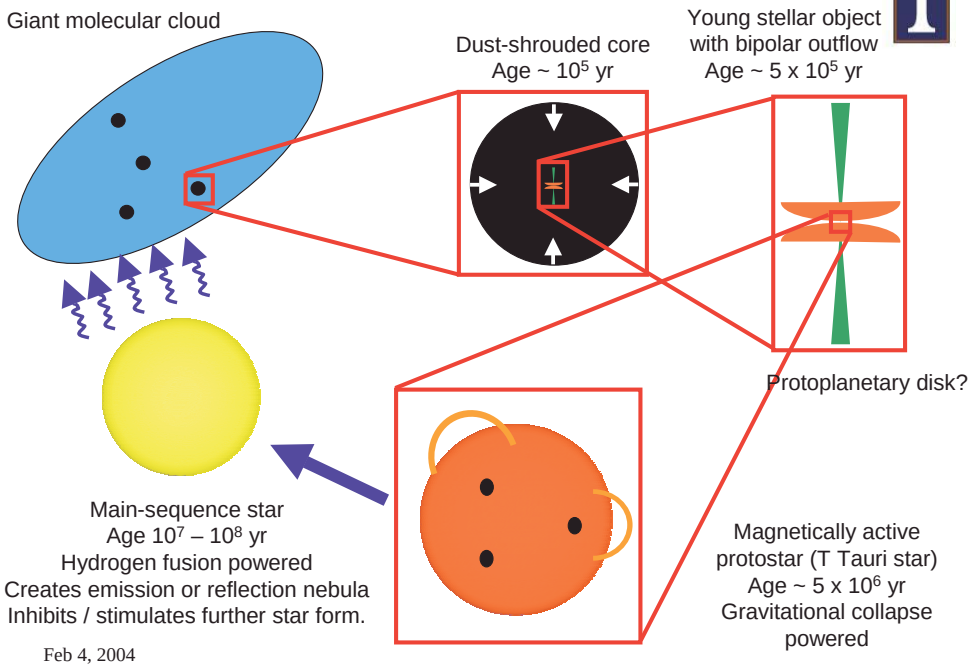
Star formation is probably triggered by
- Cloud turbulence
- Collision with another cloud
- Nearby supernova explosion
- Nearby hot star wind
- Disturbance from the Galaxy

The Protostar Stage

Gravity, Spin, & Magnetic Fields

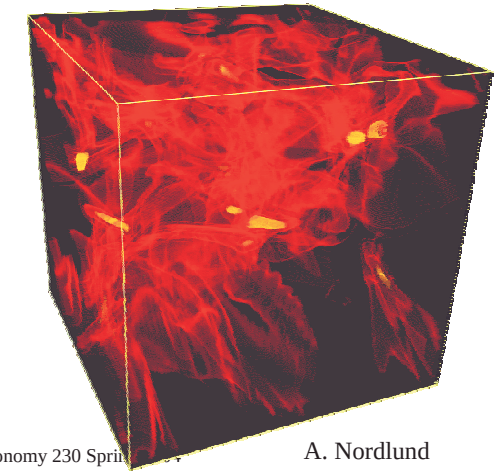


Star Formation - Summary



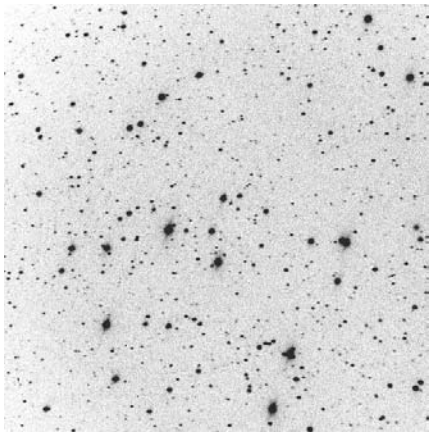
Some outstanding Star Formation Issues

- Why do the cores collapse, but not the entire molecular cloud?
- What sets the sizes of cores, and hence masses of stars?
- What determines how stars cluster, group together, or form multiple systems?



A. Nordlund

Stars Ages and ETs



So, Why would Spock Care?

