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 9):
Exoplanets
Paritosh Gangaramani

Next Class:
Moon Origins
Braden Anderson
Jennifer Bora

HW 3 is due tonight!

Music: *Planet of Sound*– Pixies

HW 2

- Ryanne Ardisana
  http://www.aliensthetruth.com/
- Clara Mount
  http://www.alienabductions.com/

Presentations

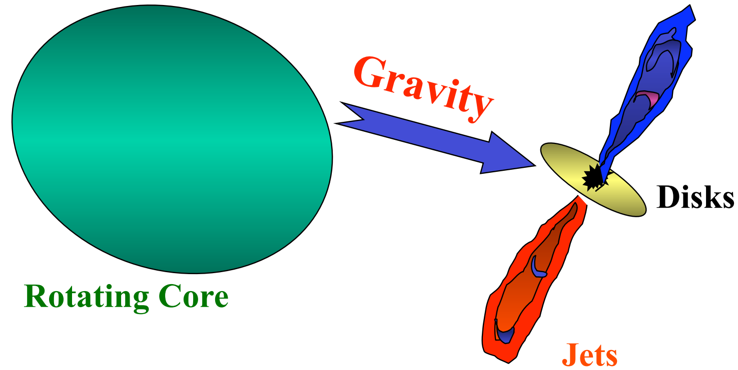
- Paritosh Gangaramani
  Aliens Built the Pyramids

Outline

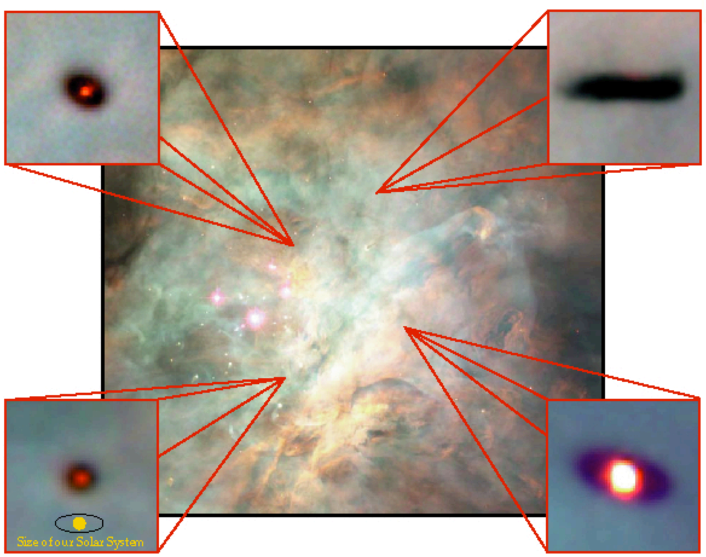
- Circumstellar disks are common!
- Exoplanets – they are all over the place.

