

Astronomy 405

Solar System and ISM

Lecture 18

Planetary System Formation and Evolution

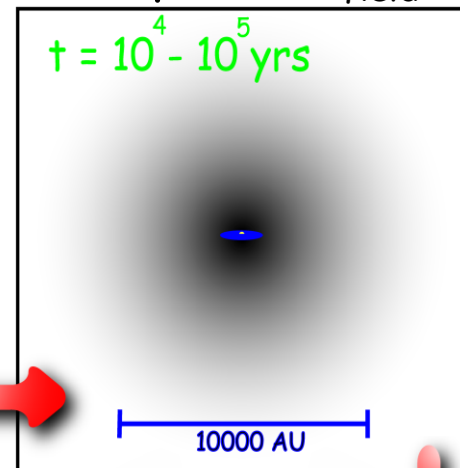
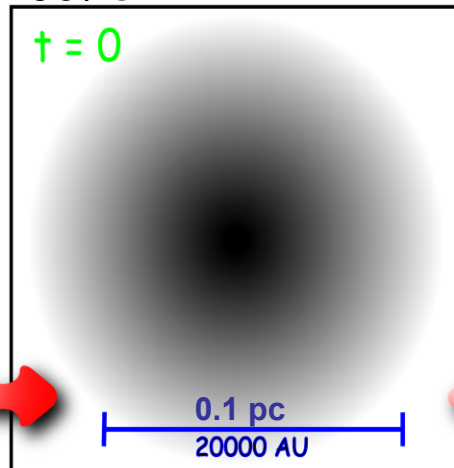
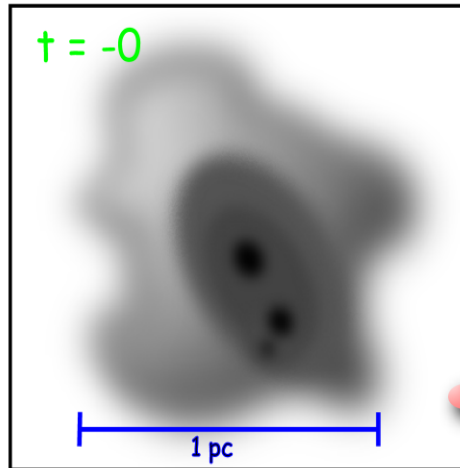
February 25, 2013

Cartoon of Star Formation

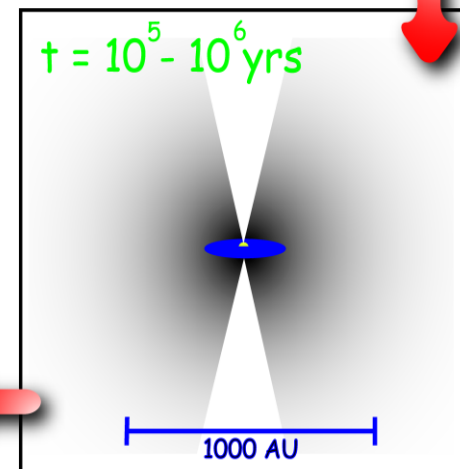
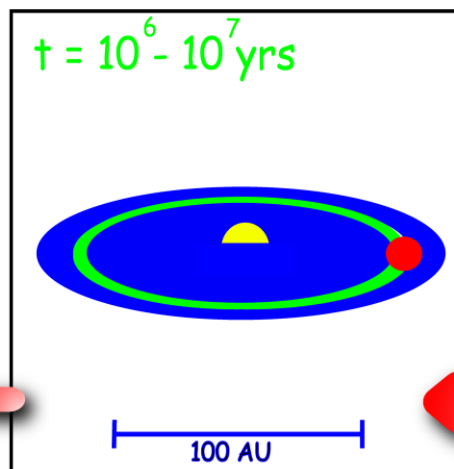
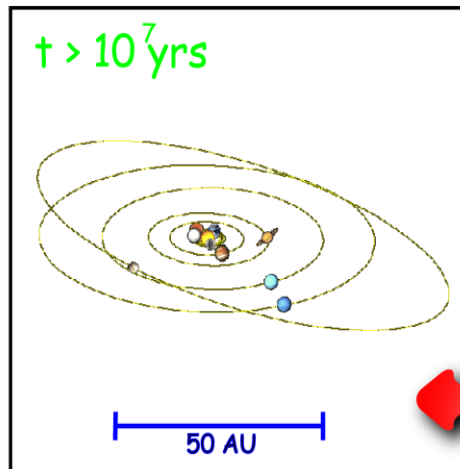
grav collapse
opposed by
turbulence, B field,
thermal

isolated, quasi-static,
unbound, isothermal
core

simple Ω/B_{field}



disk &
outflow due to
angular
momentum



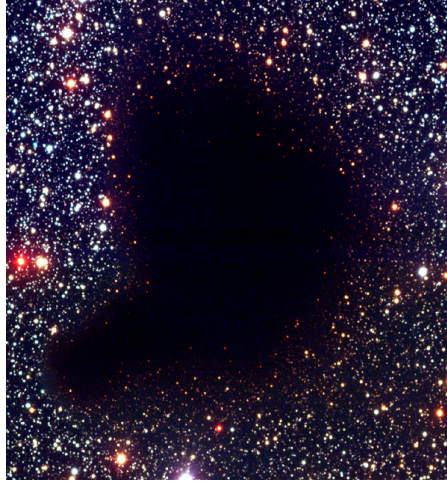
planetary
system?

clearing of
envelope by wind

After Shu et al. 1987, Shu et al. 1993

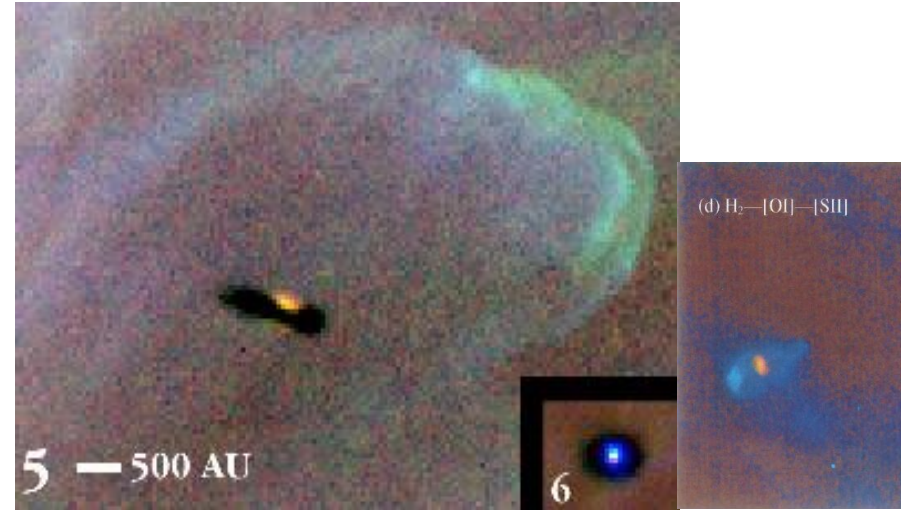
Starless cores and protostars with inward (collapse) motions

(Gregersen et al. 1997, Mardones et al. 1997, Tafalla et al. 1998, Lee et al. 2001)

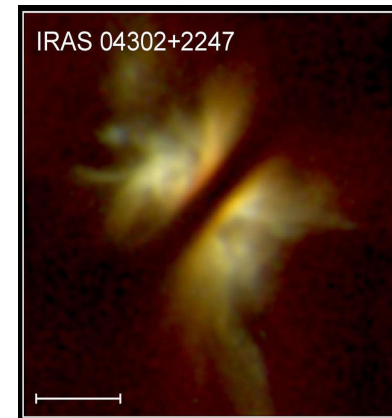
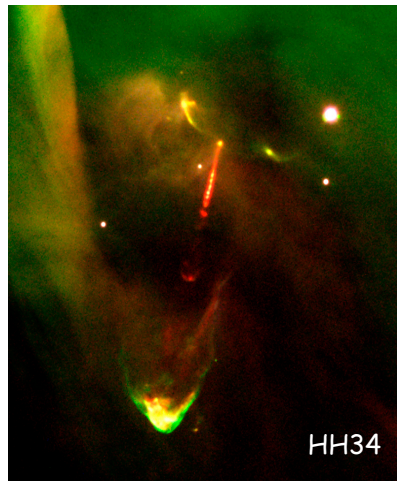
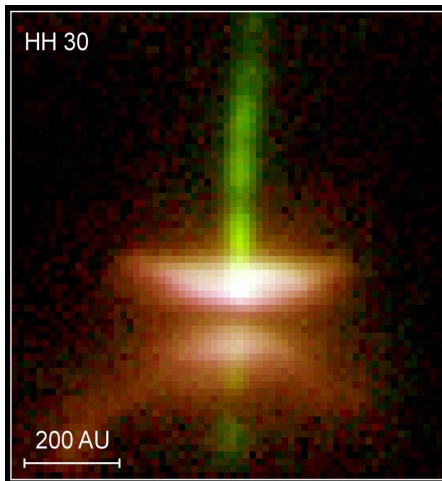


Majority of T Tauri stars have disks

(e.g. Beckwith & Sargent 1996)

