Astronomy 330

This class (Lecture 7):

Origin of planets

Next Class:

Nature of Solar Systems

HW 2 due Thursday.

Music: *Planet of Sound* – Pixies

Outline

- How stars are born.
- Circumstellar disks are thought to be common.
- Extrasolar planets: watch them wobble.
  - Not exactly what we expected.
  - What to expect in the future.
- What is f_p?

Drake Equation

The class's first estimate is

Frank Drake

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

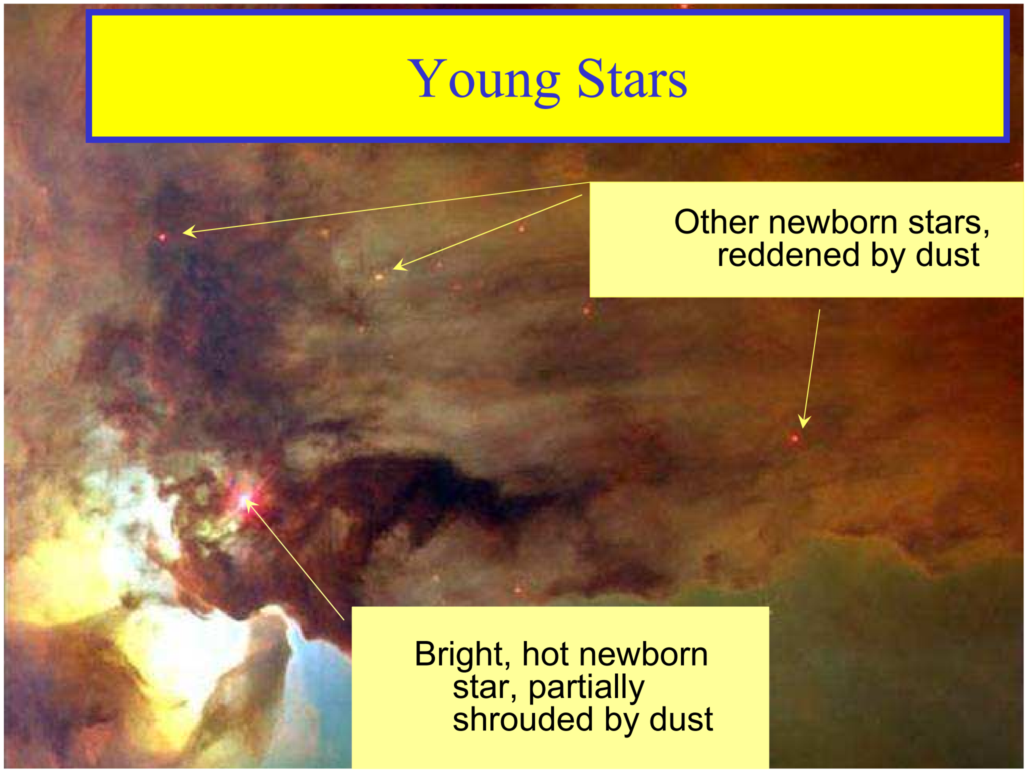
N	R_*	f_p	n_e	f_l	f_i	f_c	L
# of advanced civilizations we can contact in our Galaxy today	Star formation rate	Fraction of stars with planets	# of Earthlike planets per system	Fraction on which life arises	Fraction that evolve intelligence	Fraction that commun-icate	Lifetime of advanced civilizations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

How Do We Know that Stars Form in Molecular Clouds ?

- Young stars are seen near molecular clouds.
- In infrared light, we can see into the deeper regions of clouds, and see clusters of young stars with circumstellar material (dust and gas) surrounding them.
- Stars are continuously being formed in our galaxy.

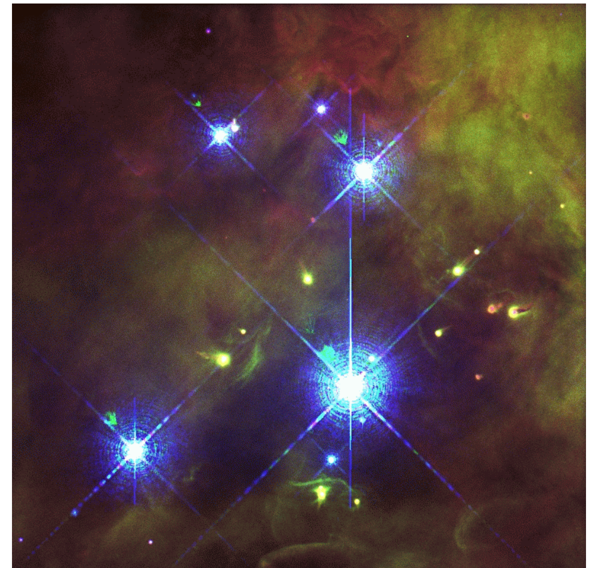
http://antwrp.gsfc.nasa.gov/apod/ap030630.html

Young Stars



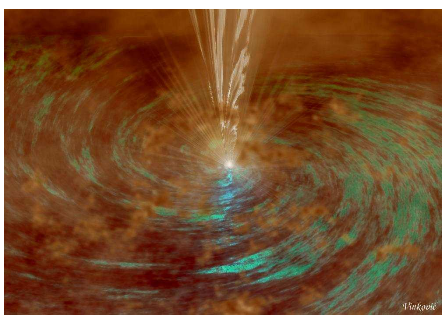
The Birthplace of Stars

- Young stars often are seen in clusters
- Very young stars are also associated with clouds of gas (nebulae)



The Trapezium

Star Formation



Stars are born in cold, dense interstellar clouds

- Cold gas
- Dust grains

Star formation is probably triggered by

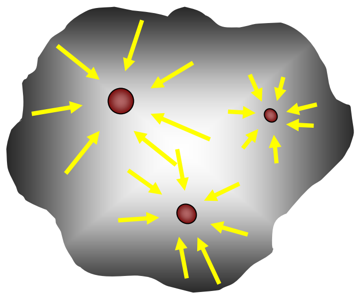
- Cloud turbulence
- Collision with another cloud
- Nearby supernova explosion
- Nearby hot star wind
- Disturbance from the Galaxy

Gravitational Contraction

- As we discussed for the first stars, the gravity of the gas and dust clumps push the clumps together, but there is some resistance from pressure and magnetic fields to collapse.
- Probably as the cloud core collapses, it fragments into blobs that collapse into individual stars.
- Cloud becomes denser and denser until gravity wins, and the clumps collapse under their own mass– a protostar.

http://www.birthingthefuture.com/AllAboutBirth/americanway.php

Cloud Contraction



But..

- Not all mass falls in directly (radially). Why?
- All gas has a small spin that preferentially causes the formation of a flattened structure
  - time for an interlude.

http://homepages.igrin.co.nz/moerewa/Pages/

Interlude: Angular Momentum

Spinning or orbiting objects in closed system have angular momentum.

Angular momentum is a single, *constant* number = *conserved*!

Keep same dist. to axis → velocity same

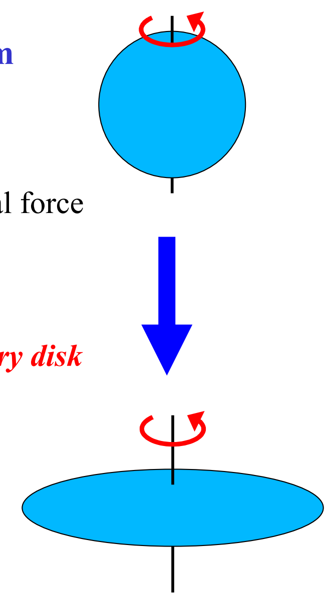
Move closer to axis → speed up!

Kepler's 2nd law – really due to angular momentum!