- If we are to suppose that ET life will be based on a planet orbiting a star, then we need to know
  - How did our solar system form?
  - How rare is it?
  - Is our solar system unusual?

http://homepage.smc.edu/balm_simon/images/astro%205/spock.jpg

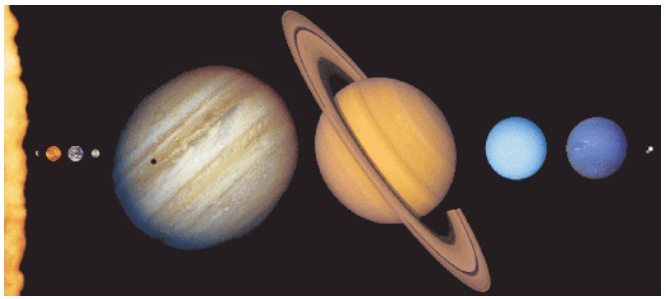
What is the origin of the Solar System?

- Explain present-day Solar System data.
- Predict results of new Solar System data.
- Should explain and predict data from other stars!

What are clues to solar system origins?

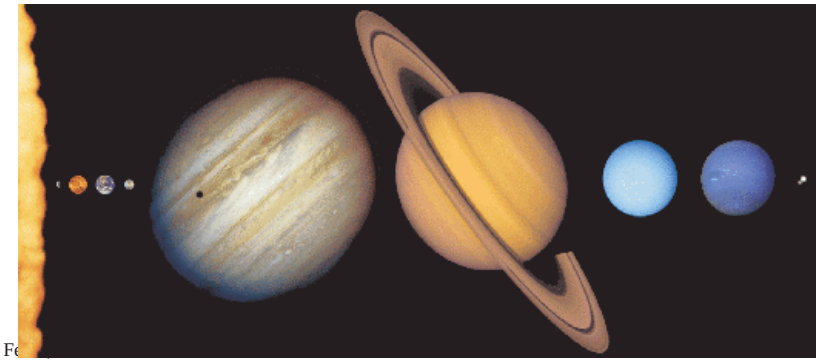
Some Facts of the Solar System

- We have 8 or 9 planets.
  - Pluto, an anomaly in many ways, probably a Kuiper object or moon of Neptune. Other Kuiper objects are being found.
- So perhaps the average extrasolar system has about 10 planets (rounded off).
- The Sun has 99.9% of the mass, but the planets have 98% of the angular momentum (energy stored in orbits)



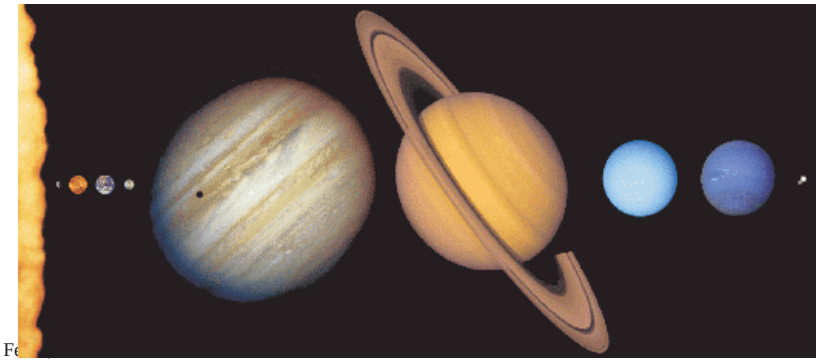
Some Facts of the Solar System

- Outer planets more massive than inner planets.
- Most of the motions in the Solar System are counter clockwise (problems with Venus, Uranus, or Pluto) in a flat system (pancake-like).
- The inner planets are rocky and the outer planets are gaseous.



Some Facts of the Solar System

- Numerous collisions occurred in the early Solar System
  - Origin of Moon, Lunar craters, Uranus's obit, and Pluto
- Planets are not evenly spaced– factors of 1.5 to 2.
  - Sun/Saturn distance is 2x Sun/Jupiter distance
  - Sun/Mars distance is 1.5x Sun/Earth distance