The Protostar Stage

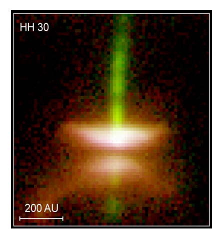
Gravity, Spin, & Magnetic Fields

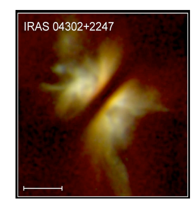


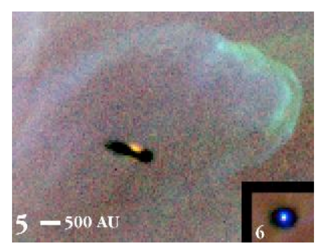
Disks around Young Stars are Common

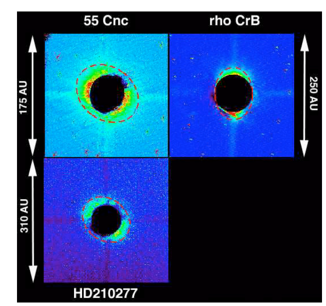


And Disks around Young Stars are Common



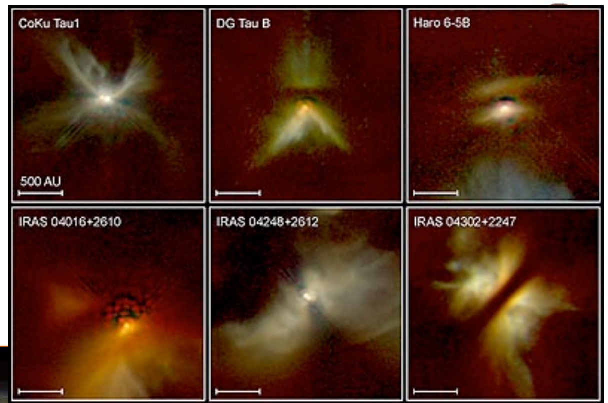






http://www.ifa.hawaii.edu/users/tokunaga/SSET/SSET.htm

Disks have been imaged with HST's infrared camera

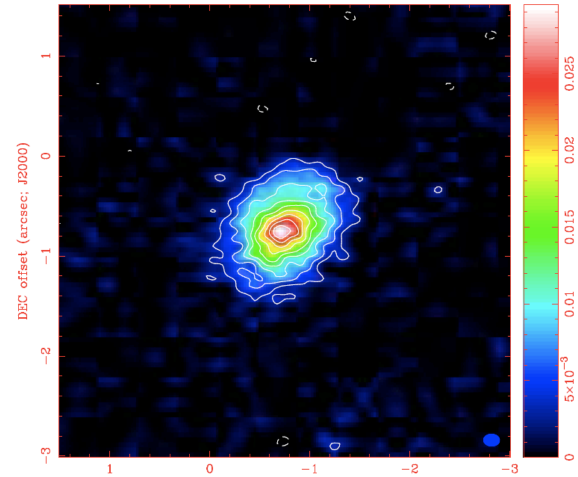


Young stars are surrounded by dense disks of gas and dust

Tracing the Bulk Material

HL Tauri

At least 80% of all young stars have circumstellar disks!



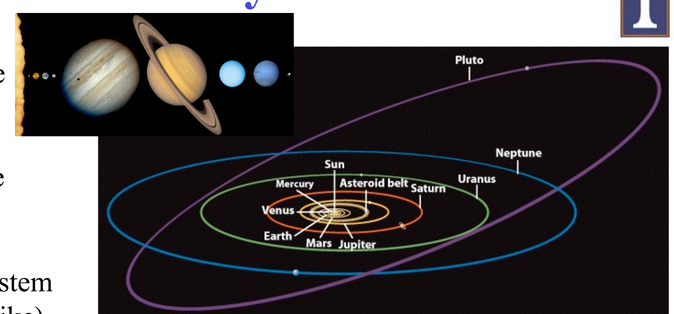
Kwon, Looney, & Mundy 2011

Interesting Question

Leslie studies circumstellar disks. What is he actually observing?

a) The disks of Galaxies.
b) The disks around Black Holes.
c) The disks around protostars.
d) The disks around planets like Saturn.
e) The disks under nice beverages.

Planetary Orbits



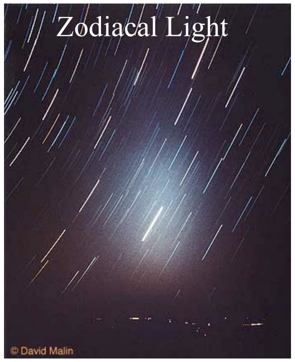
Most of the motions in the Solar System are counter clockwise in a flat system (pancake-like)

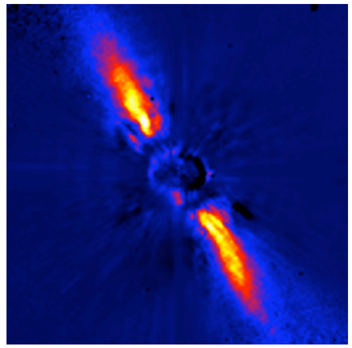
- There are some exceptions
- Venus, Uranus, and Pluto rotate clockwise (orbits are still clockwise)
- Some moons orbit backwards

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

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.