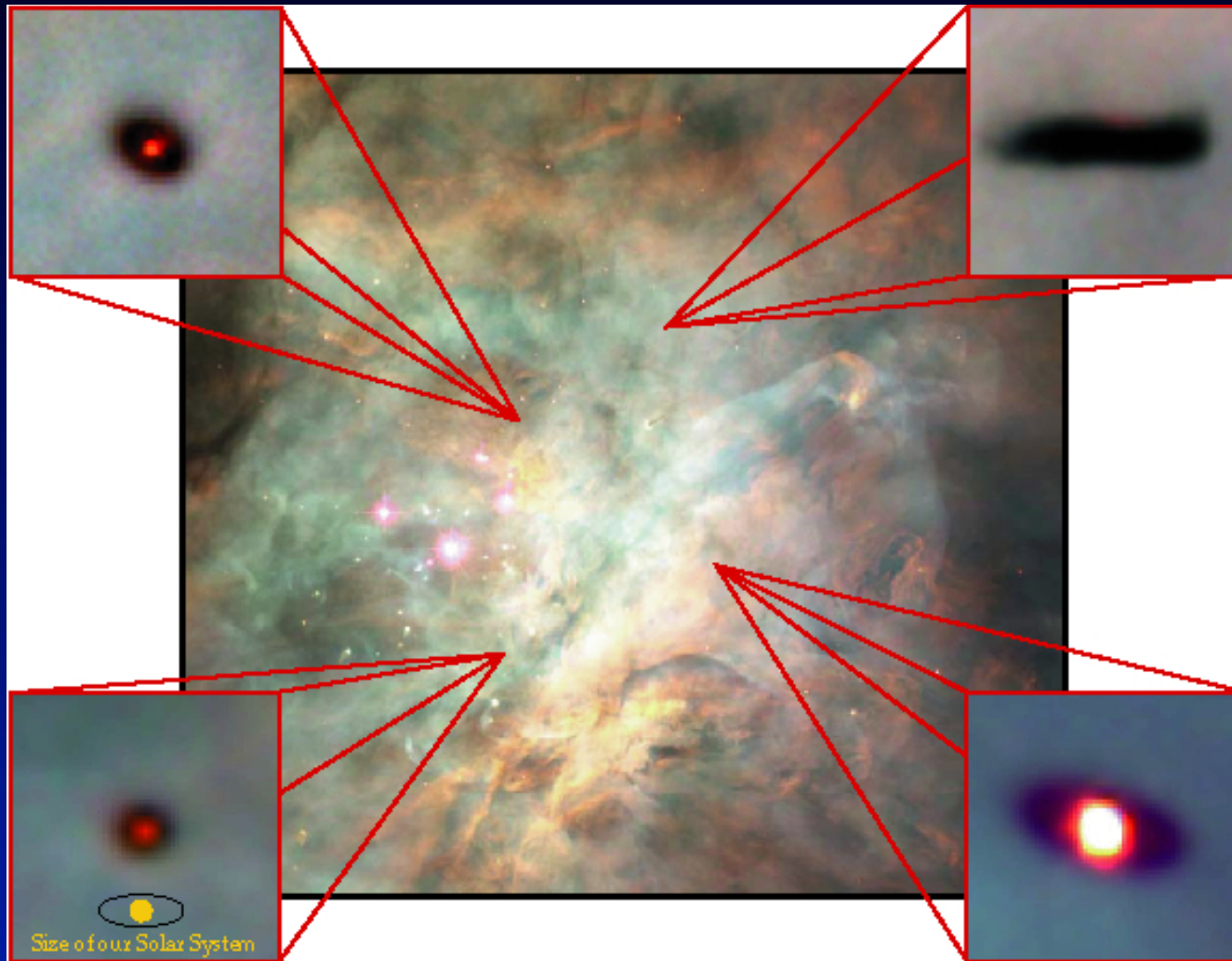


YSO outflows



Alves et al. 2001, O' Dell et al. 1994, Chen et al. 1998, Jayawardhana et al. 1998, Padgett et al. 1999, Burrows et al. 1996, ESO 2000

Protostars and Protoplanetary Disks in the Orion Nebula



Angular Momentum Problem

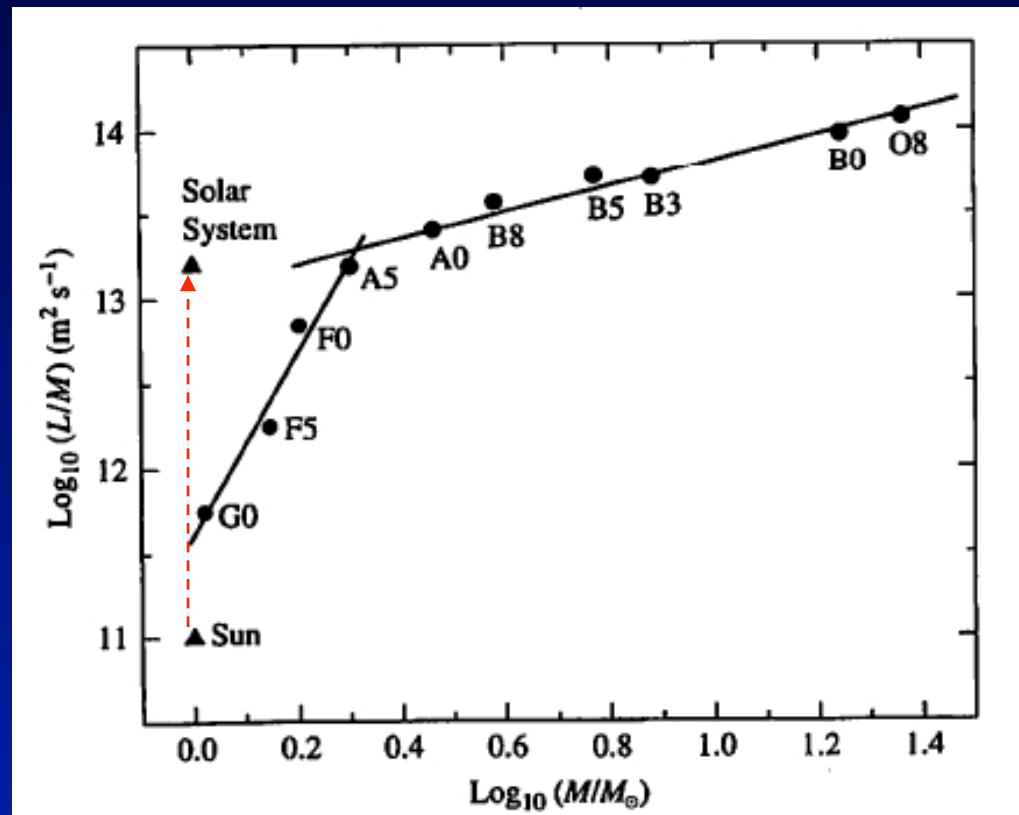
The Sun contains 99.9% of the mass, but only 1% of the angular momentum in the solar system.

Jupiter's orbital motion => most of the angular momentum

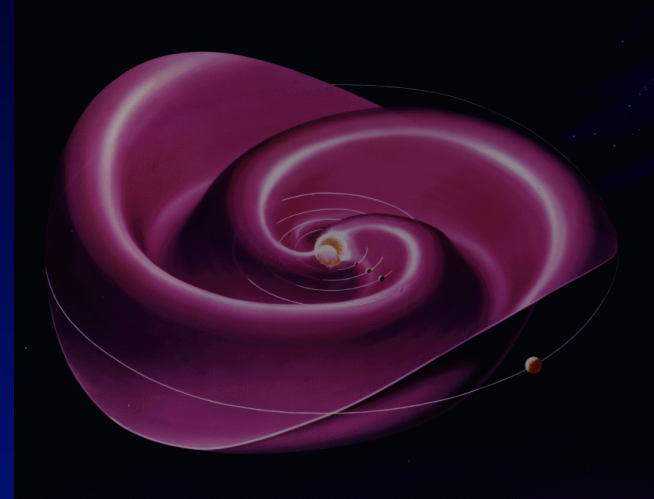
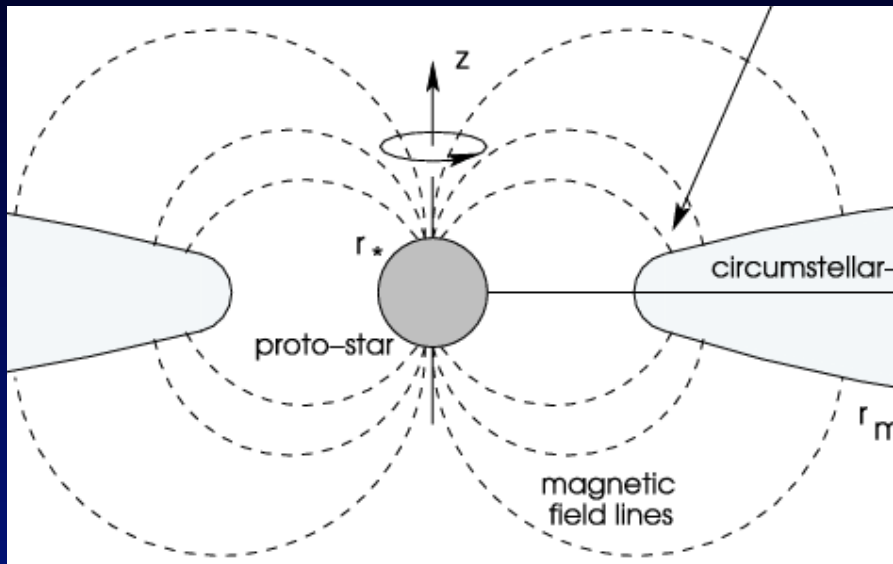
The Sun's spin axis is tilted by 7° wrt the average angular momentum vector of the planets.

Rotation of stars on the Main sequence:
massive stars rotate faster than the lower-mass stars.

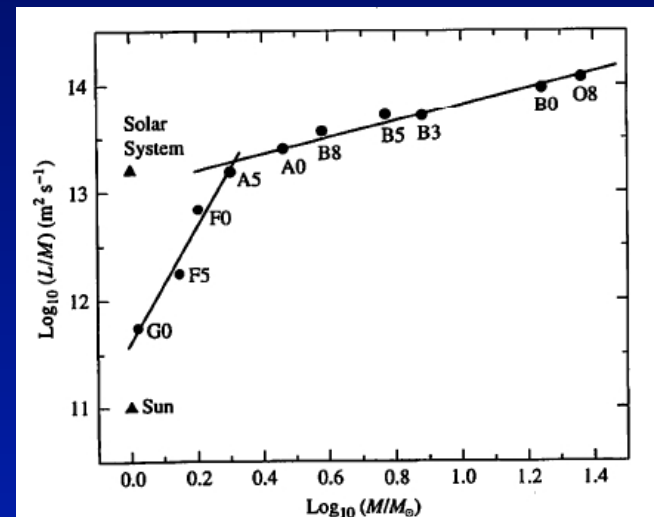
If the total angular momentum of the solar system is plotted for the Sun...