When Doves Cry and Stars Form

Solar nebula competition:
Gravity vs Angular Momentum

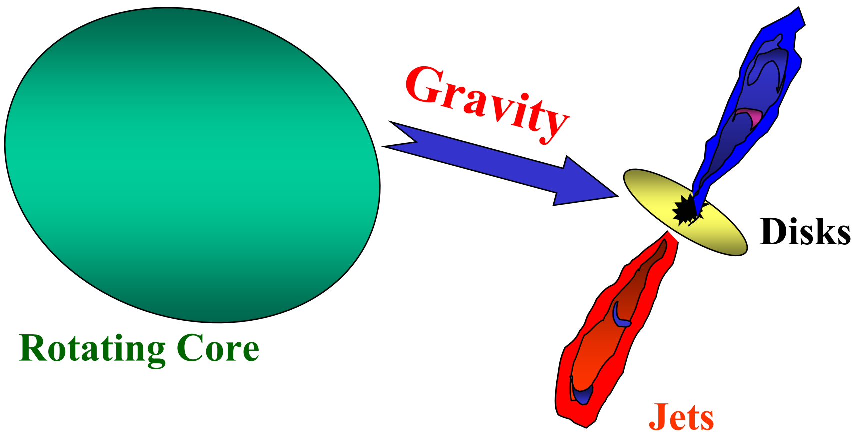
- If fall perpendicular to spin axis
  Needs to speed up
  → resistance centrifugal force
- If fall parallel to spin axis
  same speed, so no resistance
  → forms ***protoplanetary disk***



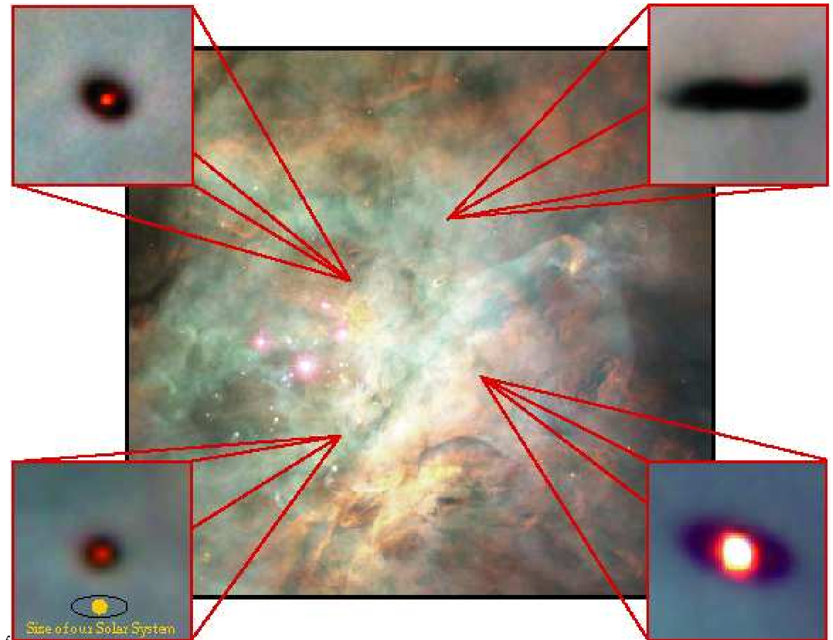
- Origin of planet's orbits!
- Organizes spins along initial spin axis

The Protostar Stage

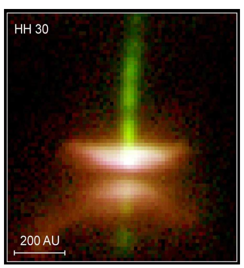
Gravity, Spin, & Magnetic Fields

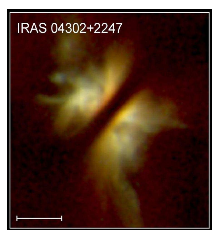


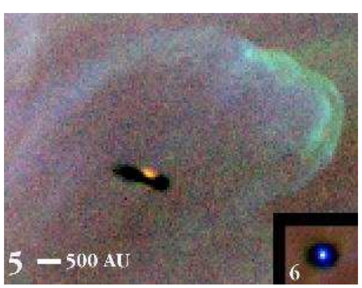
Disks around Young Stars are Common



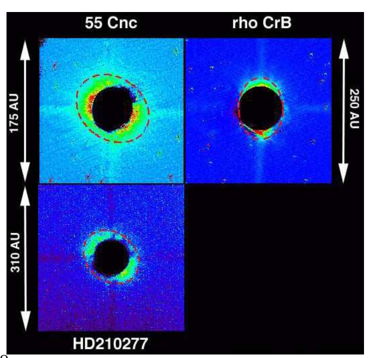
And Disks around Young Stars are Common



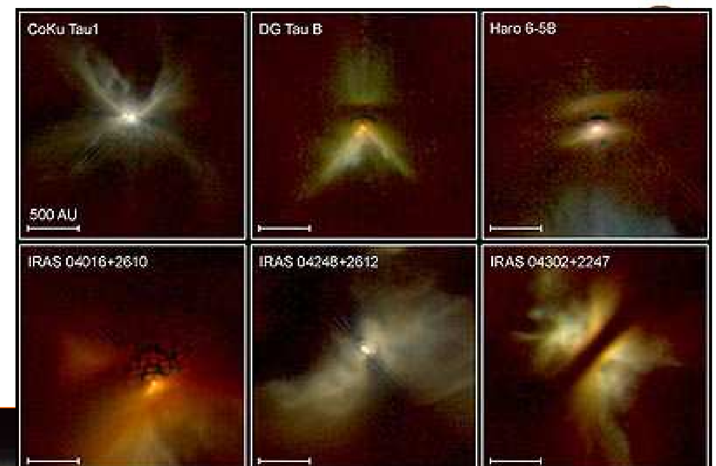




http://www.ifa.hawaii.edu/users/tokunaga/SSET/SSET.htm

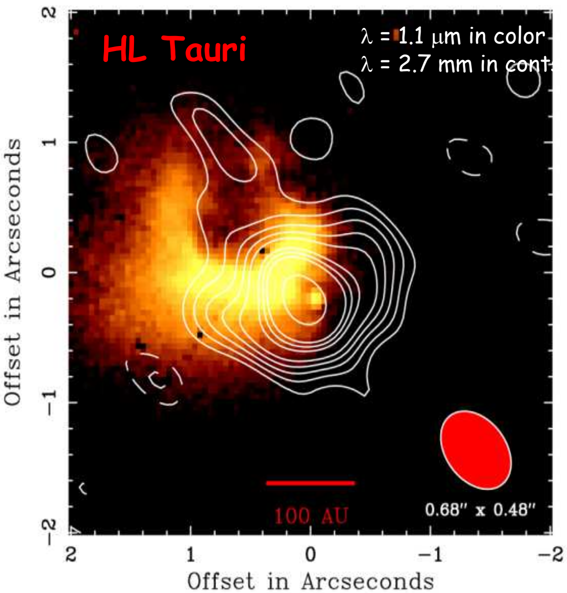


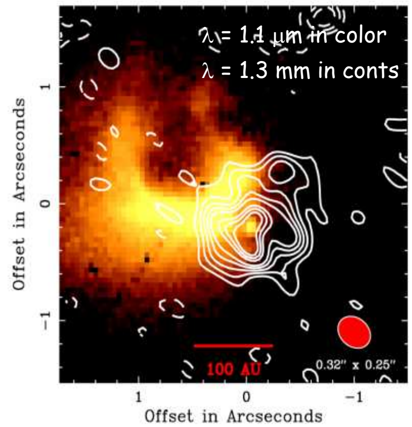
Disks have been imaged with HST's infrared camera



Young stars are surrounded by dense disks of gas and dust

Tracing the Bulk Material

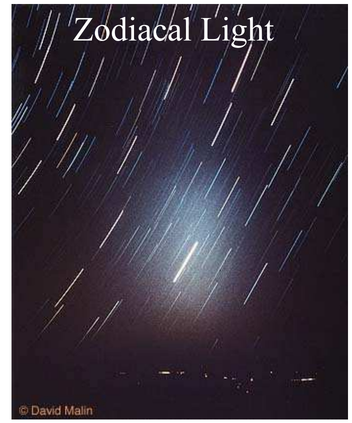


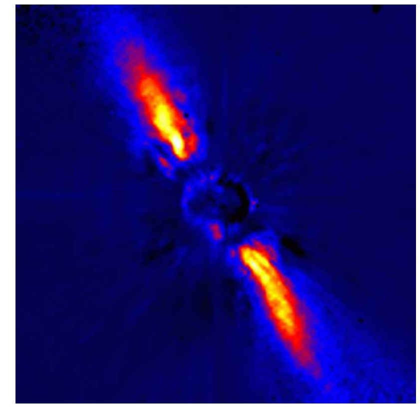


Stapelfeldt et al. 1995; Looney et al. 2000

Do Fossil Disks Exist around other Stars?