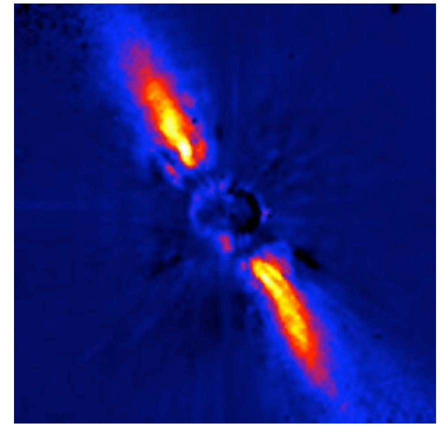




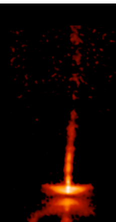
http://www.eso.org/outreach/press-rel/pr-1997/phot-16-97.html
http://antwrp.gsfc.nasa.gov/apod/ap970826.html

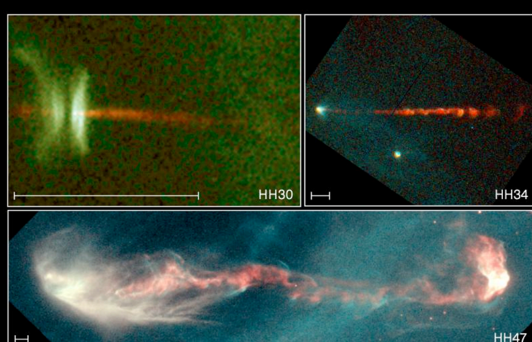
Disks Around Young Stars

- Many (> 80%) of newborn stars surrounded by a disk of material!
- Disks thick, blocks light
  - Enough material to make planets
  - Agrees with Solar Nebula theory!

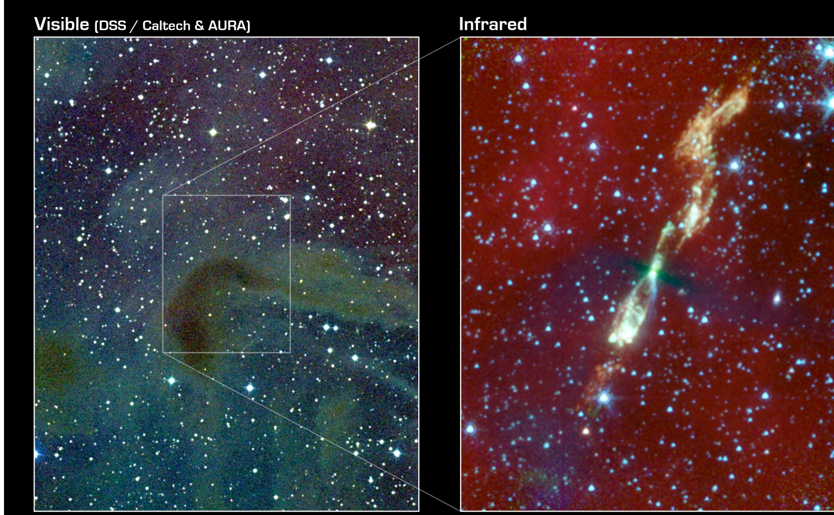


Protostellar Jets





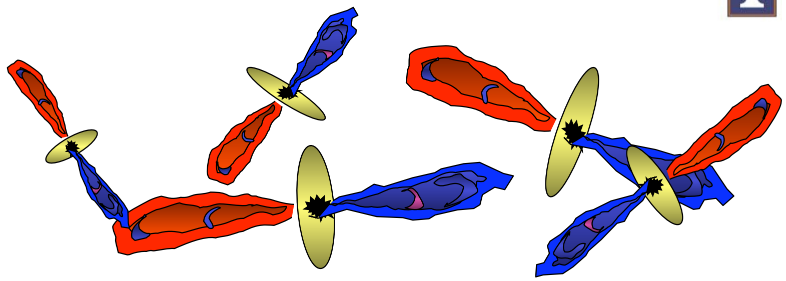
Jets from Young Stars HST • WFPC2
PRC95-24a • ST ScI OPO • June 6, 1995
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA



Flattened Envelope around L1157 Protostar **Spitzer Space Telescope • IRAC**
NASA / JPL-Caltech / L. Looney (University of Illinois) ssc2007-19a

http://www.youtube.com/watch?v=Rm3Sj8qAaWg&NR=1

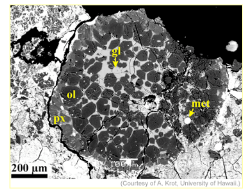
Young Stars in Groups

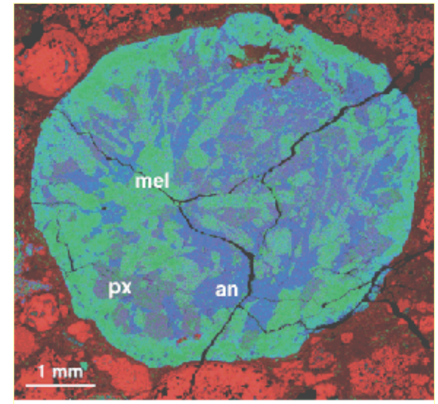


- Most stars are in multiple systems and clusters
- What about us?

The Earliest Pre-Solar Dust Grains

- Calcium-aluminum-rich inclusions (CAIs)
- Chondrules (grains found in primitive meteorites).



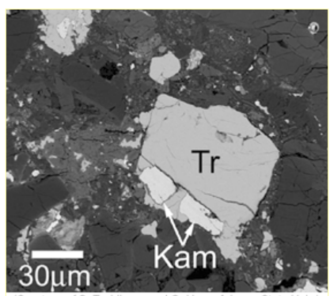


(Courtesy of A. Krot, University of Hawaii.)

Formed 4,700,000,000 years ago

CAIs Once Contained ^{60}Fe

- Contain decay products of mnay radioactive elements, such as ^{60}Fe
- As seen by an excess of nickel
- Most likely 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.)

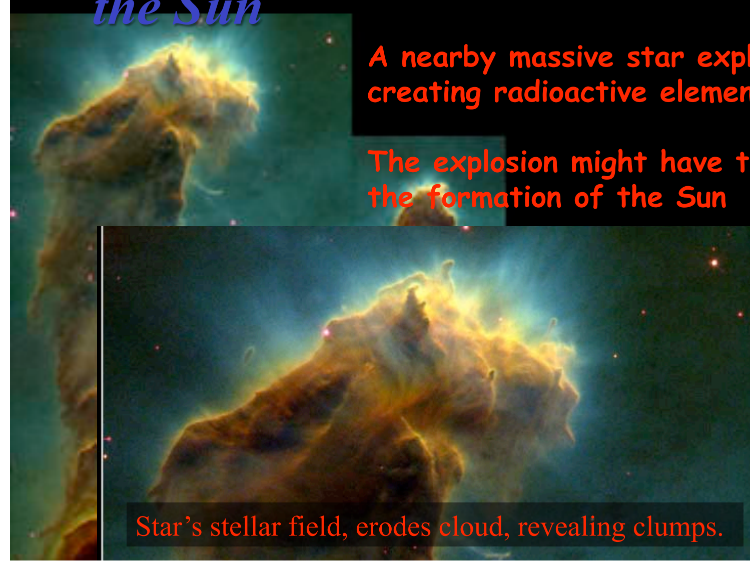
Half life 1.5 million years

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

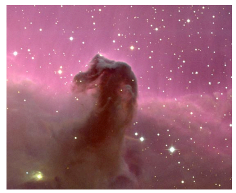
The explosion might have triggered the formation of the Sun