The angular momentum problem may be solved by the transport of angular momentum outward via plasma drag in a corotating magnetic field. Solar wind helps, too.

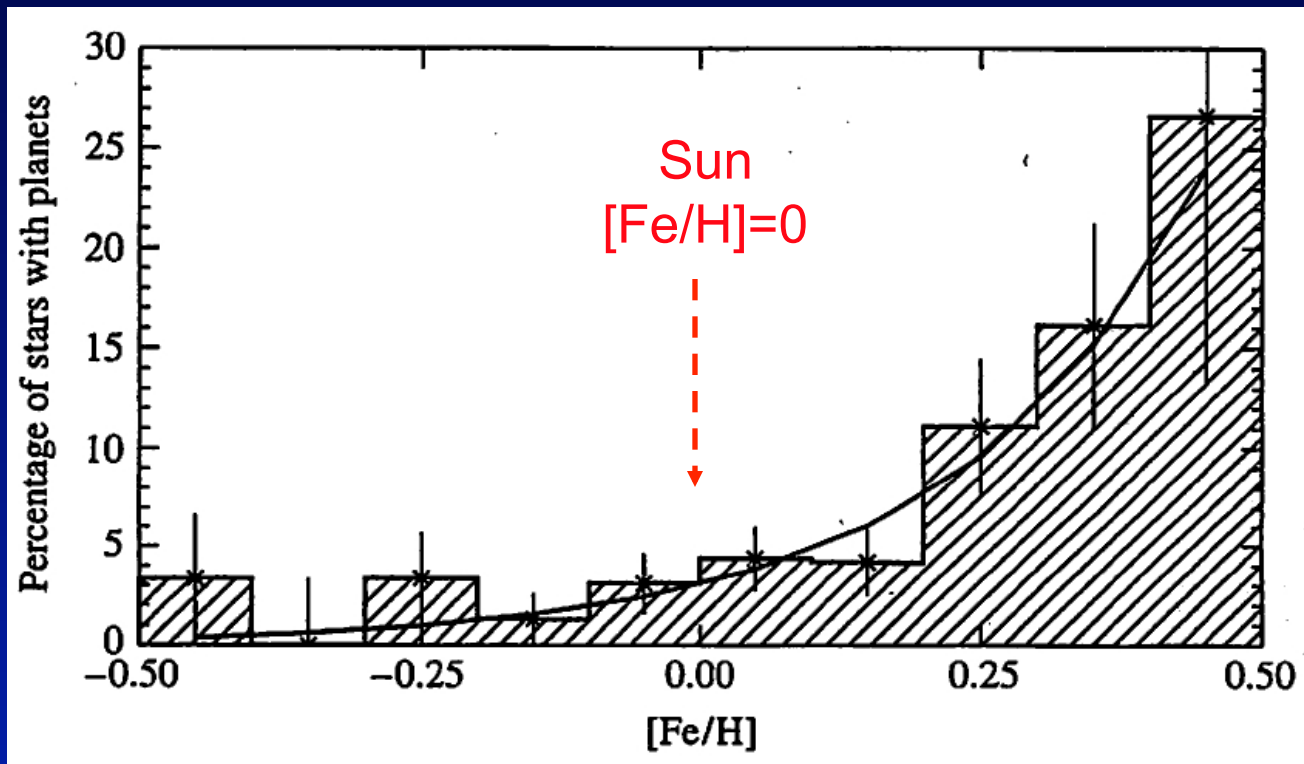


The slope change in the $L/M - M$ plot occurs at stellar masses corresponding to the onset of surface convection in low-mass stars \Rightarrow magnetic field \Rightarrow corona \Rightarrow mass loss (stellar wind)



Stars with metallicities similar to or higher than the Sun may form planets.

How does the star/planet formation model explain the composition differences between terrestrial and Jovian planets, between rocky and icy moons, across the asteroid belt, etc?

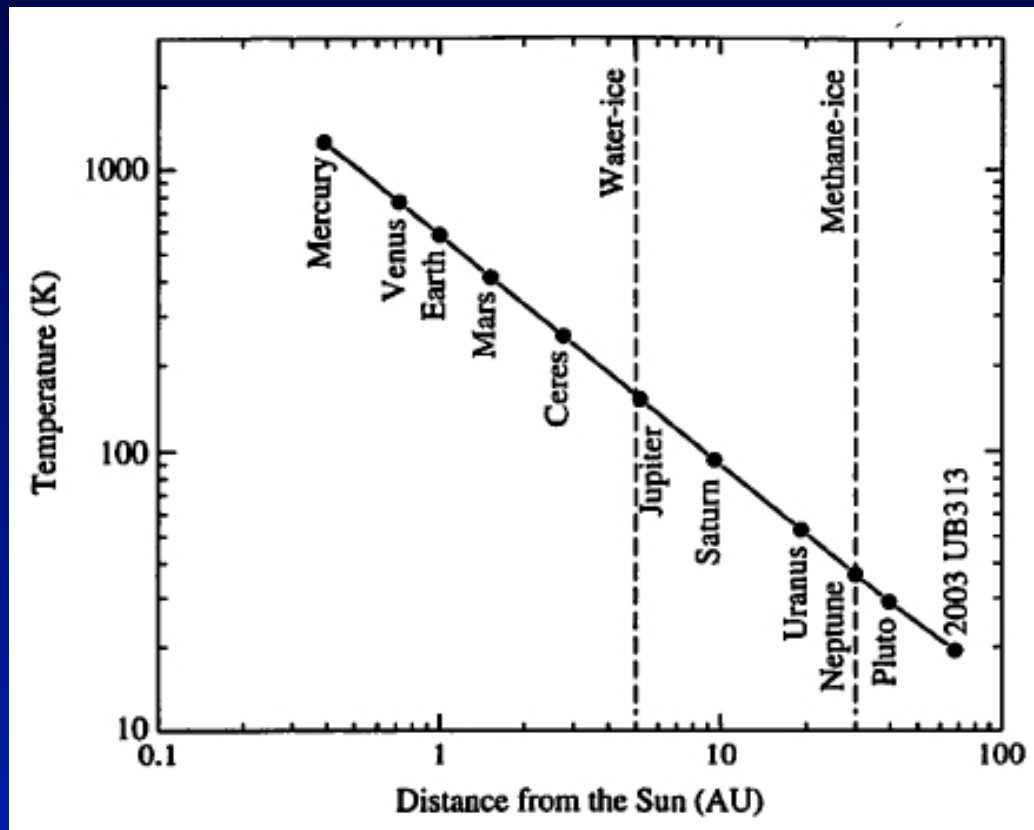


Composition/Temperature Trend in the Solar System

A temperature gradient in the accretion disk naturally explains the trend of these composition differences.

In an accretion disk, the release of gravitational energy generates heat, and the temperature is $T \propto r^{-3/4}$.

This temperature gradient existed in the solar nebula.



At ~ 5 AU,
ice line, snow line,
blizzard line

Dynamic environment:
accretion rates may
vary and the twisted
magnetic fields may
reconnect and
generate outbursts.

Consequences of Heavy Bombardment

The solar system has a wide range of objects: small rocky planets, gas giants, icy giants, moons, rings, asteroids, comets, KBOs, meteoroids, dust.

Evidence of collisions:

- cratered surfaces on objects of all sizes
- high mass density of Mercury
- extremely volatile-poor composition of the Moon
- heavy bombardment until 700 My after the Moon was formed
- the huge Herschel crater on Mimas
- retrograde rotation of Uranus and Pluto
- spin axis tilt of planets (except Venus and Mars - tidal)

These require collisions of planets or protoplanets with large planetesimals.

Constraints Imposed by Timescales

Collapse of a molecular cloud $\sim 10^5$ yr.

Onset of violent T-Tauri and FU Orionis activity and extensive mass loss follows the initial collapse in some 10^5 to 10^7 yr.

\Rightarrow the remaining dust and gas will be blown away in 10 Myr.

The inclusion of radioactive Al in carbonaceous chondrites indicates that meteorites have to be formed within a few Myr from the creation of unstable Al, either SNe or FU Ori.

Sun's age 4.57 Gyr, Allende meteorites 4.566 Gyr

\Rightarrow Formed rapidly after the Sun was born.

The lunar surface underwent a late spike of heavy bombardment ~ 700 Myr after the Moon formed.

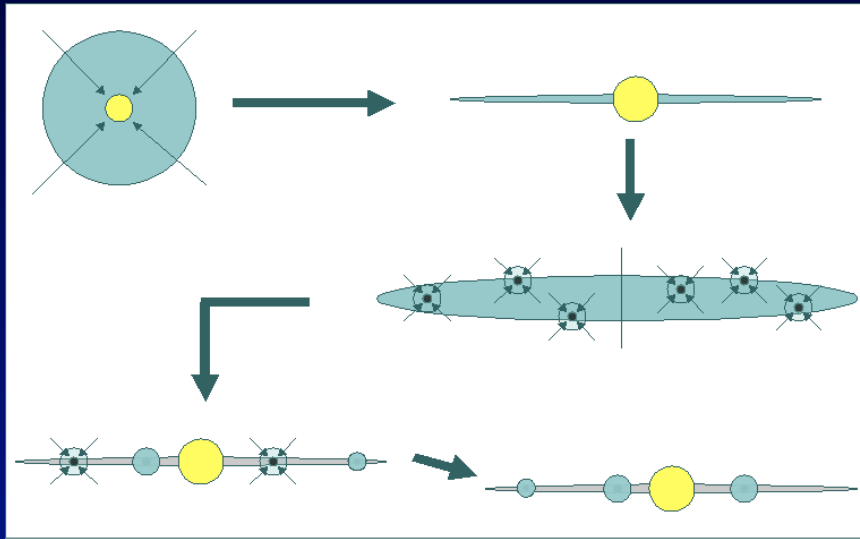
Planets grow and migrate in accretion nebulae inward.