- We see old disks around other stars (e.g. Vega and Beta Pictoris) as well as our own.

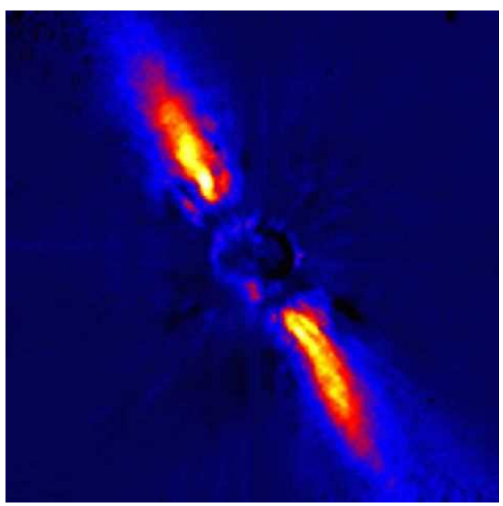




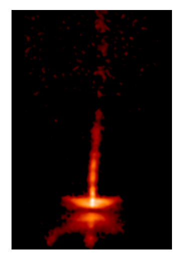
http://www.eso.org/outreach/press-rel/pr-1997/phot-16-97.html
http://antwrp.gsfc.nasa.gov/apod/ap970826.html

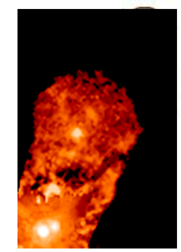
Disks Around Young Stars

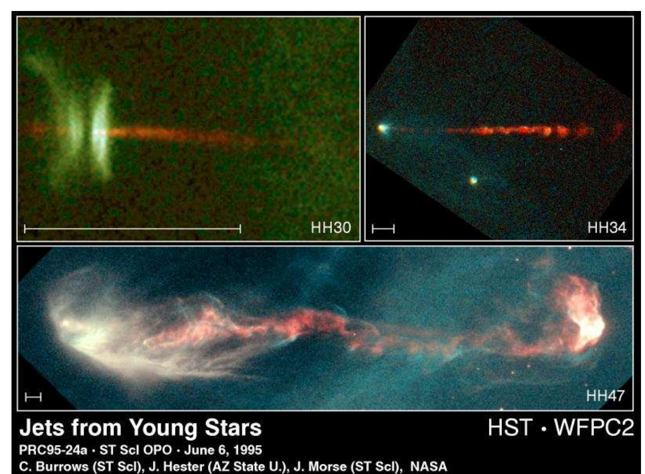
- Many (> 50%) of newborn stars surrounded by a disk of material!
- Disks thick, blocks light
  - Enough material to make planets
  - Agrees with Solar Nebula theory!



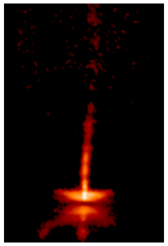
Protostellar Jets

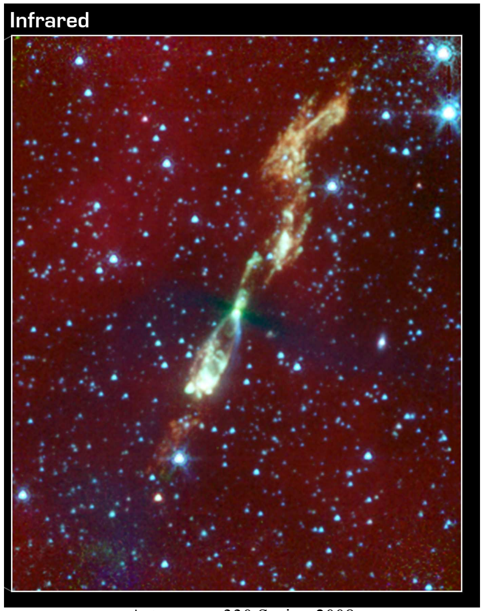


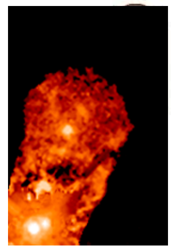


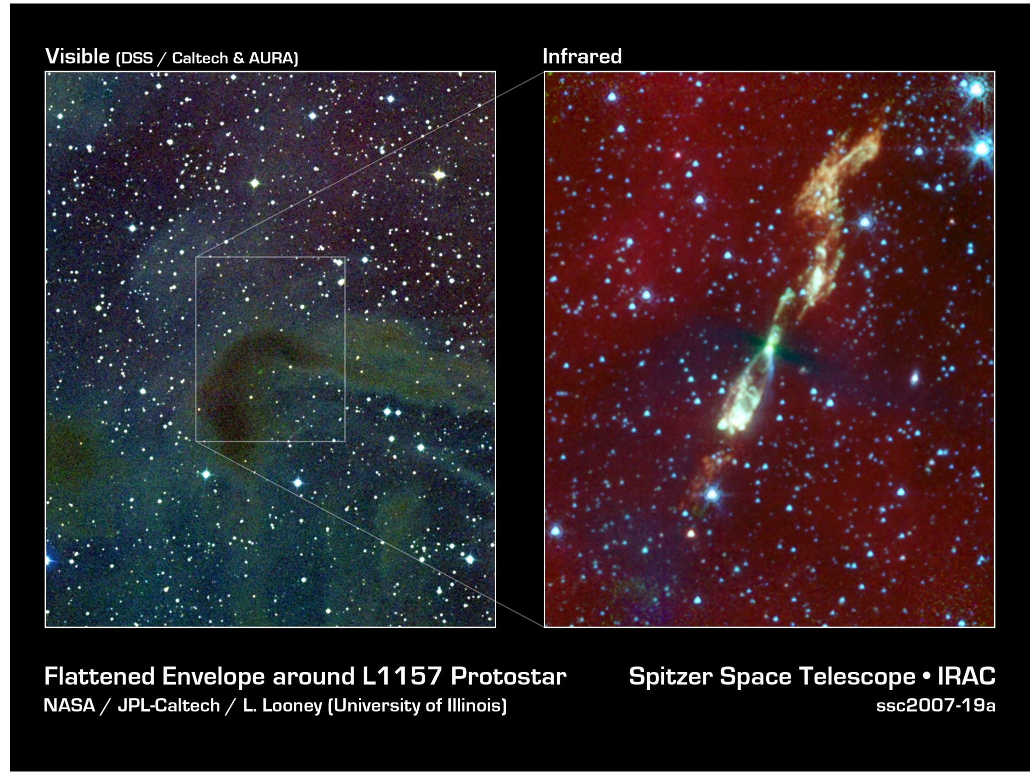


Protostellar Jets



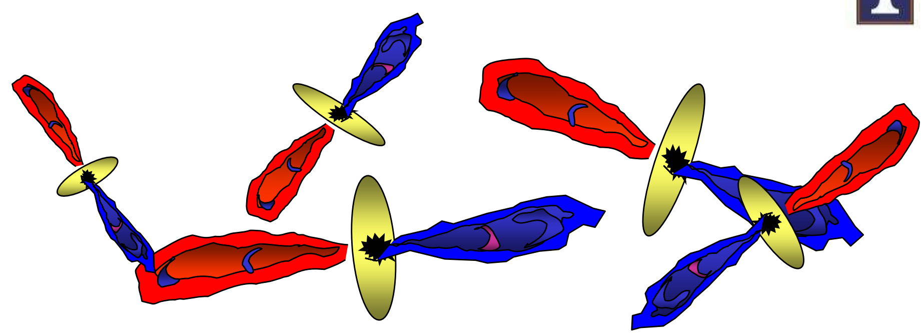






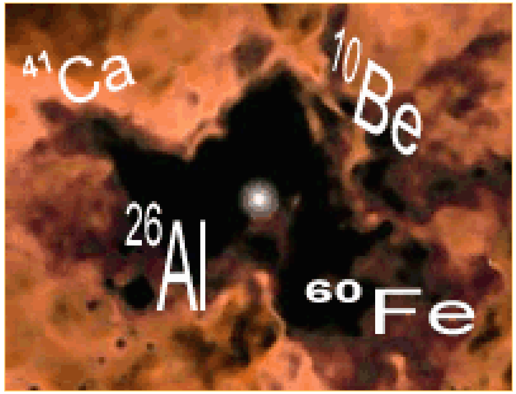
The Movie

Young Stars in Groups



- Most stars are in multiple systems and clusters
- What about us?