Data: Planet's Dance

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

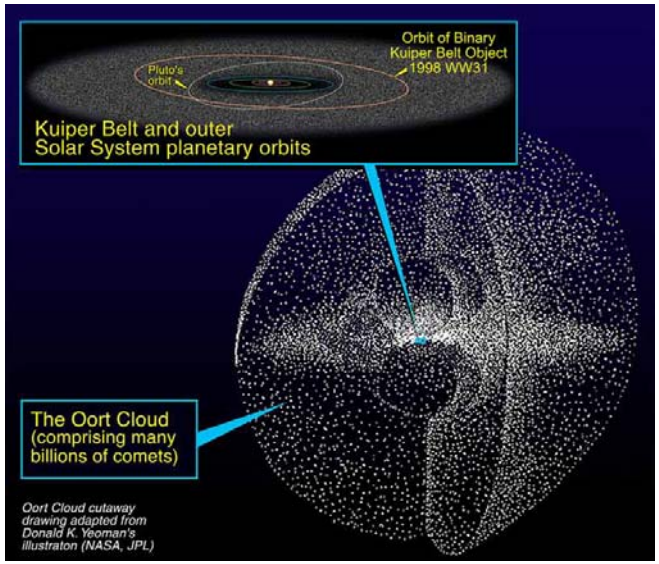
Data: The Structure of the Solar System

- 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

Gravitational Collapse

"*nebula*" = cloud

- The basic idea was put forth by Immanuel Kant (the philosopher)– Solar System came from a Gas Nebula:
- 4.5 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

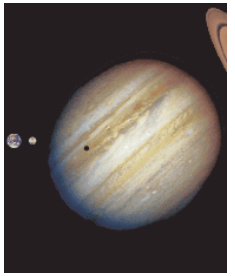
What it might have looked like.

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

Why are the Planets so different then?

Temperature is key factor

- Inner Solar System: **Hot**
  - Light gas (H, He), ice evaporated, blown away
  - Icy mantles of dust grains (NH_3, CH_4, etc.) evaporated at varying distances
  - Only heavy elements left
- Outer Solar System: **Cool**
  - H, He remain
  - Fall onto rocky planet core "seeds"



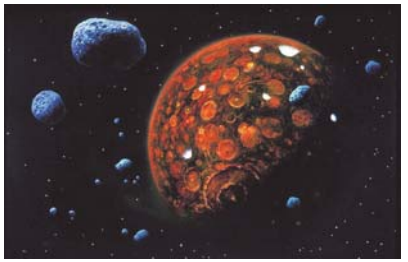
Jupiter as an Example

- Probably had its own disk
- 4 inner moons are rock
- 4 Galilean moons mock those in Solar System
  - More dense moons are close, less dense further out
- Mass of core is about 12 earth masses.
- Local processes heat the ice, releasing NH_3 and CH_4

http://www.the-solar-system.net/galilean-moons.html

Fate of planetesimals

- Those nearest planets collided with planets
- Those between Mars and Jupiter remain as asteroids
- Those near Jupiter & Saturn gravitationally ejected from solar system
- Those near Uranus and Neptune ejected to Oort cloud
- Those beyond Neptune remain in Kuiper belt.

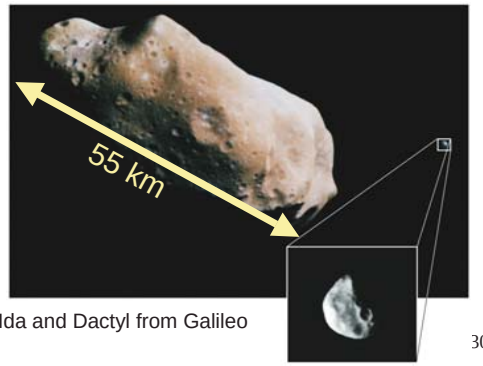


http://www.usm.uni-muenchen.de/people/gehren/vorlesung/4.1_Himmelsmechanik/kosmogonie/dia_15.html