A protoplanet can migrate 5 AU within 1-10 Myr.

All objects large or small must be formed in 4.75 Gyr.

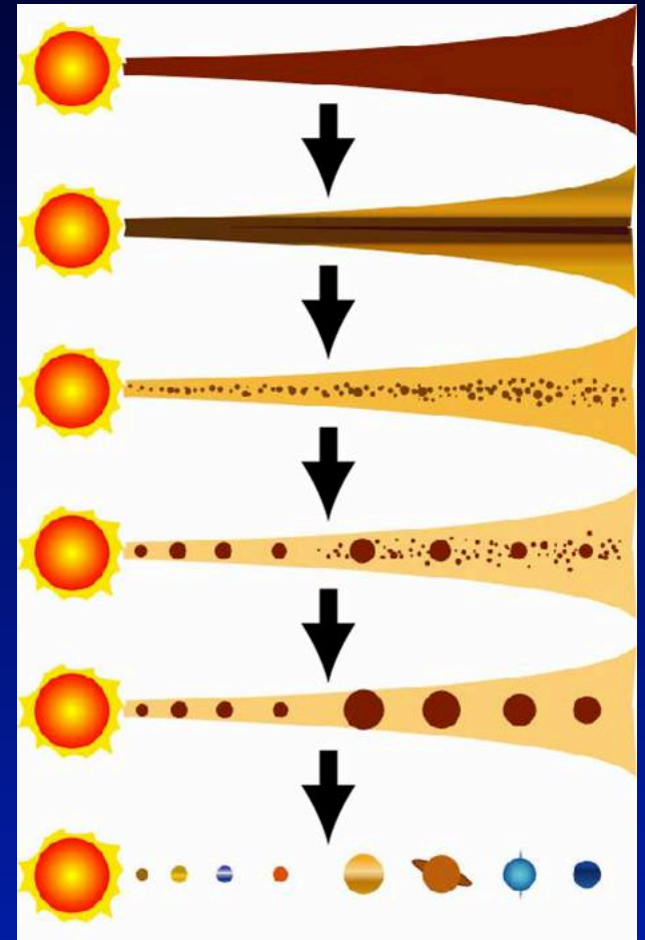
Two Competing Formation Mechanisms

Gravitational instability - “top-down”



This model does not allow Uranus and Neptune enough time to form, and it cannot explain the formation of smaller objects.

Accretion - “bottom up”



In the solar nebula, particles collide and stick together. Large objects begin to gravitationally influence others.

“Hill radius” is the distance from a planetesimal where orbital period of a test particle around the planetesimal = orbital period of the planetesimal around the Sun.

Kepler’s third law:
$$P = 2\pi \sqrt{\frac{R^3}{GM}}$$

At a distance a from the Sun,
$$\sqrt{\frac{a^3}{M_\odot}} = \sqrt{\frac{R_H^3}{M}}.$$

The Hill radius is
$$R_H = \left(\frac{M}{M_\odot}\right)^{1/3} a.$$

The planetesimal’s mass $M = \frac{4}{3}\pi R^3 \rho$, thus

$$R_H = R/\alpha, \text{ where } \alpha \equiv \left(\frac{\rho_\odot}{\rho}\right)^{1/3} \frac{R_\odot}{a}.$$

A particle coming within $1 R_H$ with a low velocity can become gravitationally bound to the planetesimal.

$$R_H = R/\alpha, \text{ where } \alpha \equiv \left(\frac{\rho_{\odot}}{\rho}\right)^{1/3} \frac{R_{\odot}}{a}.$$

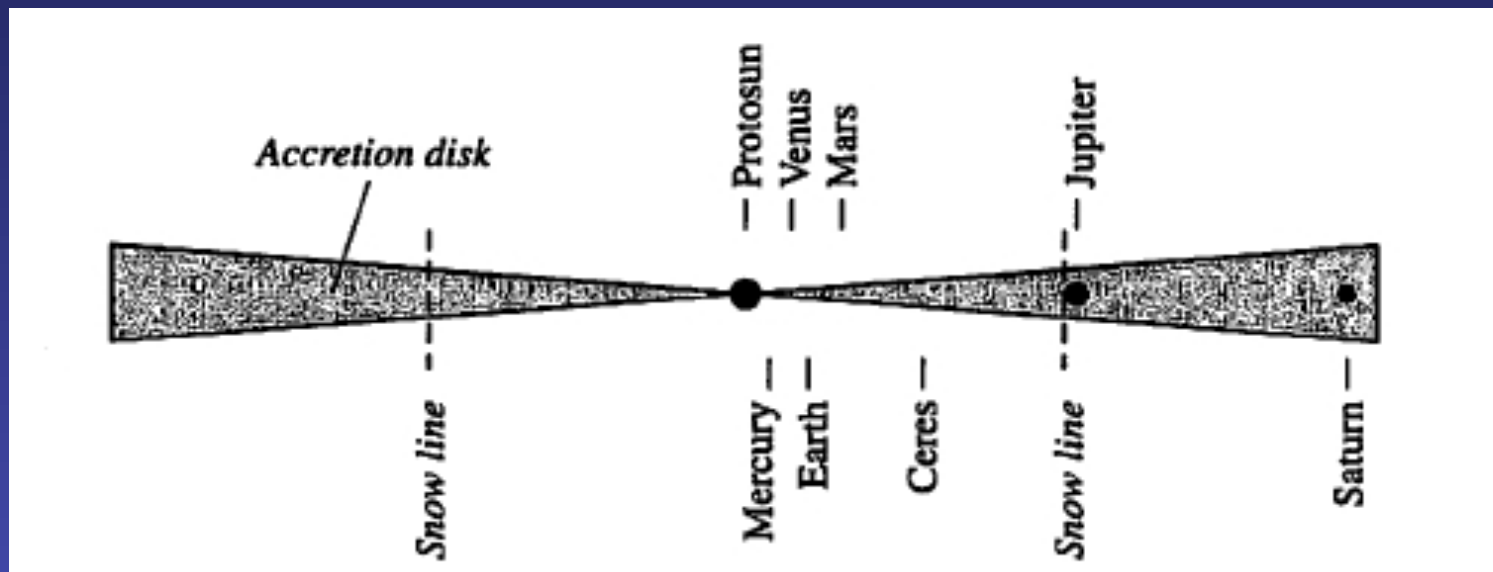
For a planetesimal of density 0.8 g/cm^3 and radius 10 km , located at 5 AU from the Sun (density 1.41 g/cm^3 , the planetesimal's Hill radius is $8.9 \times 10^6 \text{ m} = 1.4 \text{ Earth radii}$.

This planetesimal is similar to present-day cometary nuclei.

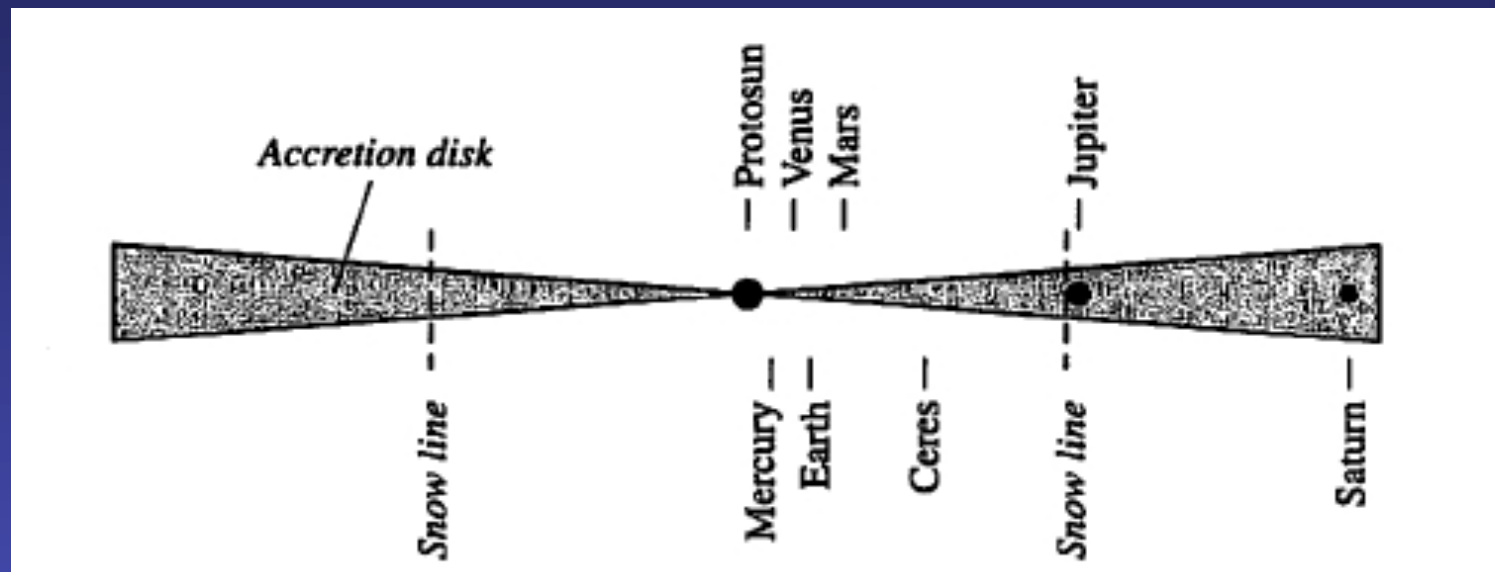
Low-energy collisions => planetesimals formed and grew
Within 5 AU, the accreting particles were composed of
CAIs, silicates, Fe, Ni.

At distance > 5 AU, just inside Jupiter's present-day orbit,
water-ice could form and be included in planetesimals.
Further out, ~30 AU, methane-ice could form and be
included.

Thanks to the water-ice and rocky material, Jupiter grew fast.
When Jupiter's core reached $10\text{-}15\ M_{\oplus}$, its gravitational
influence is strong enough to form its own accretion disk.