Isotopes in the Pre-Solar Nebula



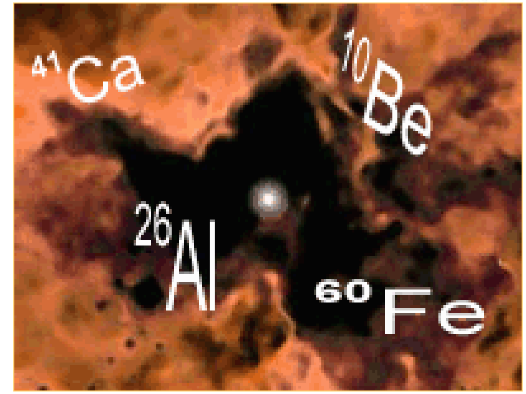
- The Solar nebula had short-lived radioactive material (e.g. ^{26}Al or ^{60}Fe)
- Small mineral grains in meteorites contain evidence of this decayed material.
- The radioactive material decayed, and left rare forms of some elements in the rock

^{26}Aluminum
- 13 protons
- 13 neutrons

↓

^{26}Magnesium
- 12 protons
- 14 neutrons

Isotopes in the Pre-Solar Nebula



When we find an excess of ^{26}Mg, we know ^{26}Al must have been present

Half of the ^{26}Al decays each 740,000 years

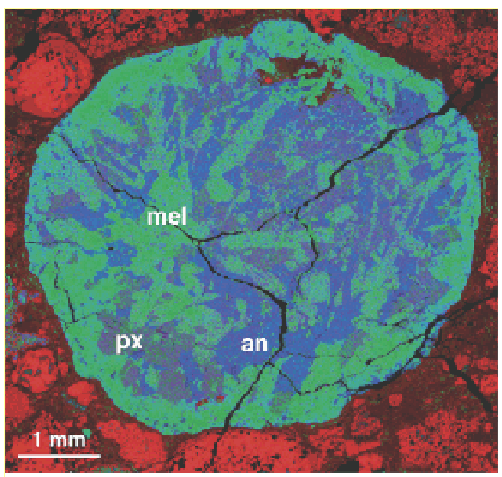
^{26}Aluminum
- 13 protons
- 13 neutrons

→

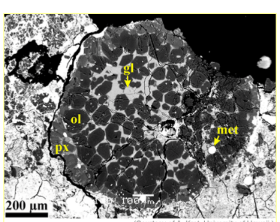
^{26}Magnesium
- 12 protons
- 14 neutrons

The Earliest Pre-Solar Dust Grains

- Calcium-aluminum-rich inclusions (CAIs)
- Chondrules (grains found in primitive meteorites).
- Both contain the "daughter products" of decayed ^{26}Al
- Chondrules formed about 2 million years AFTER the CAI rich inclusions



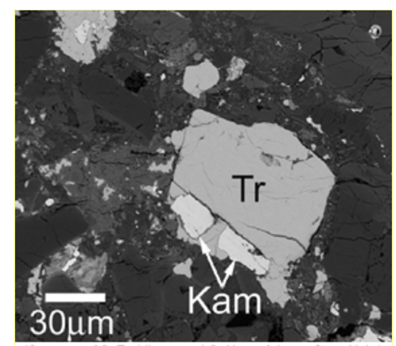
(Courtesy of A. Krot, University of Hawaii.)



Formed 4,700,000,000 years ago

CAIs Once Contained ^{60}Fe

- Contain decay products of ^{26}Al and ^{60}Fe
- As seen by an excess of nickel
- Can only be produced by nearby supernova explosion!
- Can use the ensemble of all radioactive elements to estimate distance to the supernova
  - 0.1 to 1.6 pc away



(Courtesy of S. Tachibana and G. Huss, Arizona State Univ.)

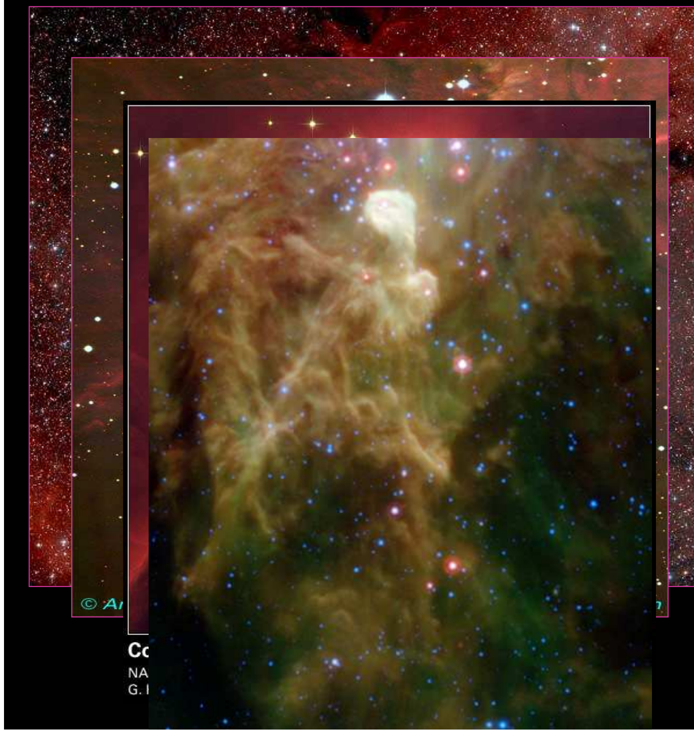
Half life 1.5 million years

The Birth of the Sun

The Sun formed as part of a modest-sized cluster of stars

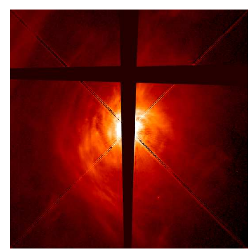
A nearby massive star exploded, creating radioactive elements

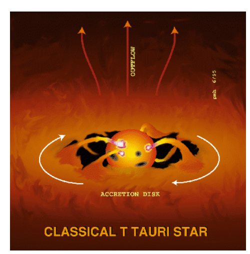
The explosion might have triggered the formation of the Sun



The Cone Nebula

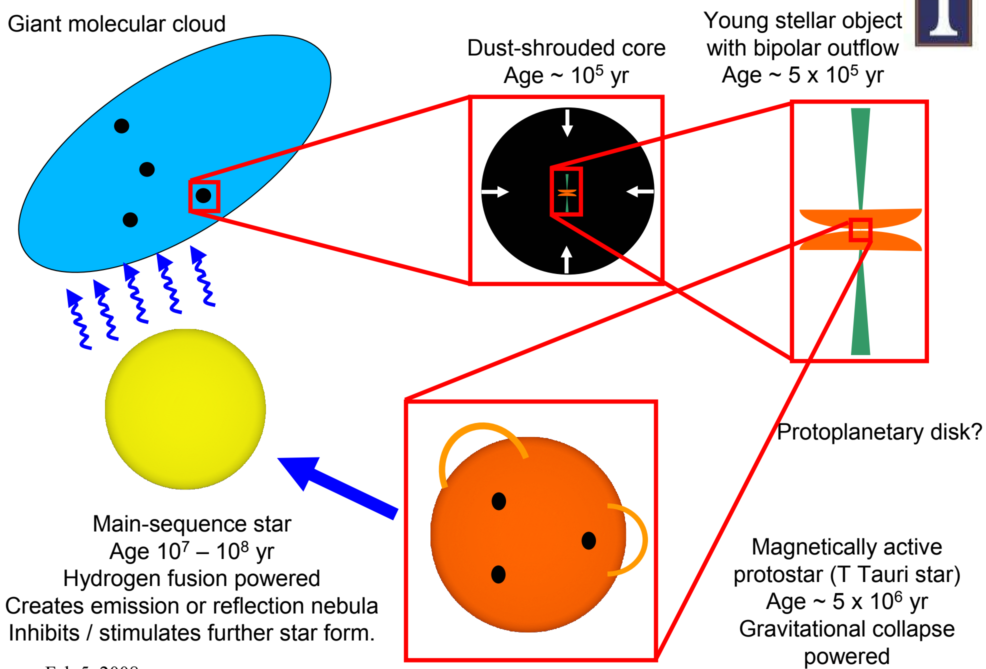
On to the Main Sequence: A Star is Born!