Results

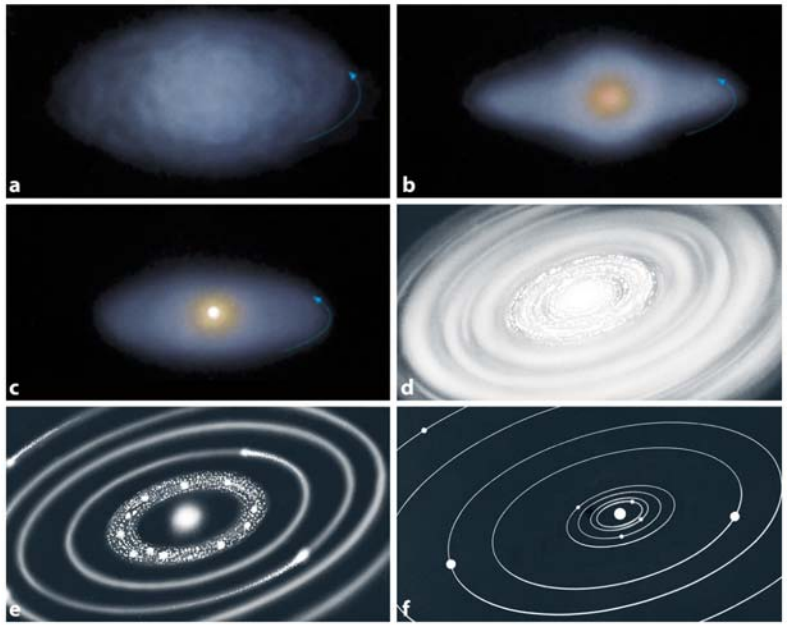
So: most disk matter goes into planets

- Except stable zones where existing planet gravity prevents clumping
  - Between Mars and Jupiter, beyond Neptune:
  - Asteroids and comets are leftover planetesimals! "Fossils" of solar system birth!



Ida and Dactyl from Galileo

Formation of the Solar System
4.6 billion years ago



Fitting the Data

1. There should be about 10 planets orbiting in the same direction and with the same spin.
2. The inner planets should be rocky and the outer planets gaseous.
3. Distance between planets should increase with distance away from the star.

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?

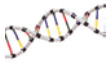
? Are massive planets farther away?

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 formation of Sun-like stars	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

Test Of Exoplanets

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

Hard to find!

Cannot just look at star
- planet lost in glare

The Earth is 1 billion times fainter than the Sun!!!!!

Can use Newton's laws
- Gravity: Star pulls on planet,
- Newton 3rd Law: But planet pulls on star with equal & opposite force
- Planet lighter, moves faster
- But star must move too!

Finding Planets

1. Radial Velocity
2. Astrometry
3. Transit Method
4. Optical Detection

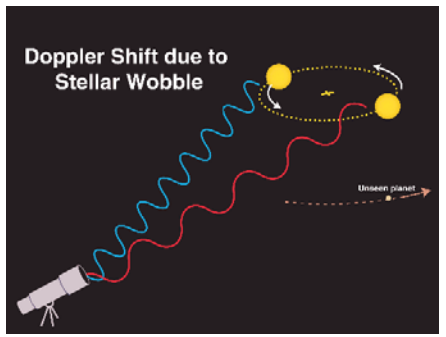
To date no extrasolar planet has been detected directly. Remember that planets in our Solar System are bright because they reflect light from the Sun.

Star Wobble

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

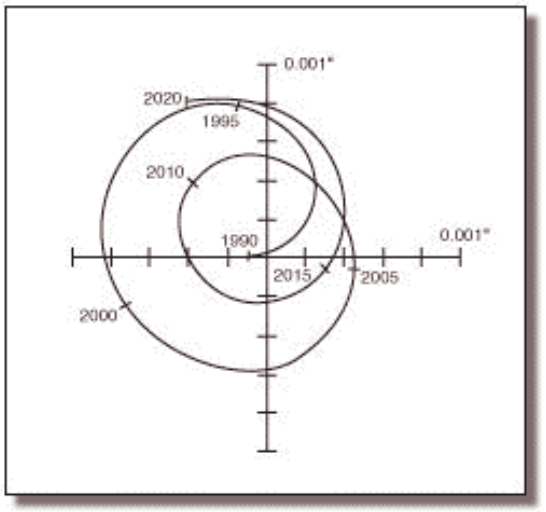
http://www.howstuffworks.com/planet-hunting2.htm

- 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!