Saturn, Uranus, and Neptune also developed cores of 10-15 M_{\oplus} , but they were further out where density is low. Thus, they were unable to acquire the amount of gas that Jupiter captured during the same period of time.



In the inner portion, temperature is high, so no volatiles could condense out. The most refractory elements first condense out to form the CAIs, then the silicates followed. Low-velocity collisions => stick together => planetesimals

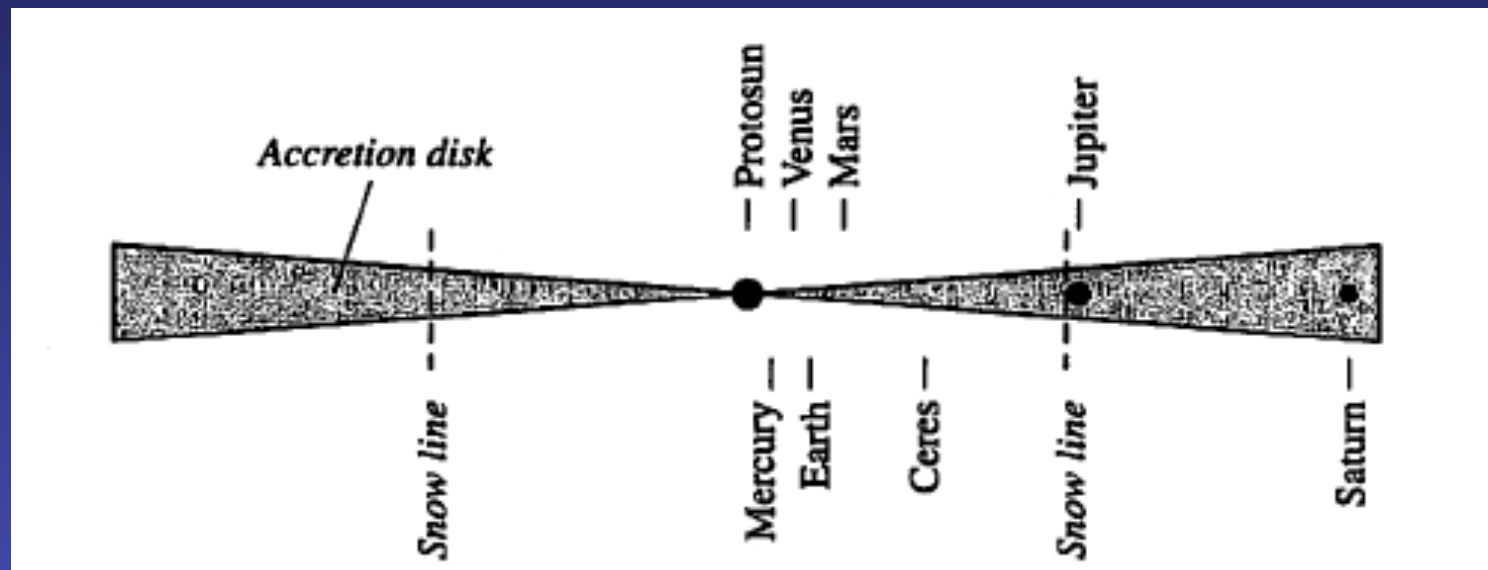
~100 planetasimals roughly the size of the Moon

~ 10 with masses comparable to Mercury

~ several as large as Mars

The large ones got incorporated into Venus and Earth.

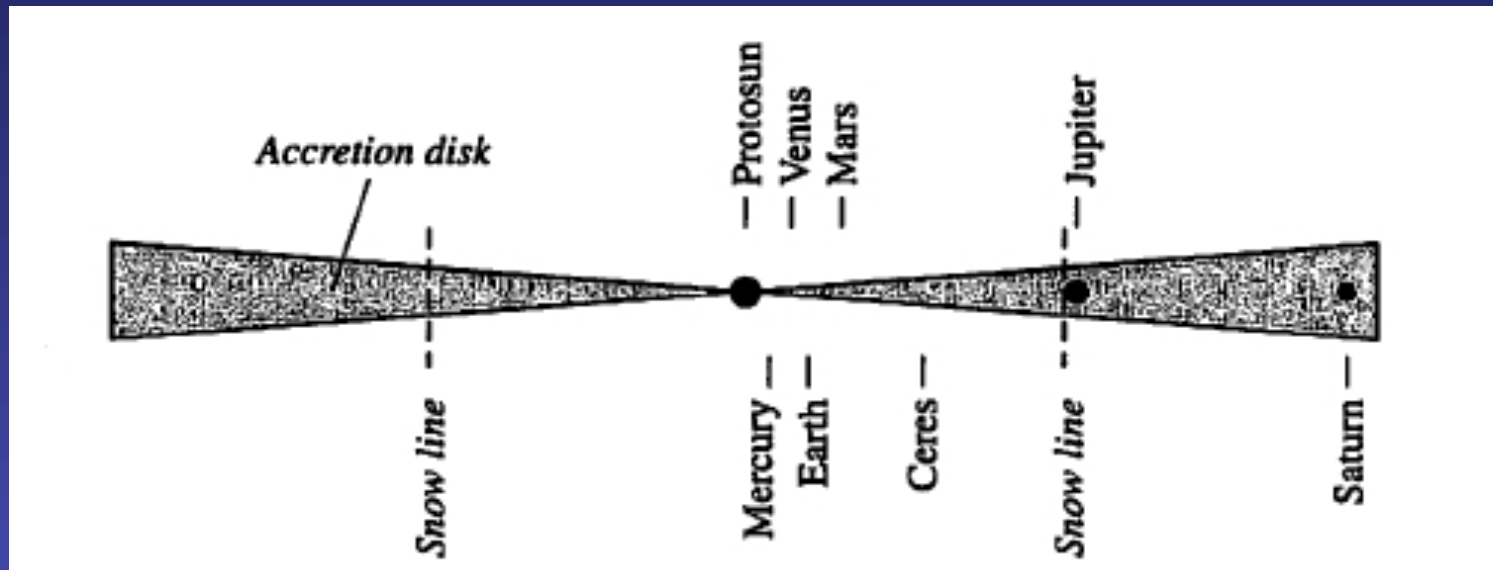
Heating => gravitational separation => chemical differentiation



Jupiter, just beyond 5 AU, gravitationally perturbs the planetesimals in its vicinity.

The asteroid belt objects have their orbits “pumped up” into more and more eccentric orbits. Some were absorbed by Jupiter, and some got ejected from the Solar System.

This process reduced the “feeding zone” of Mars. Perturbations also lead to higher velocity collisions. Double whammy!



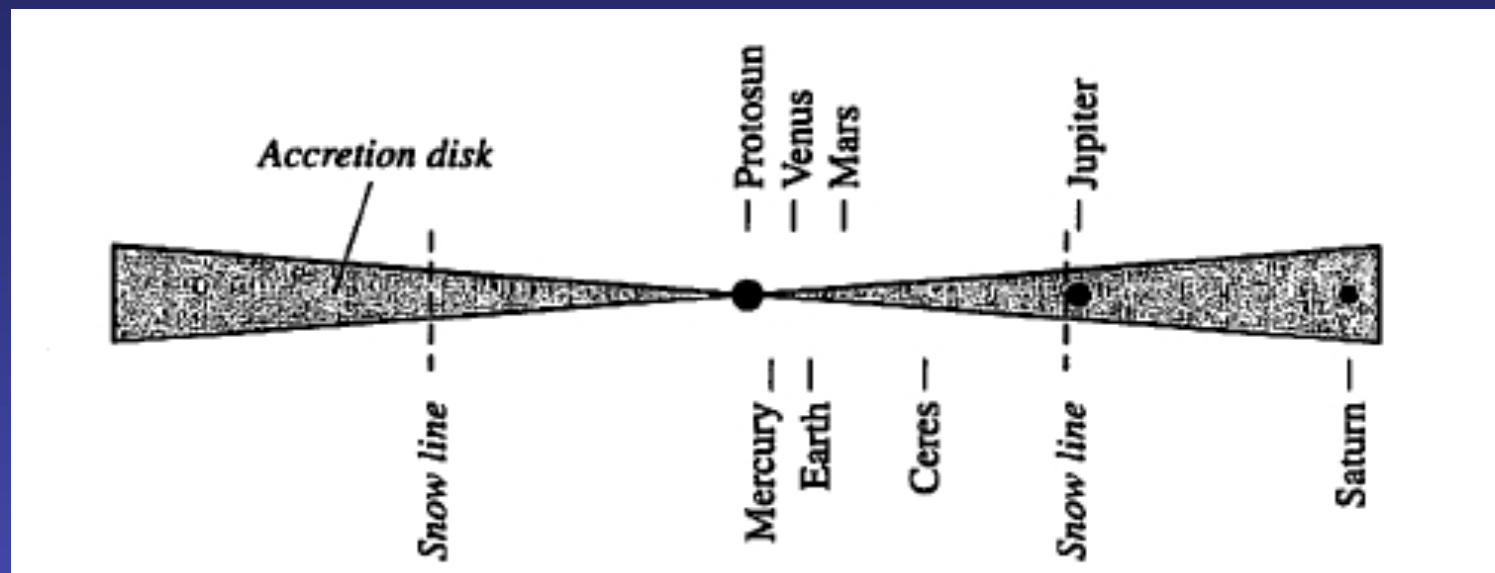
As planetesimals grew, they also collided with one another.

Mercury lost its mantle through collision.

Earth-Moon system formed in a collision.

Collisions lead to planets' axis tilts.

Before terrestrial planets finished feeding on planetesimals, the Sun ignited thermonuclear reaction, and started the T Tauri phase with wind clearing out the remaining dust/gas.