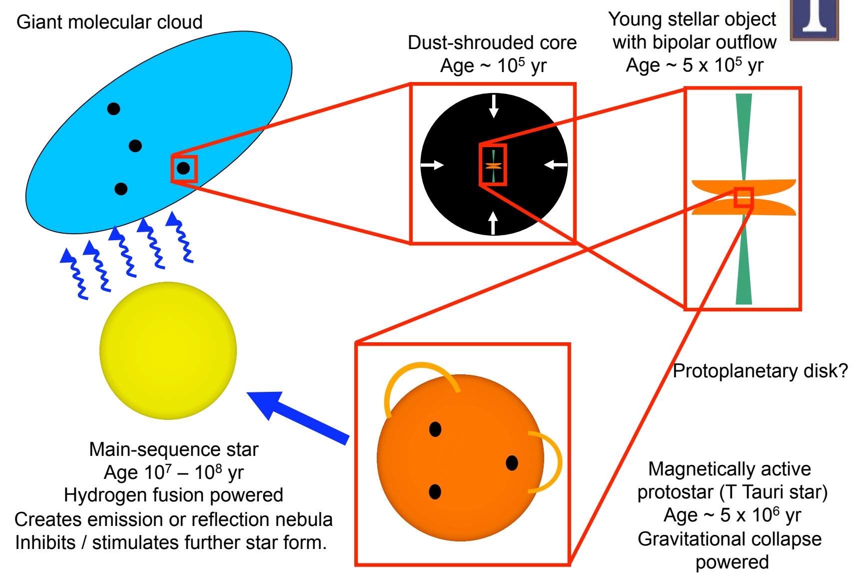
The Early Solar System

- 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.



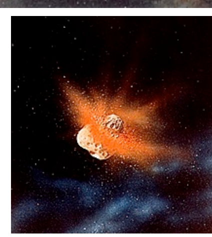
Star Formation - Summary



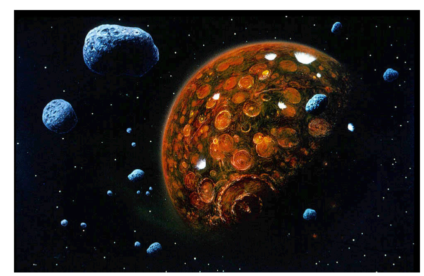
Planet Formation in the Disk

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



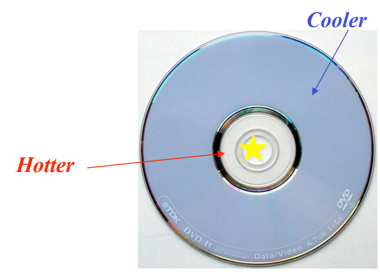
- There were billions of planetesimals in the early solar system
- Many collided with the young planets
  - Look at the Moon & Mercury!
  - Period of **heavy bombardment**
  - Lasted for about the first 800 million years of the Solar System
- Others were ejected from the solar system…

Fates of the Planetesimals

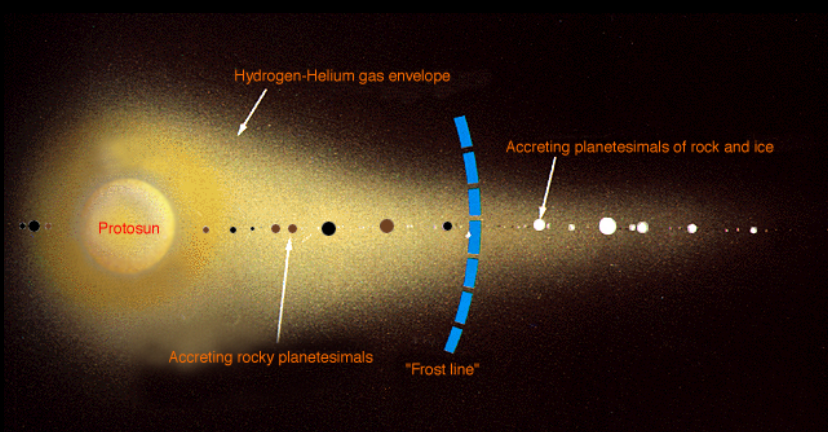
- Between Mars and Jupiter
  - Remain as the asteroids
- Near Jupiter & Saturn
  - Ejected from the solar system
- Near Uranus & Neptune
  - Ejected to the Oort Cloud
- Beyond Neptune
  - Remain in the Kuiper Belt