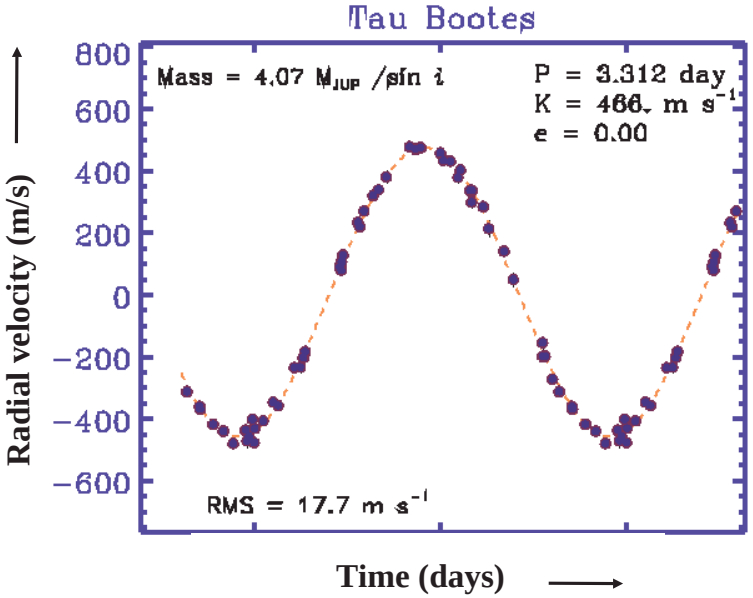
The Sun's Wobble

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.



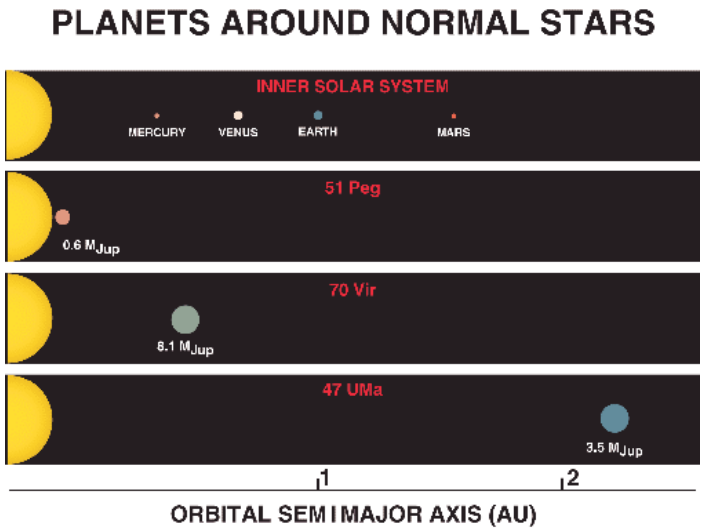
http://planetquest.jpl.nasa.gov/Keck/astro_tech.html

Planets around other Stars?

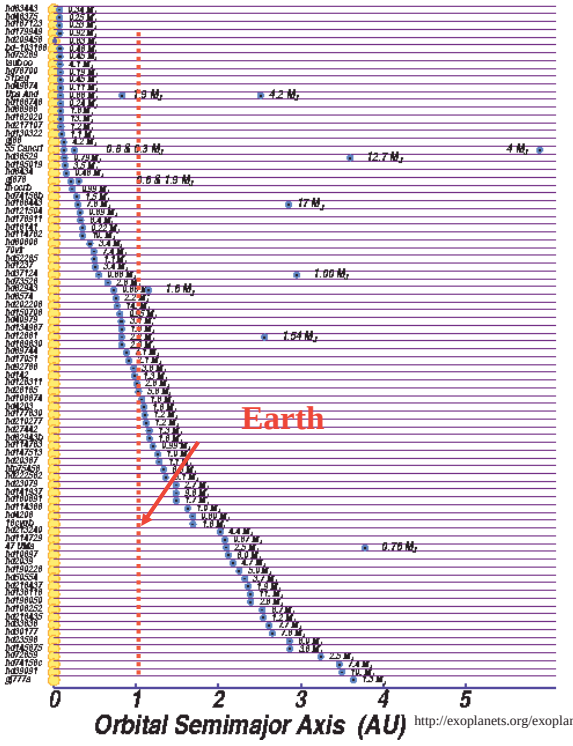


Early Discovery-- 1996

Hear all about it.