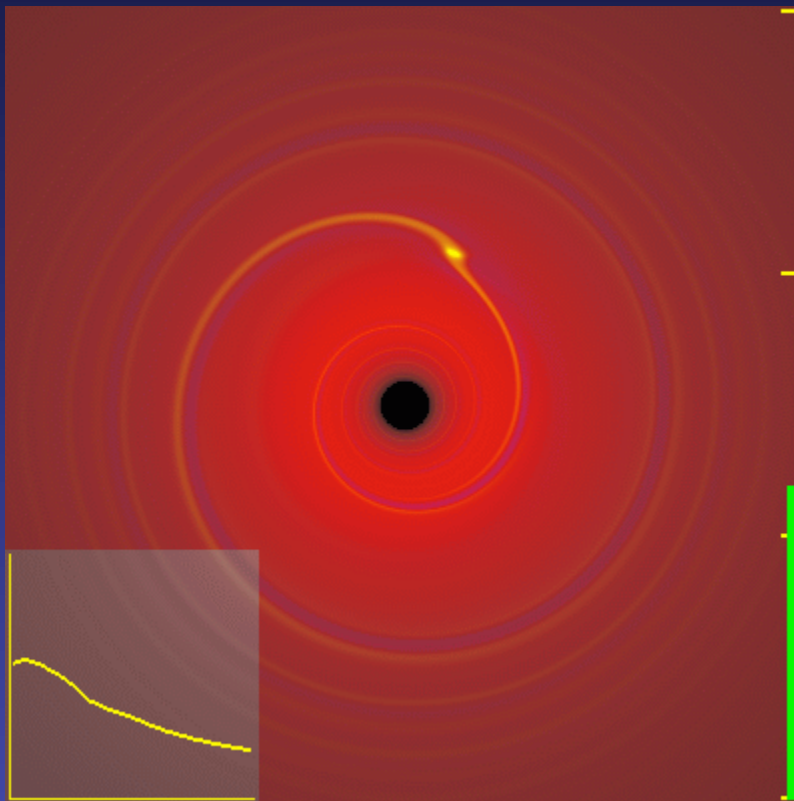
The discovery of “hot Jupiters” suggests that planets migrated inward while they were forming.

Type I - density wave in the disk;

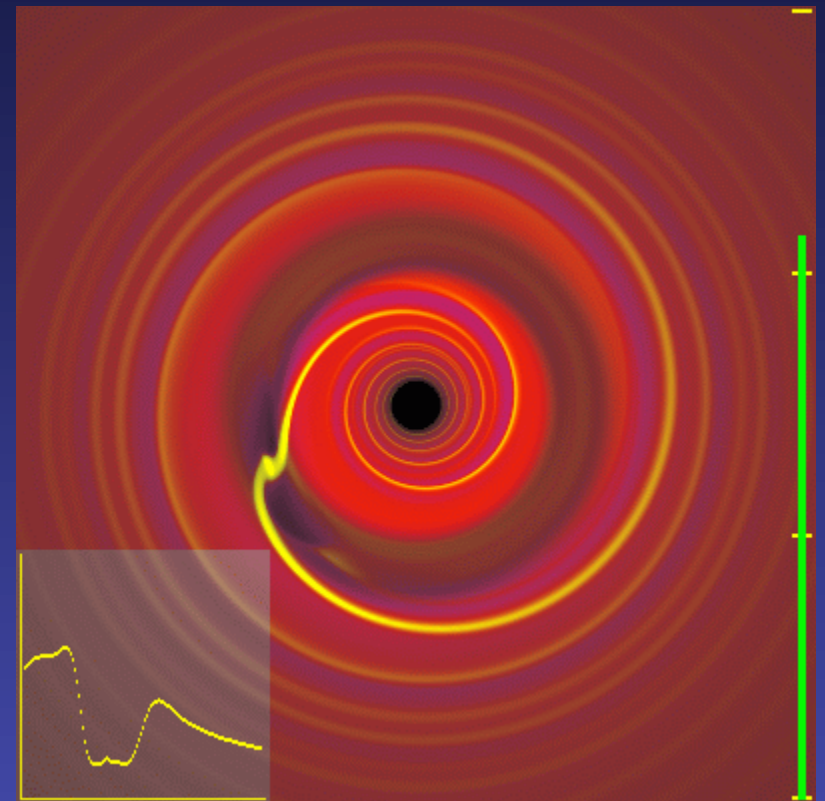
mass inward, angular momentum outward

Type II - viscosity in the disk

Type I migration



Type II migration

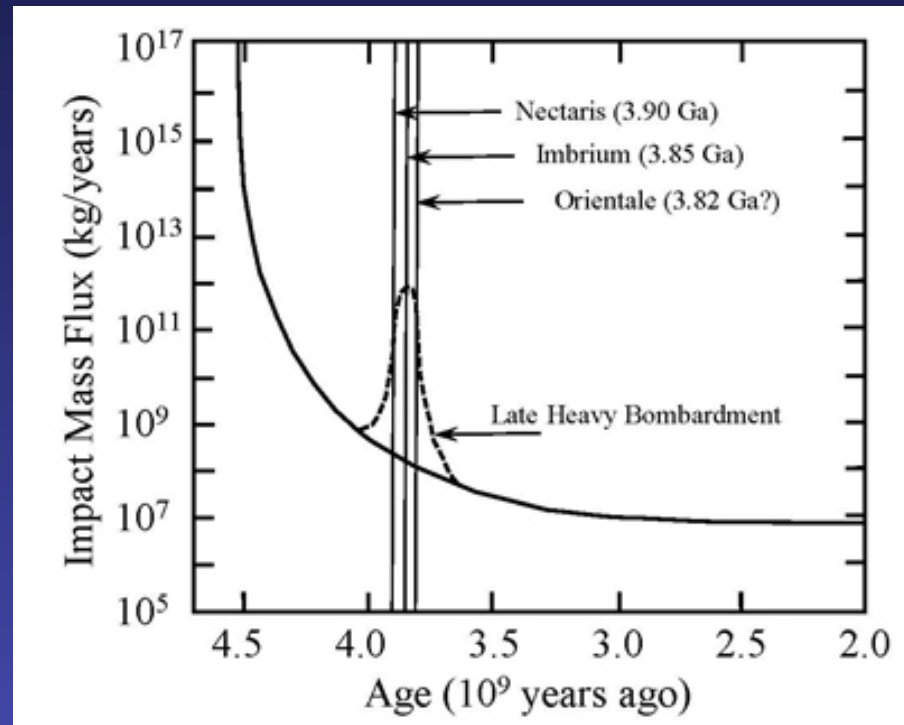


Jupiter migrated from 5.7 AU to 5 AU from the Sun.

For a short period in the past, Jupiter and Saturn had a 2:1 resonance in orbital periods. The combined perturbation in the Asteroid Belt and Kuiper Belt caused the episode of late heavy bombardment recorded on the lunar surface.

About 700 Myr after the formation of the inner planets and the Moon.

Neptune migrated outward and pumped up the Oort Cloud.



Where did Chondrules come from?
They were formed from molten droplets.