- Density increase, temperature increases until fusion can occur.
  - Blows away most of its natal circumstellar material.
  - Becomes a star on the main sequence of the HR diagram,
  - For low mass stars, this whole process can take a few 10^6 years.
  - Expect to see a large number of embedded protostars.

Star Formation - Summary



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

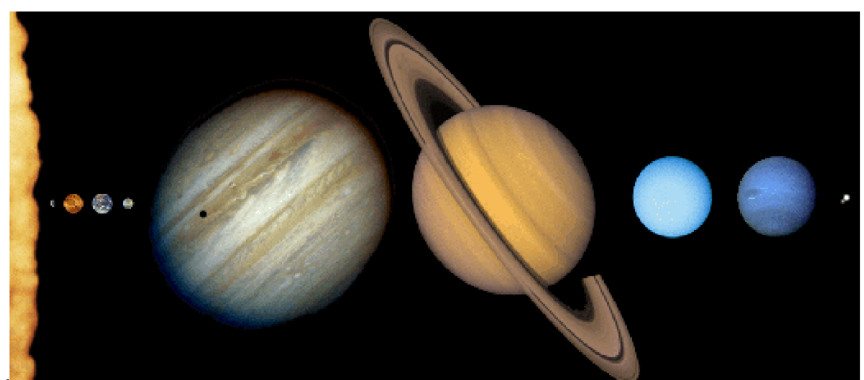
What is the origin of the Solar System?

- 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?

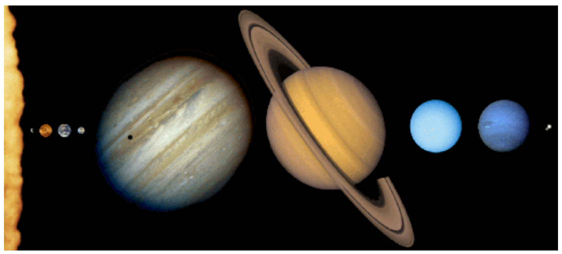
Some Facts of the Solar System

- We have 8 or 9 planets.
- So perhaps the average extrasolar system has about 10 planets (rounded off).



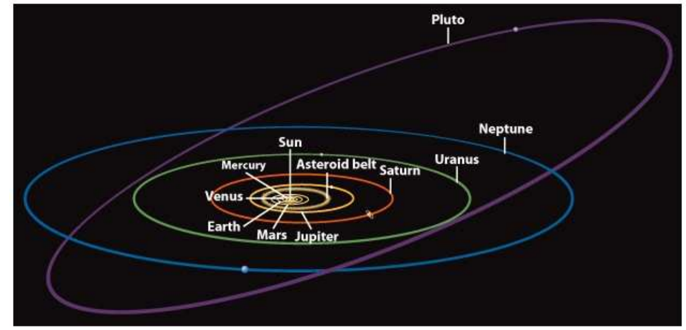
Some Facts of the Solar System

- Mass of solar system
  - 99.85% in the Sun (planets have 98% of ang. mom.)
  - Outer planets more massive than the inner ones
  - Jupiter is more than twice as massive as the rest of the planetary system combined!
- The inner planets are rocky and the outer planets are gaseous



Planetary Orbits

Most of the motions in the Solar System are counter clockwise in a flat system (pancake-like)

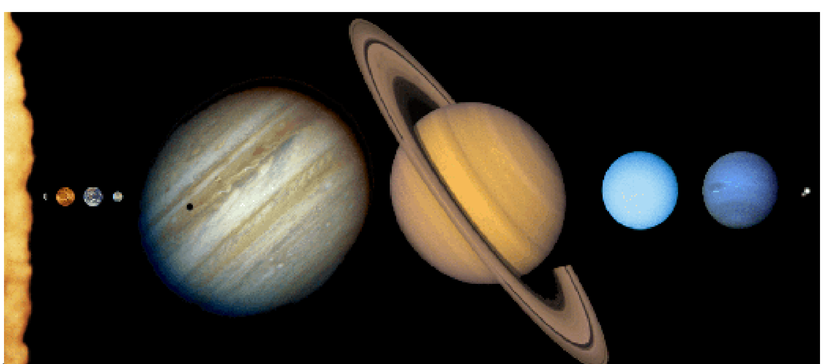


- There are some exceptions
- Venus, Uranus, and Pluto rotate clockwise (orbits are still clockwise)
- Some moons orbit backwards

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

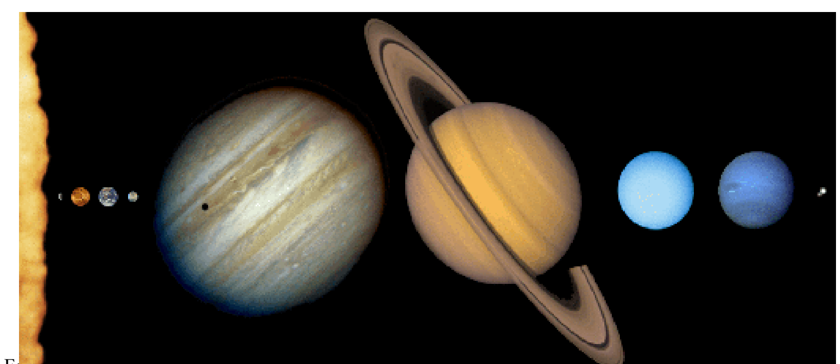
Some Facts of the Solar System

- Outer planets more massive than inner planets.
- 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



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

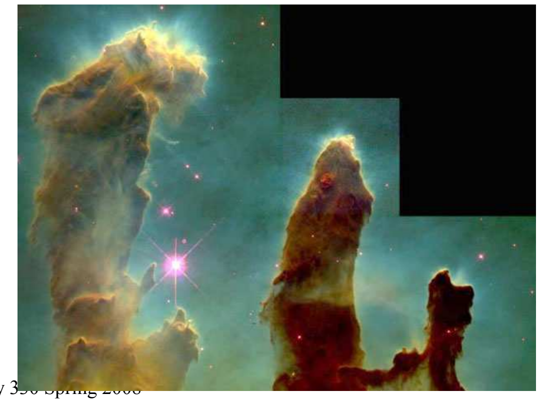
- **Age of Solar System is probably around 4.6 billion years old**

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 in class.



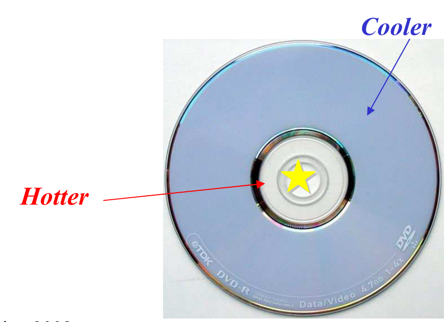
The Early Solar System

- 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.

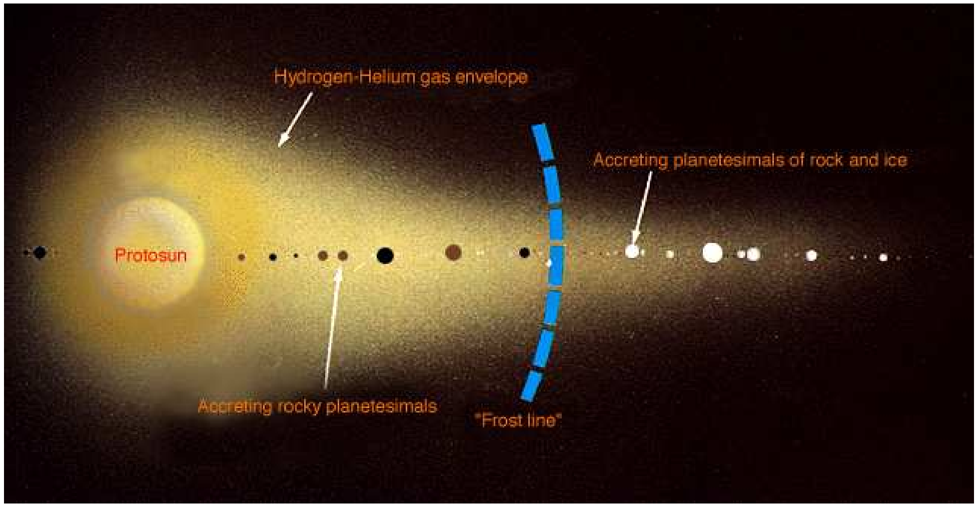
The cloud collapsed under its gravity and formed the circumstellar disk from which our solar system formed. Most theories for solar system formation require disks with masses of 0.01 to 1 solar masses.