As of Jan, there are at least 118 planets around other nearby Stars.



http://exoplanets.org/exoplanets_pub.html

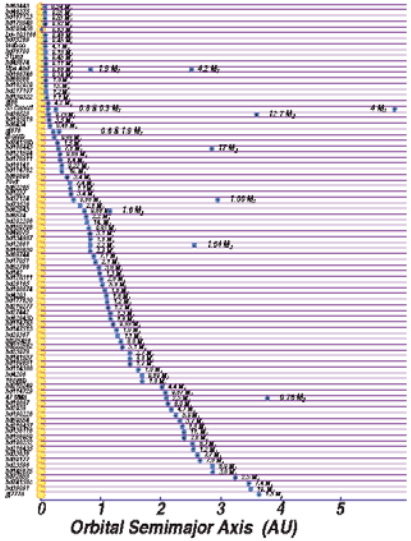
Exoplanets: *Results to Date*

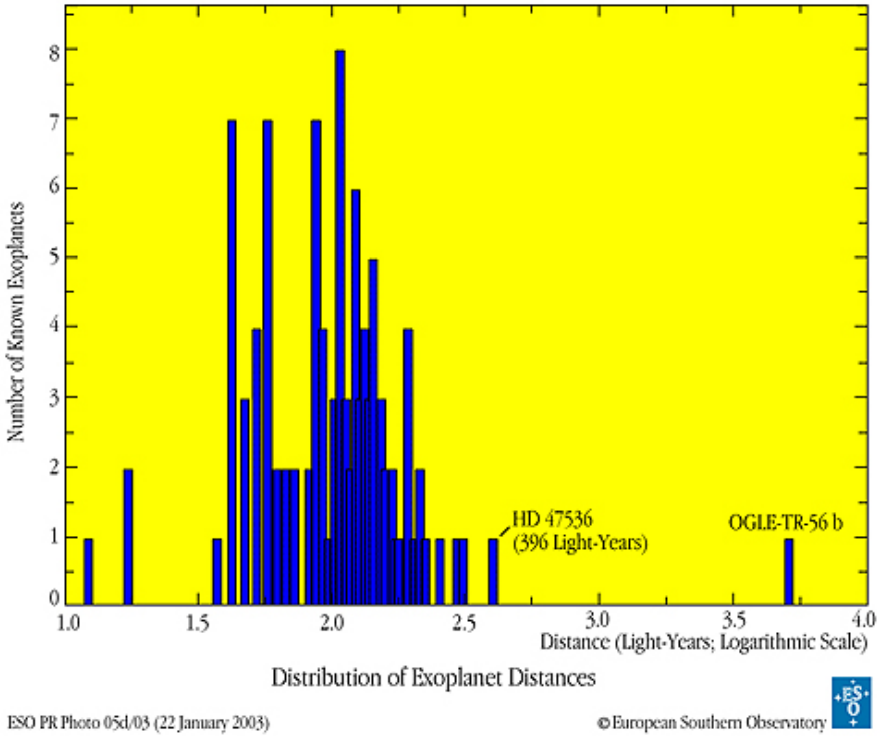
Over 118 planets detected so far

- More than 10 times the number in our Solar System!

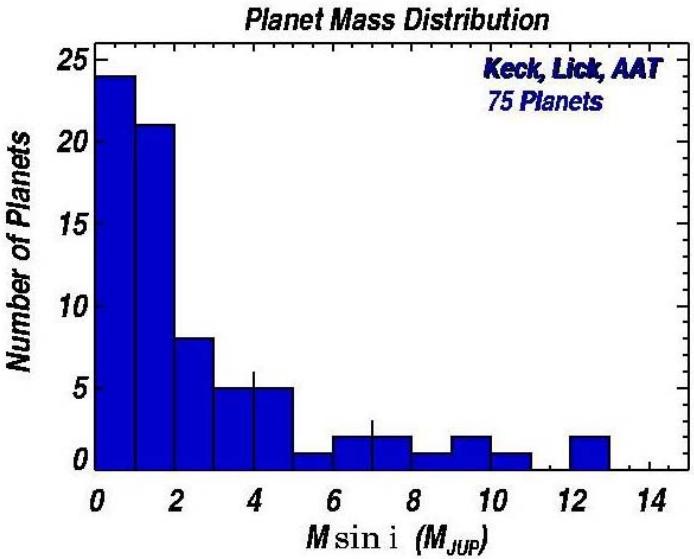
- Measure $P_{star} = P_{planet}$
  Kepler/Newton give:
  - Planet distance $P^2 = a^3$
  - Note: Get distance w/o directly measuring it!