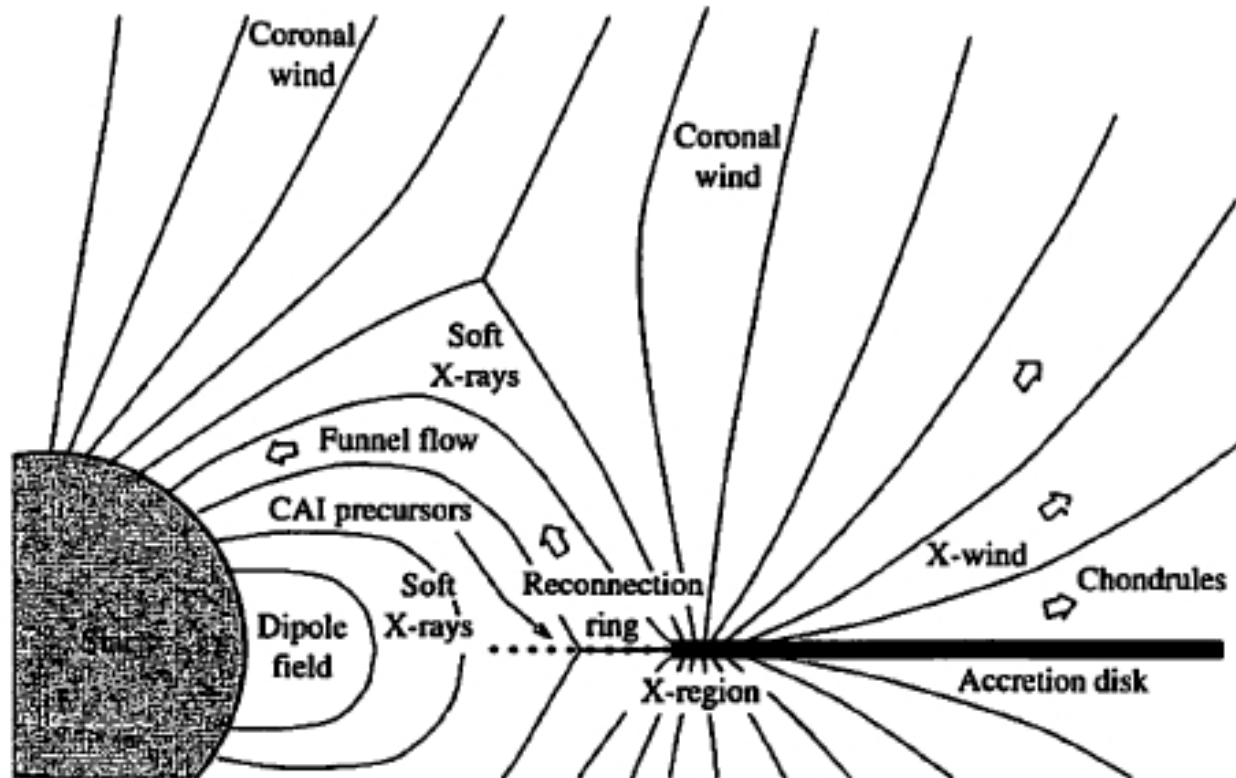
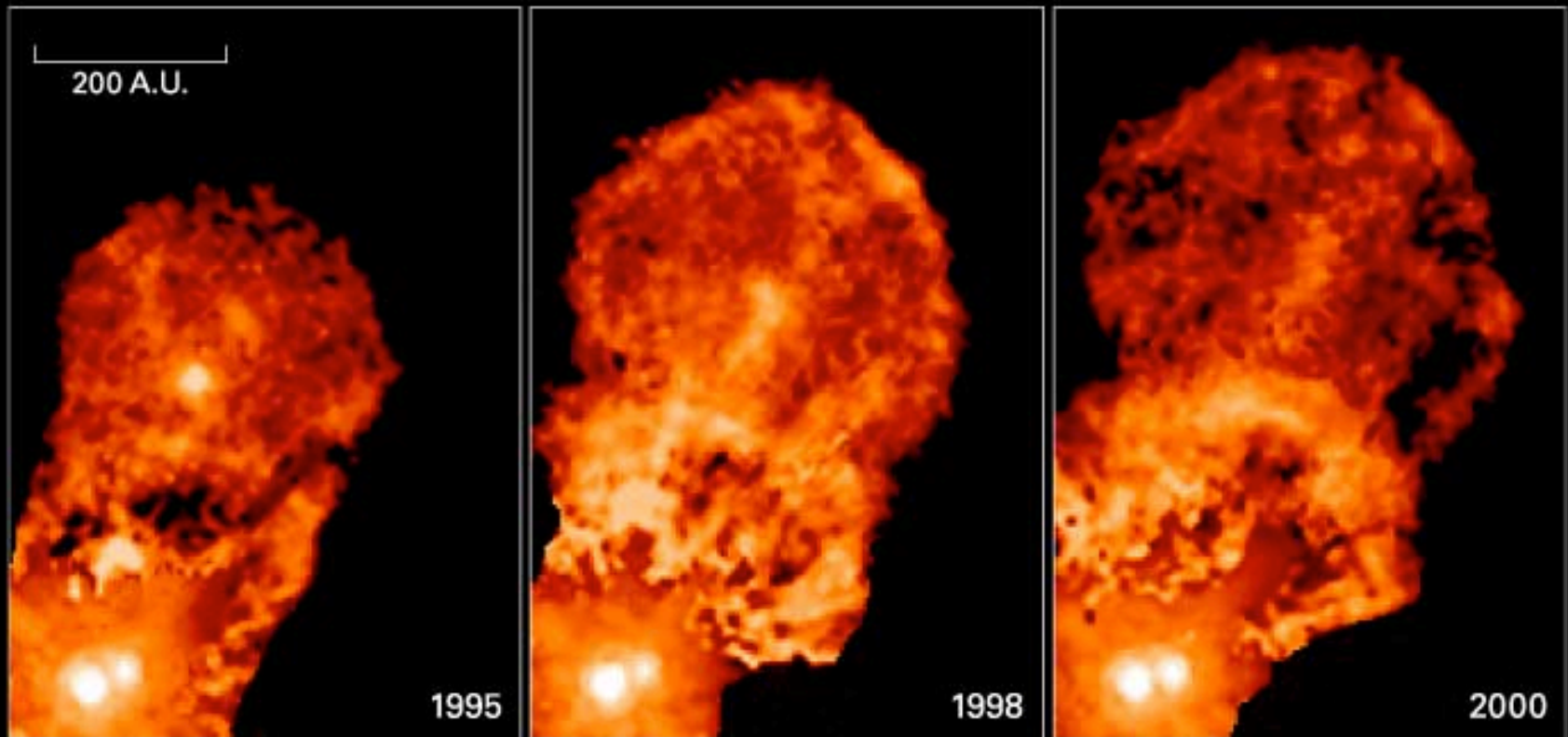


FIGURE 23.11 A schematic diagram of the X-wind model. (Figure adapted from Shu et al., *Ap. J.*, 548, 1029, 2001.)



Hot Gas Bubble Ejected by Binary Star XZ Tauri
Hubble Space Telescope • WFPC2

NASA and J. Krist (STScI) • STScI-PRC00-32

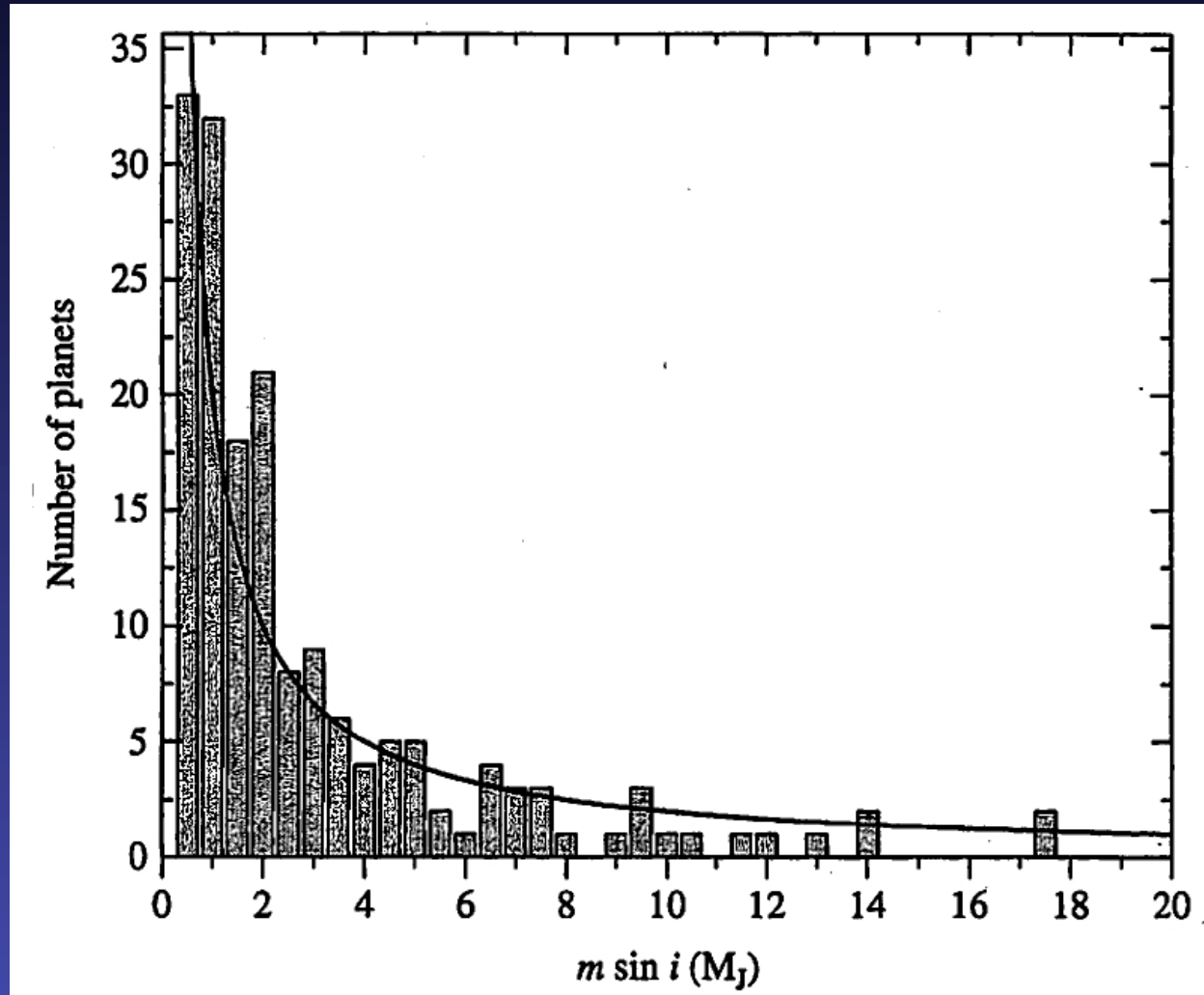
The Sun was formed near a supernova remnant.
This might be common. For example, N63.



Green - $H\alpha$ (ionized gas); Red - $8\ \mu\text{m}$ (dust); Blue - X-ray (SNR)

Initially, only planets with large mass or short orbital periods are detected, but this selection effect is gradually eliminated with a large number of exoplanets discovered.

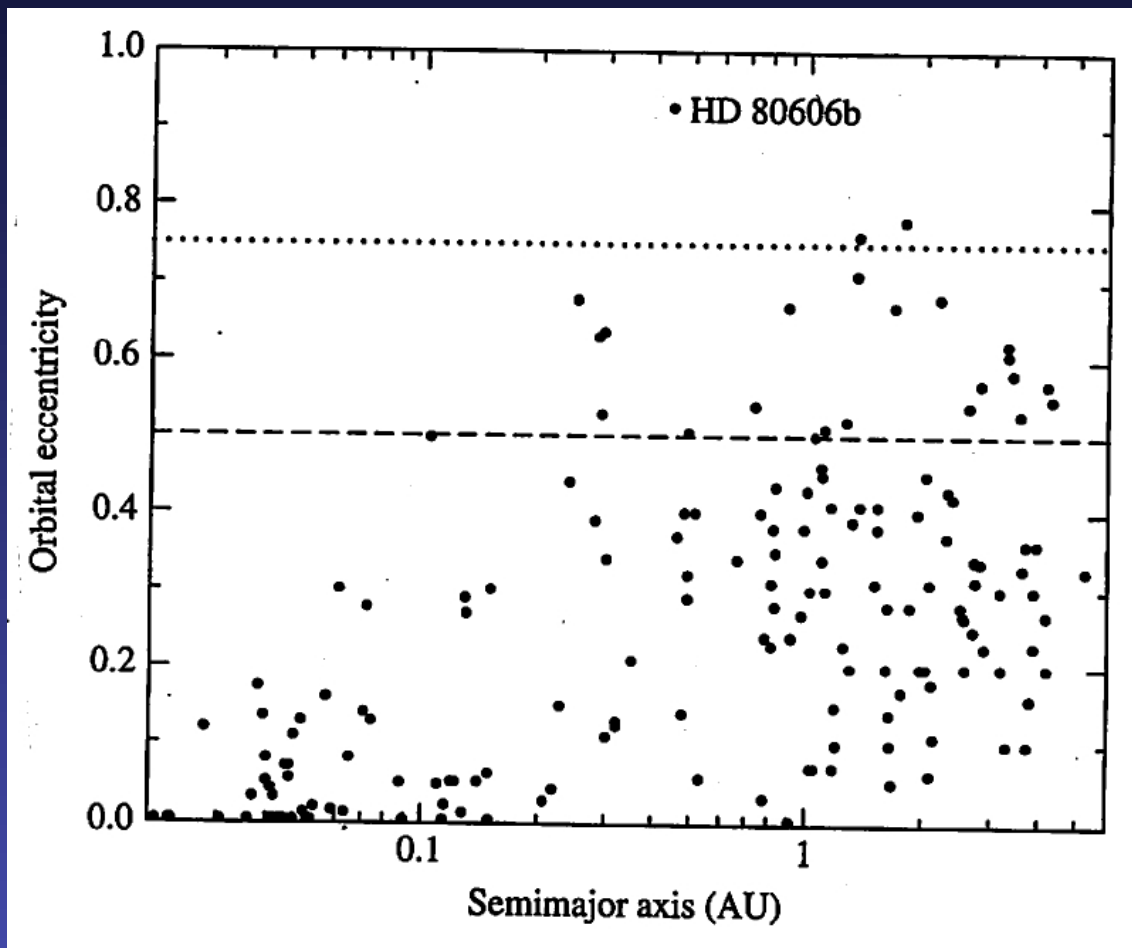
Mass distribution of exoplanet : $dN/dM \propto M^{-1}$