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.



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

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

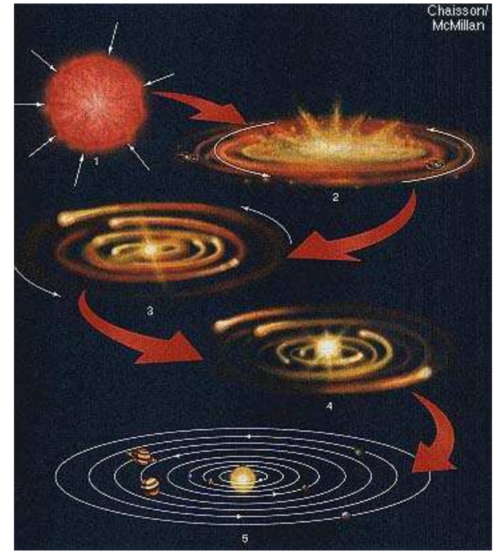
- Between Mars and Jupiter
  - Remain as the asteroids
- Near Jupiter & Saturn
  - Ejected from the solar system
- Near Uranus & Neptune
  - Ejected to the Oort Cloud
- Beyond Neptune
  - Remain in the Kuiper Belt

Planet Formation in the Disk

Heavy elements clump

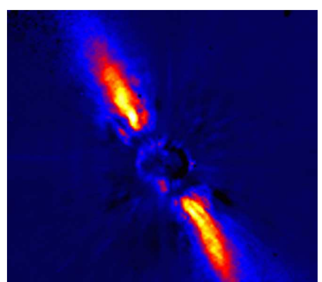
1. *Dust grains* collide, stick, and form planetesimals– about 10^{12} of them, sort of like asteroids! All orbit in the same direction and in the same plane.
2. Gravity Effects: Big planetesimals attract the smaller planetesimals. So, fewer and fewer of large objects (100’s). Collisions build-up inner 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

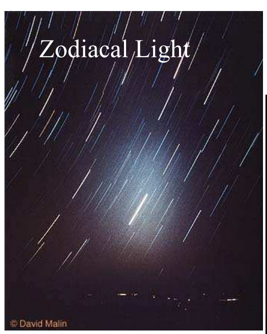
Formation of the Solar System 4.6 billion years ago

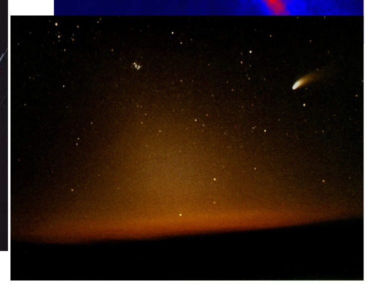


Fossil Disks Exist around other Stars?

- 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

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!!!!!

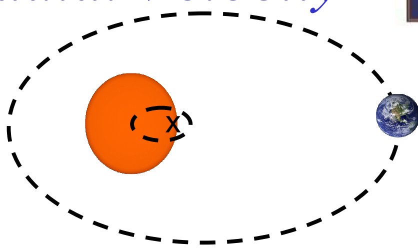
Finding Planets

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

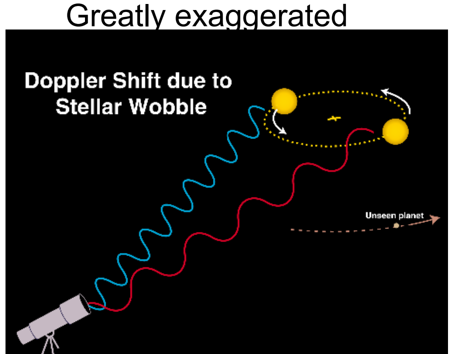
Arguable 2 extrasolar planets have been detected directly in the IR. Remember that planets in our Solar System seem bright because they reflect light from the Sun in the visible.

Star Wobble: Radial Velocity

Newton's 3rd 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

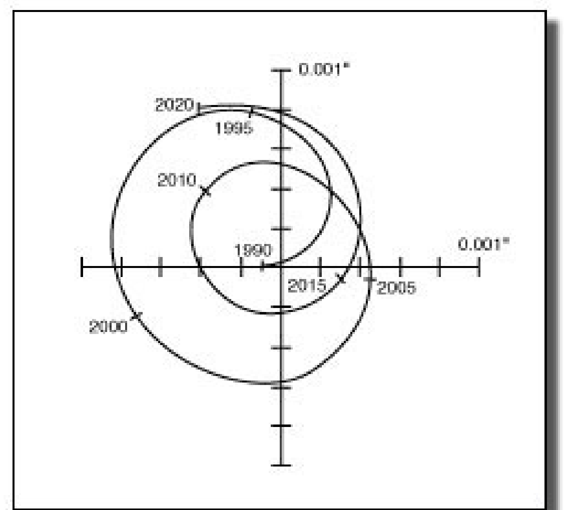


http://www.howstuffworks.com/planet-hunting2.htm

The Sun's Wobble

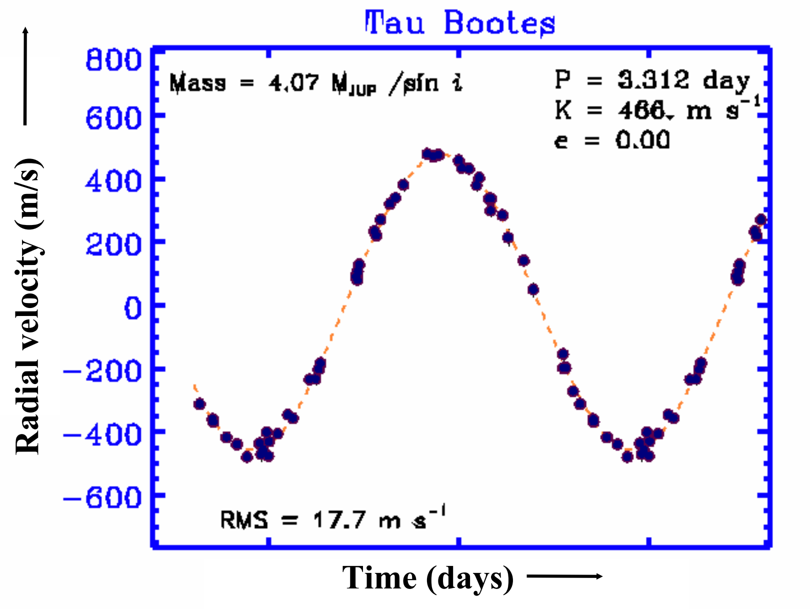
Astrometric displacement of the Sun due to Jupiter (and other planets) as at it would be observed from 10 parsecs, or about 33 light-years.