- Wobble speed gives planet mass



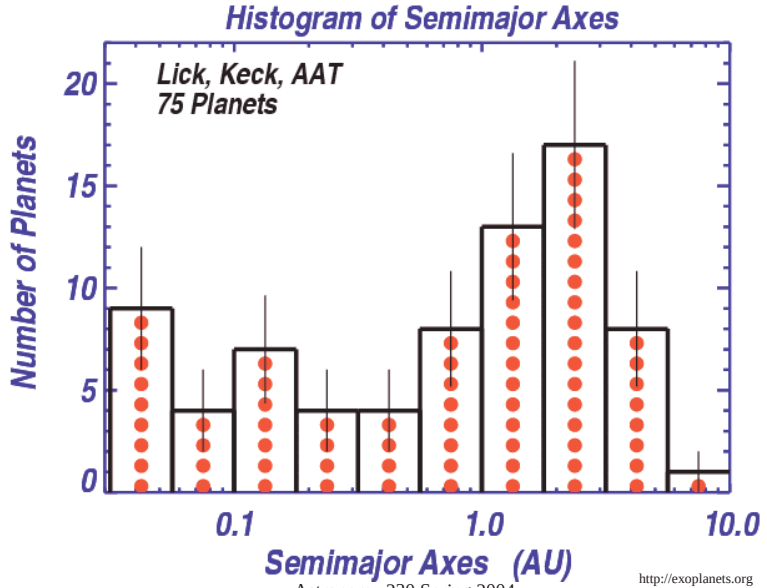


Masses



http://exoplanets.org

Semi-Major Axes

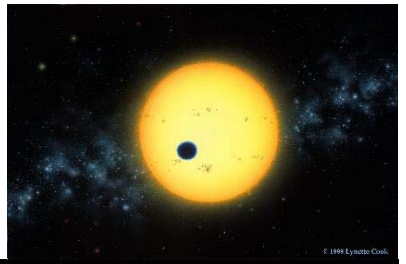


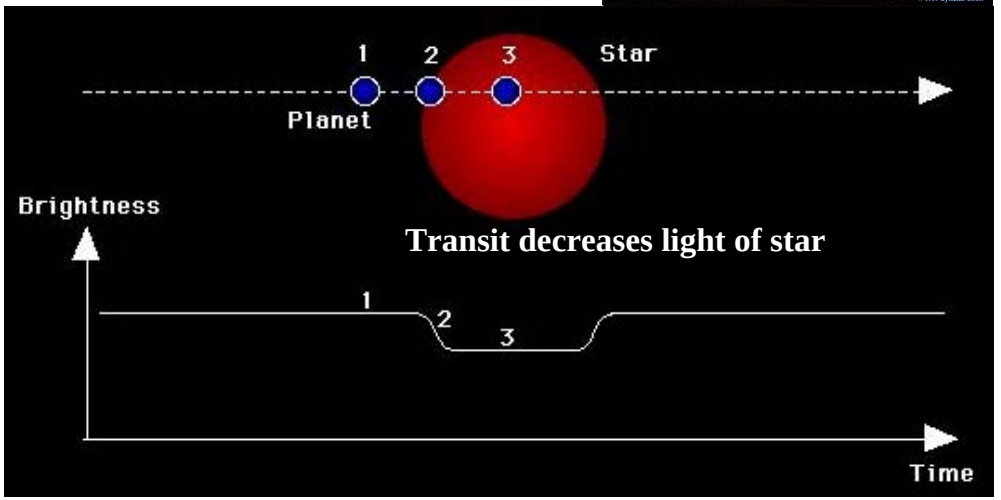
http://exoplanets.org

List

http://exoplanets.org/planet_table.shtml

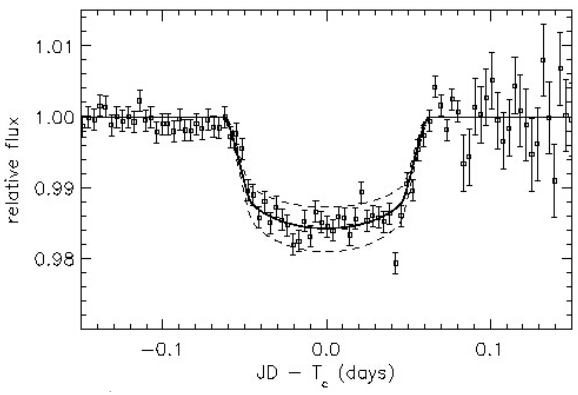
Planet Transits

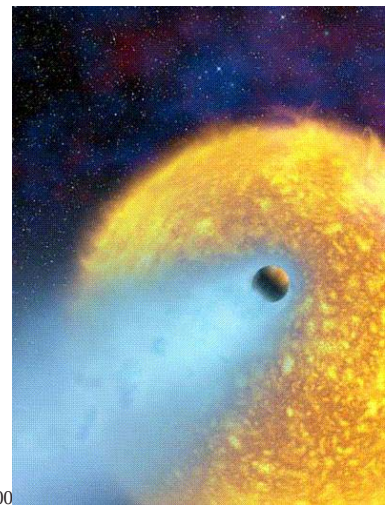




Transits

- http://www.howstuffworks.com/planet-hunting2.htm
- A few solid detections.





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!

Exoplanets: *Results to Date*

No Surprise:
- ✓ New planets are massive
- ✓ Why? Needed to get big wobble
- ✓ If not massive, we could not have found them

Big Surprise:
- ? Period of few days--whip around stars