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?

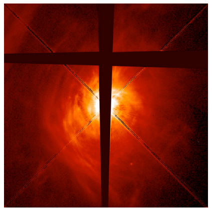


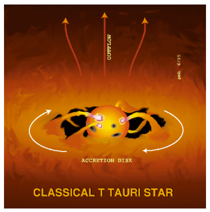
Temperature is the key factor!

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

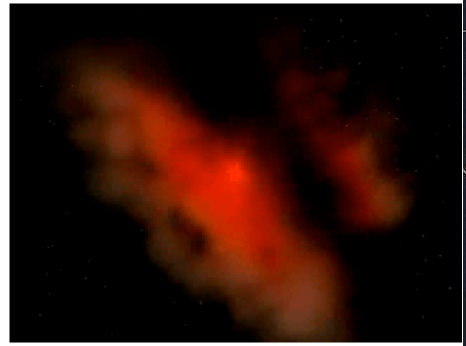
On to the Main Sequence: A Star is Born!

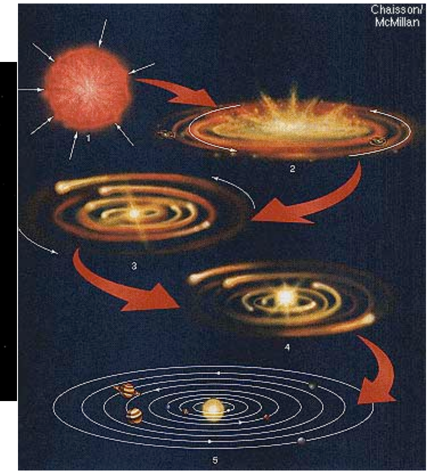




- For 1 solar mass star, process takes about 10 million years
- Density increase, temperature increases until fusion can occur.
  - Blows away most of its natal circumstellar material.
  - Becomes a hydrogen burning star
  - http://www.youtube.com/watch?v=mZL7VBmeFxY&feature=related

Formation of the Solar System 4.6 billion years ago





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*"

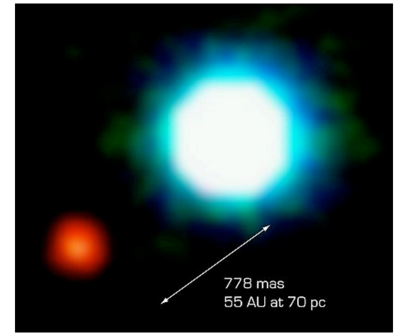
Would our solar system nebula formation theory account for other solar systems around other stars?

Hard to find!

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

Extrasolar planets are hard to find

- Detection is hard
- Separation between the extrasolar planet and its star is miniscule compared to interstellar distances
- Any planet is an extremely faint light source compared to its parent star (Earth is 1 billion times fainter!)