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

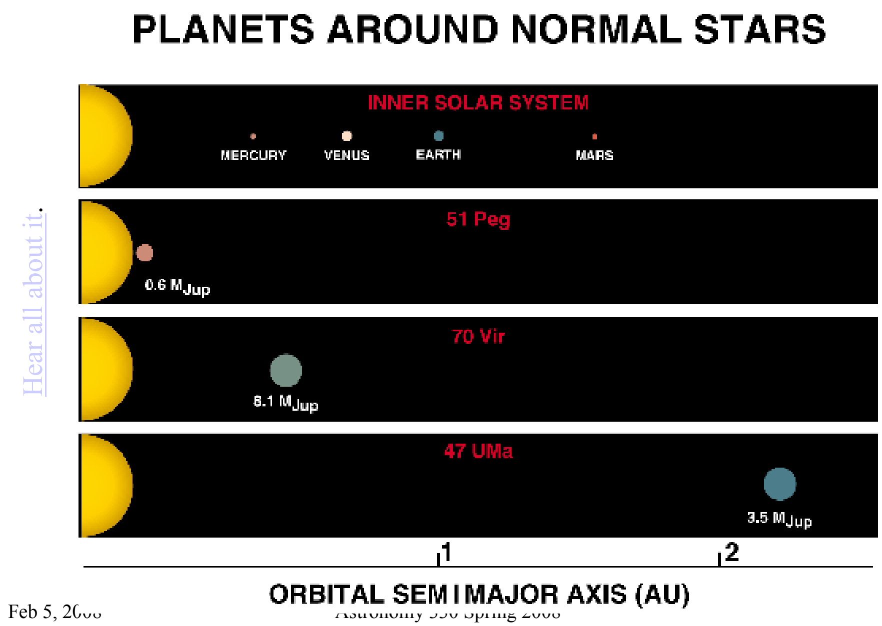


http://planetquest.jpl.nasa.gov/Keck/astro_tech.html

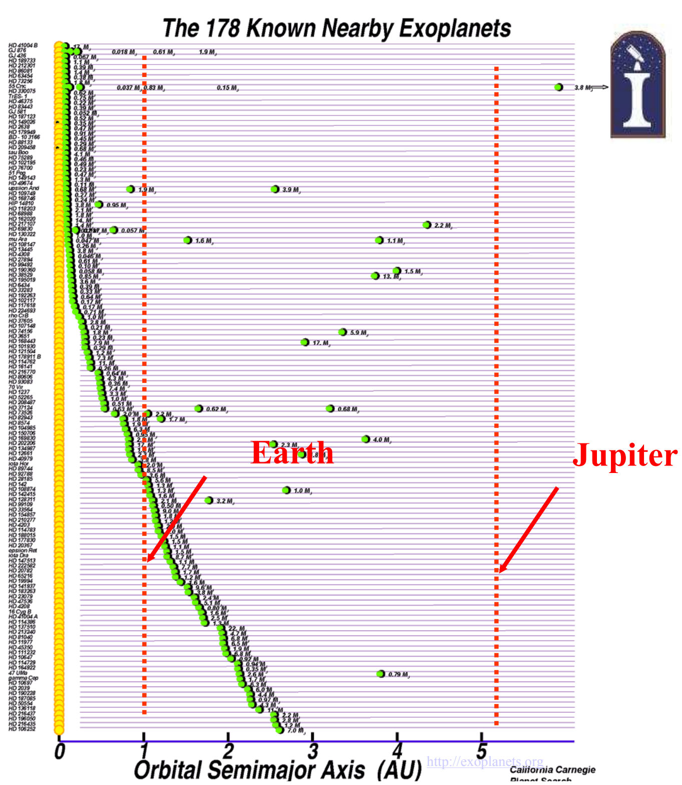
Radial Velocity Shifts: Planets around other Stars?



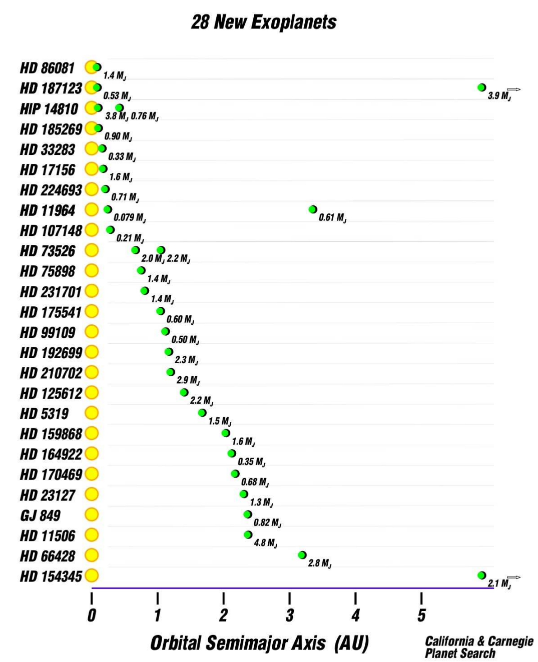
Early Discovery-- 1996



As of today, there are 228 planets known around nearby stars.



Recent Ones

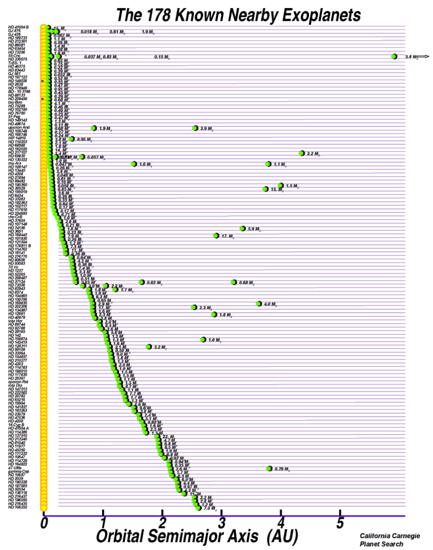


Exoplanets: Results to Date

Over 228 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

At least 20 multi-planet systems!

Note: Jupiter is 318 time the mass of Earth or

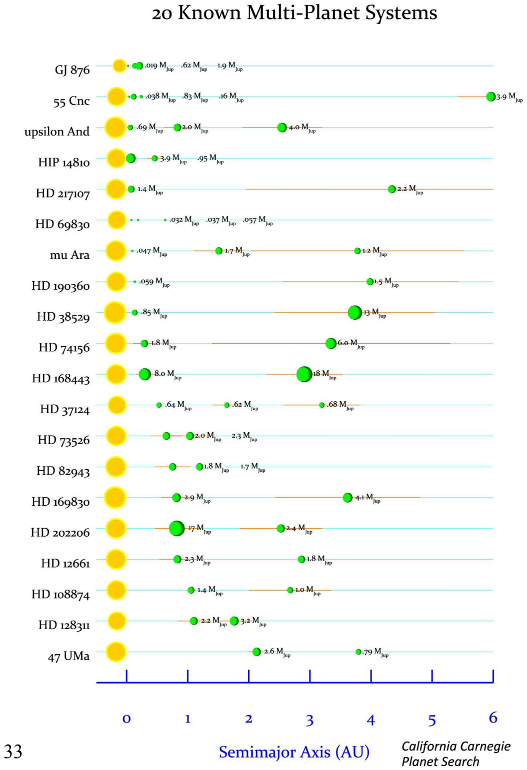
$M_E = 0.003\ M_J$

$M_J = 0.001\ M_{Sun}$

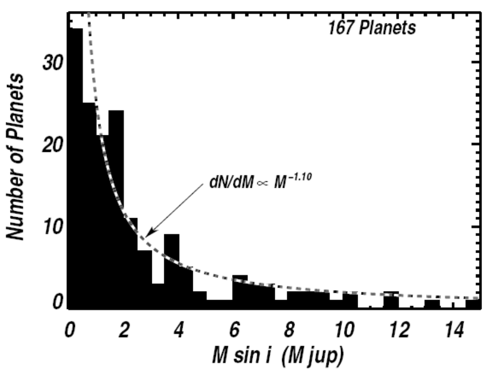
$M_{red\ dwarf} = 80\ M_J$

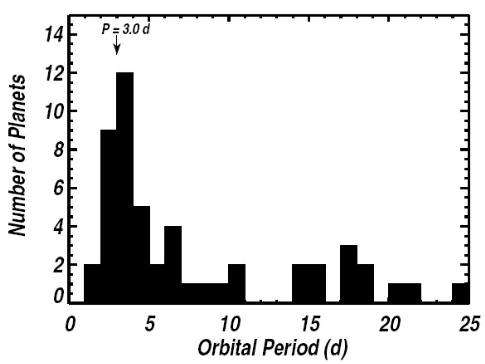
$M_{brown\ dwarf} = 18\ M_J$

$Period_J = 12$ years



Masses/Periods of Extrasolar Planets





http://exoplanets.org

List

http://exoplanets.org/

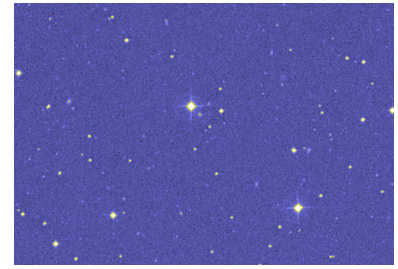
Other Planets, Other Stars

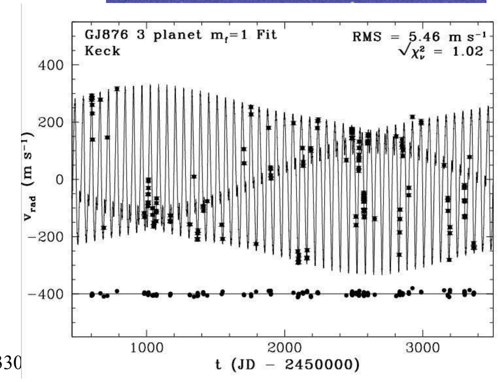
47 Ursae Majoris System– 51 light years away (near the Big Dipper). 13 years of data has shown 2 planets– 1 Jupiter like and 1 Saturn like.