- ? Most planets are very near stars!
- ? Example: tau Boo is 3.6 x Jupiter mass, but closer than Mercury's orbit!
- ? If an Jupiter like planet formed close in, perhaps that prevents terrestrial planets from forming.

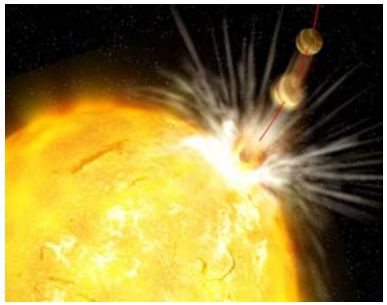
What Are We Looking For?

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!
- ? Are massive planets farther away?
  Not most of the ones found so far!

Exoplanets: Implications

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



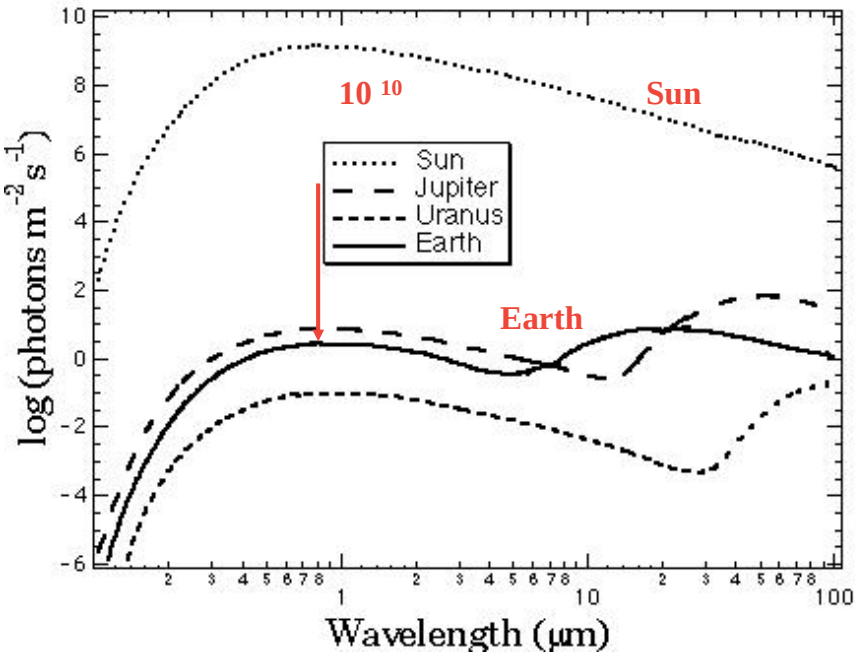
Exoplanet Data:
- Giant planets found very close

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 common.
- ✓ good news in search for life elsewhere...maybe

It is a Hard Business



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