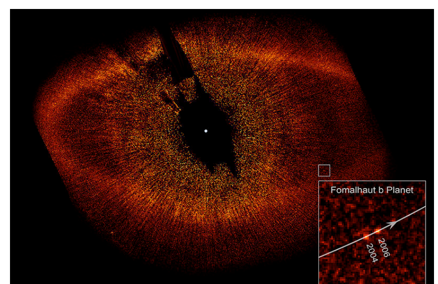
Infrared image of star 2M1207 (blue) and planet 2M1207b (red)

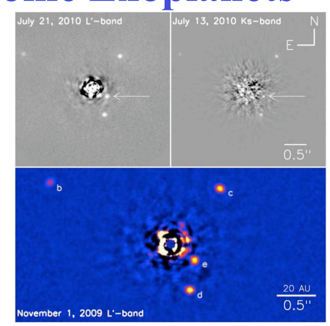
Finding Planets

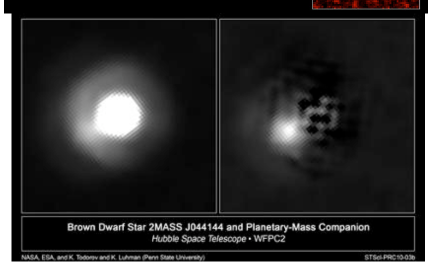
1. Transit Method: Occultation
2. Radial Velocity: Stars will wobble
3. Direct Detection: Direct imaging
4. Astrometry: See the stars move

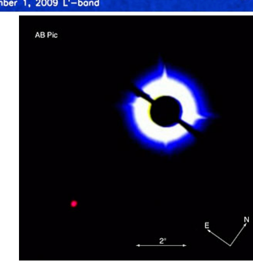
Only a few planets have been detected directly in the optical and IR. Remember that planets in our Solar System seem bright because they reflect light from the Sun in the visible.

We have imaged some Exoplanets

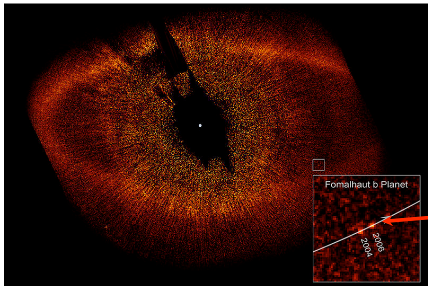




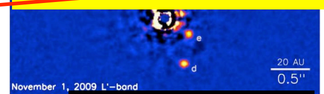


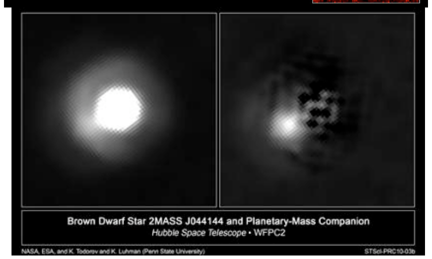


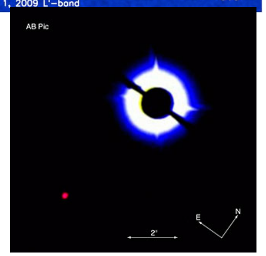
We have imaged some Exoplanets



Fomalhaut as imaged by the HST. The star was obscured to block as much light as possible. There is a dusty disk seen in scattered light and a planet!