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 are inside 1 AU!





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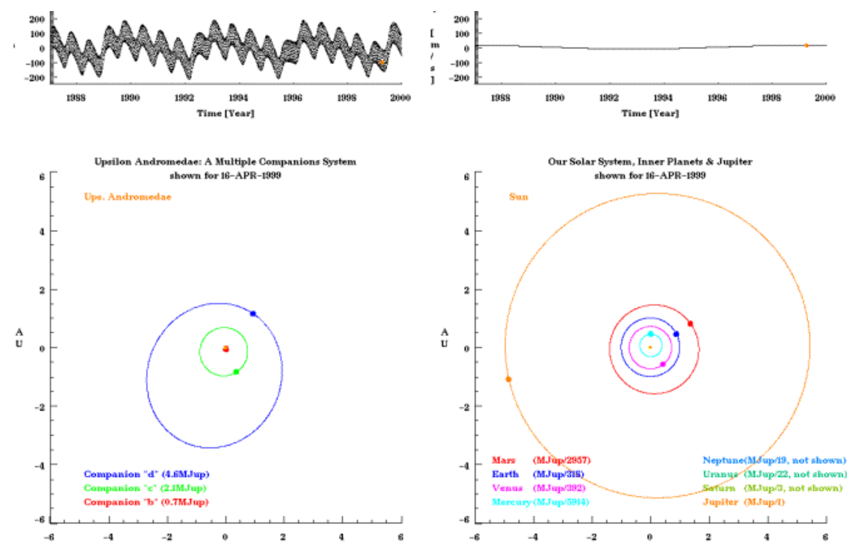
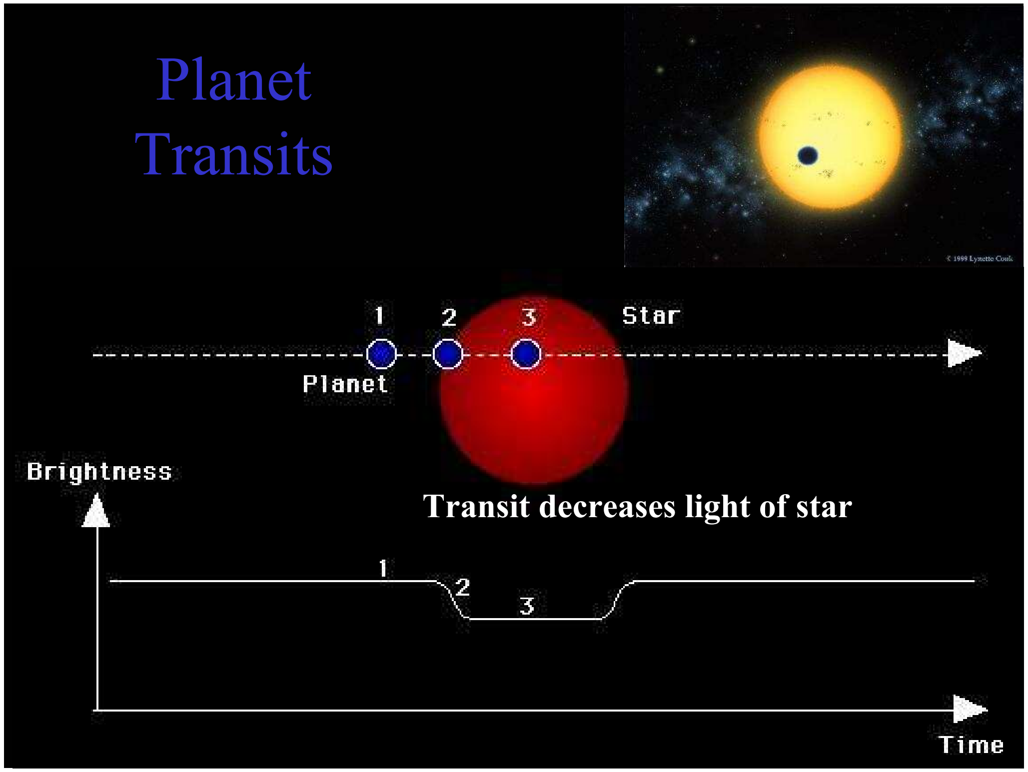
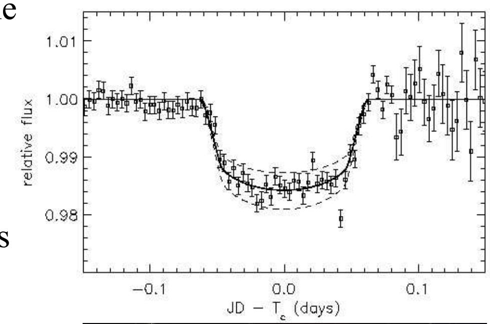
Detecting the Solar System

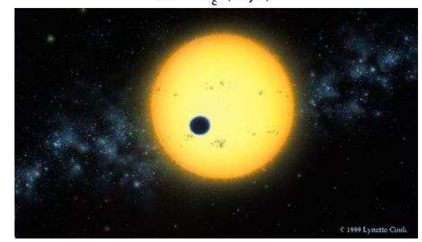


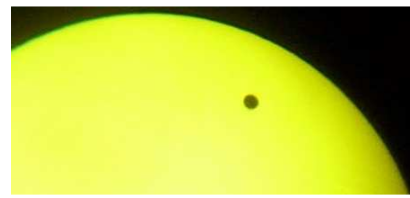


Transits

- 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

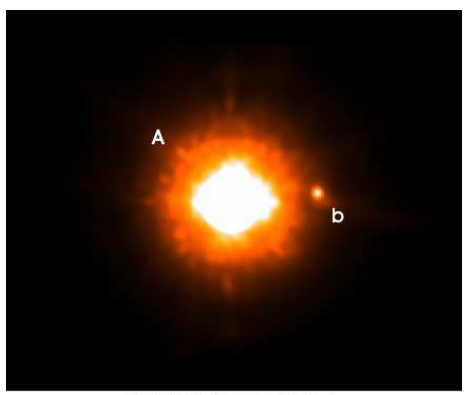






Direct Detection?

- 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?

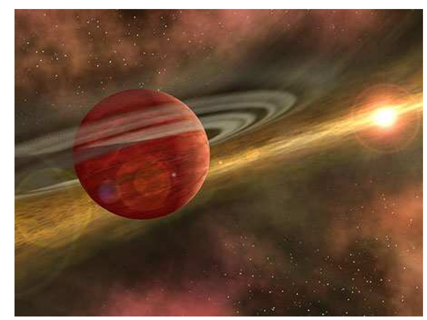


The Sub-Stellar Companion to GQ Lupi (NACO/VLT)

Results to Date

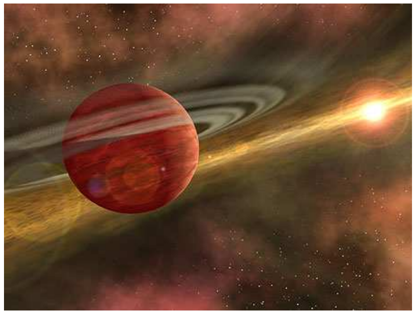
No surprise

✓ 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.