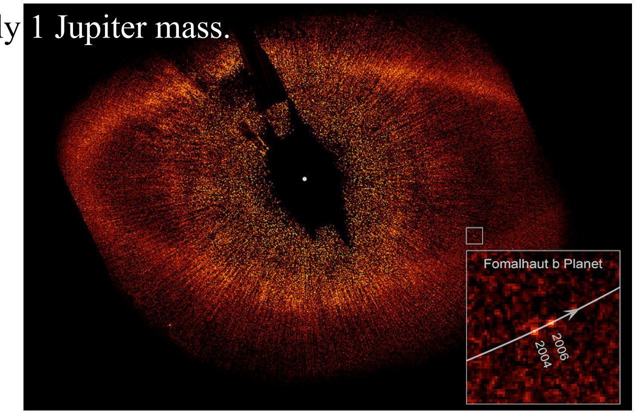






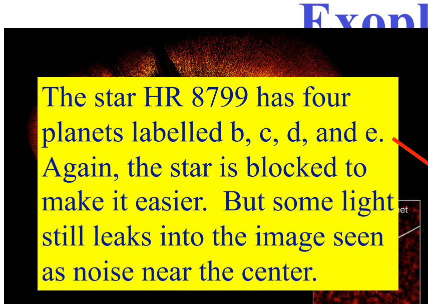
Imaging: Fomalhaut

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

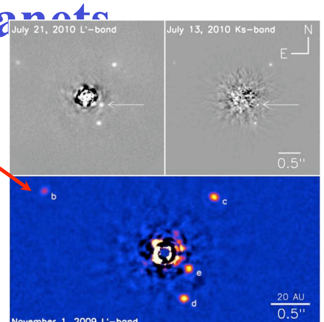


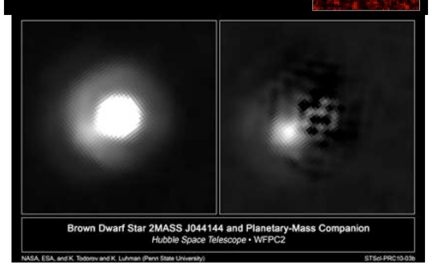
http://hubblesite.org/newscenter/archive/releases/2008/39/image/

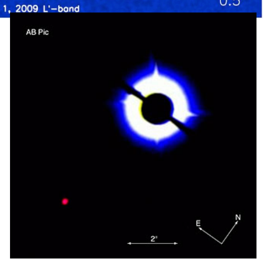
We have imaged some Exoplanets



The star HR 8799 has four planets labelled b, c, d, and e. Again, the star is blocked to make it easier. But some light still leaks into the image seen as noise near the center.

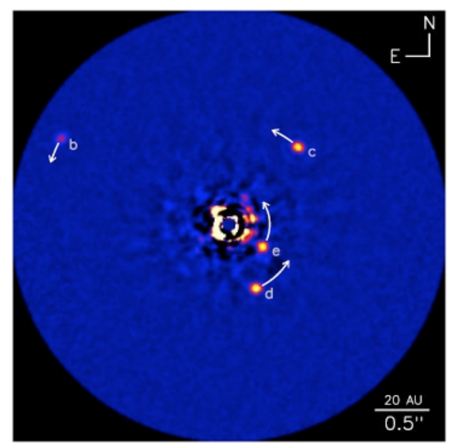




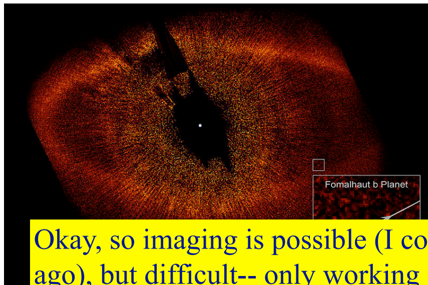


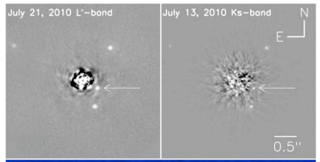
Imaging: HR 8799

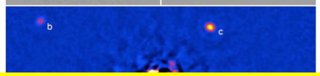
- First detection of exoplanet in IR.
- Four planet system
  - 7 M_J (14 AU)
  - 7 M_J (24 AU)
  - 7 M_J (38 AU)
  - 5 M_J (68 AU)

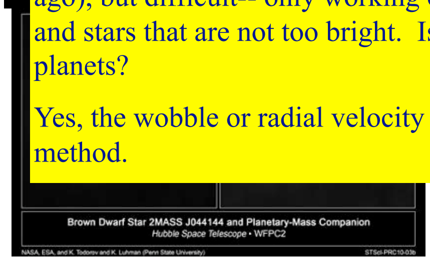


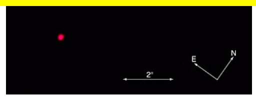
We have imaged some Exoplanets











Okay, so imaging is possible (I couldn’t say that a few years ago), but difficult-- only working on the planets that are big and stars that are not too bright. Is there a better way to find planets?

Yes, the wobble or radial velocity method and now the transit method.