Distribution of Orbital Eccentricities

Planets orbit close to their parent stars have more circularized orbits, due to tidal interaction with stars. Most exoplanets have $e < 0.5$.

Planets with the largest e are in binary star systems.

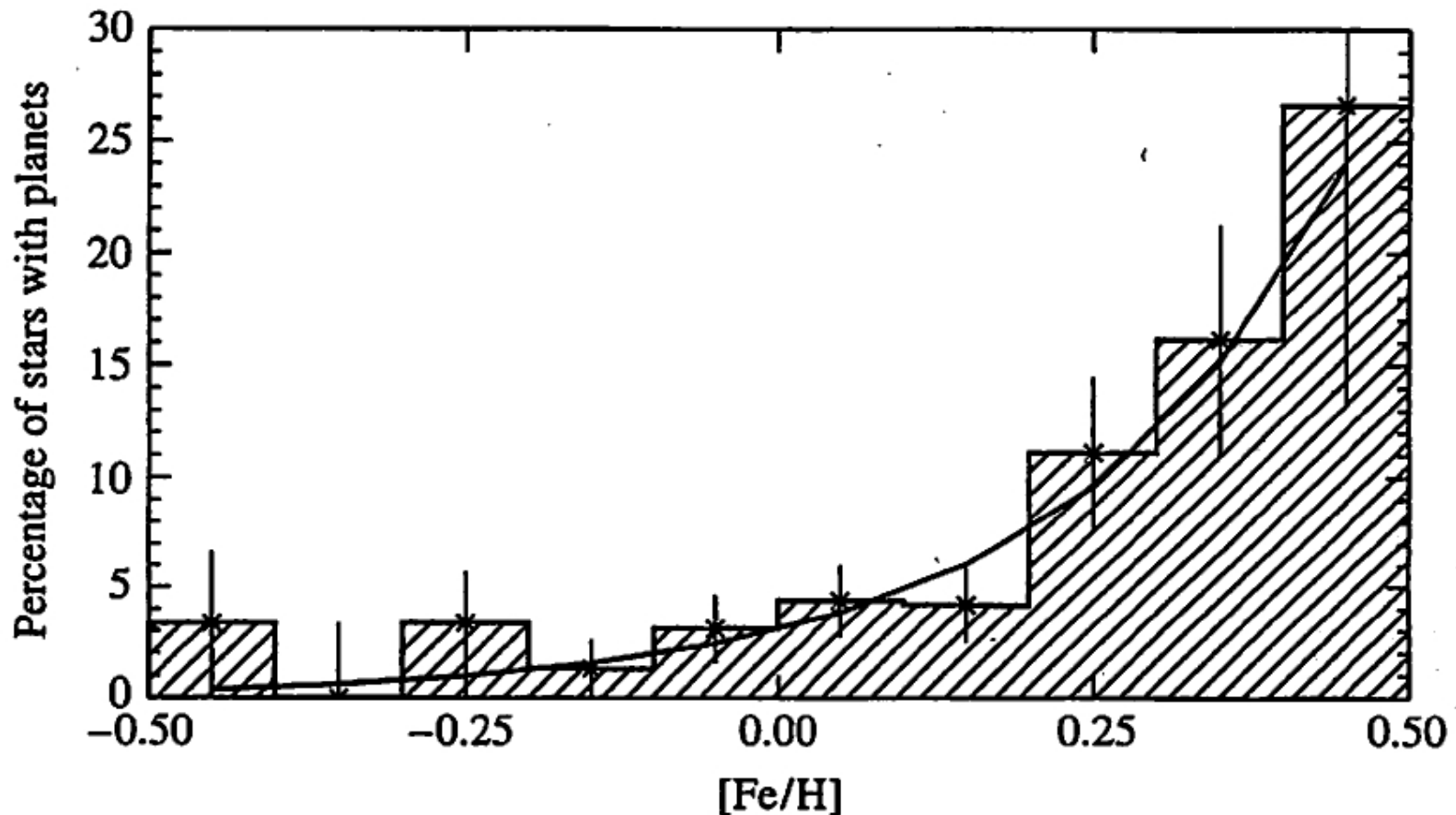


Exoplanets are found around stars with high metallicities.

Metallicity: $[\text{Fe}/\text{H}] \equiv \log_{10} \left[\frac{(N_{\text{Fe}}/N_{\text{H}})_{\text{star}}}{(N_{\text{Fe}}/N_{\text{H}})_{\odot}} \right]$

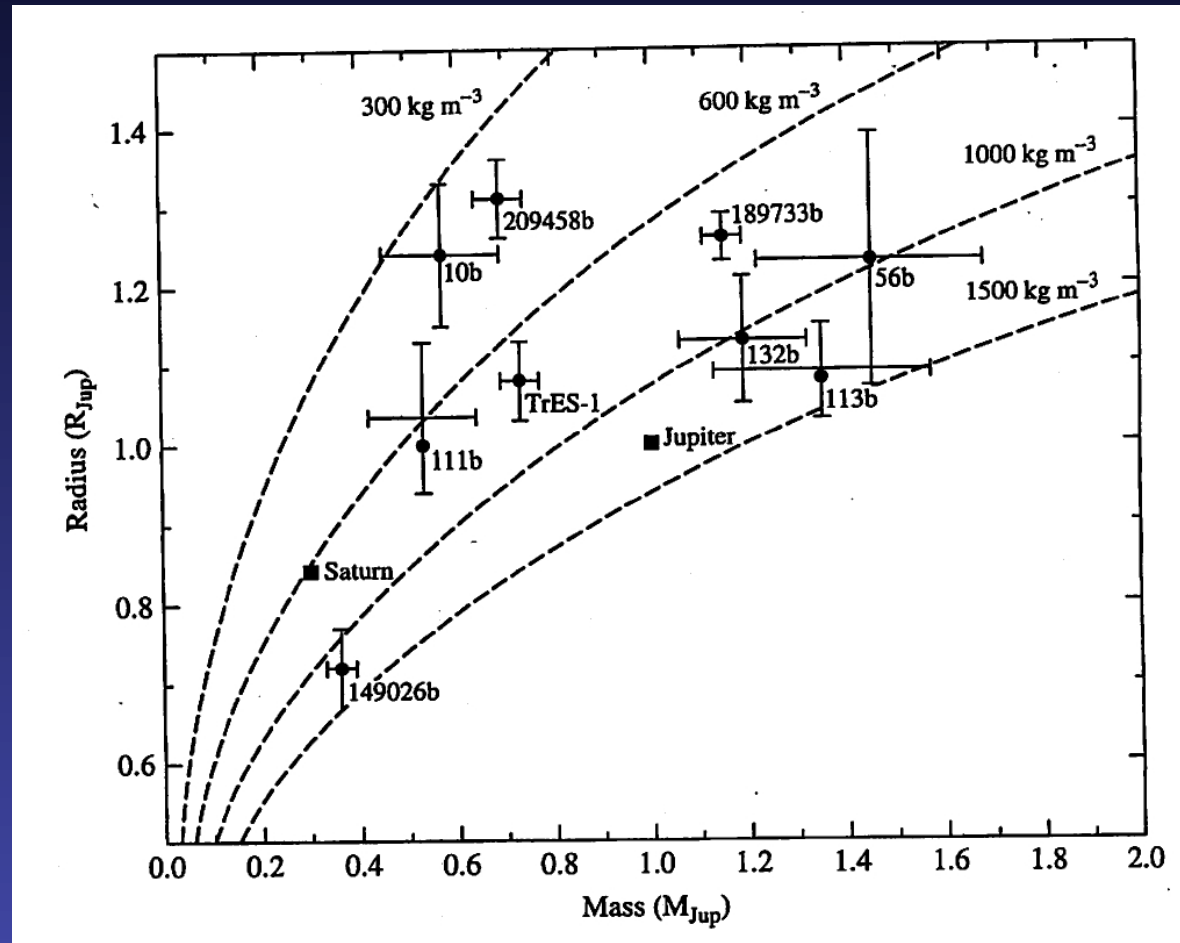
Milky Way stars have $[\text{Fe}/\text{H}] = -5.4$ to 0.6 .

Exoplanets are found only around stars with $[\text{Fe}/\text{H}] > -0.5$.



“Hot Jupiters” - close orbits to star, heated by tidal interaction?

HD 149026b has a rocky core.



The detection of planetary atmosphere would be exciting, but very difficult.

This is done only through differencing spectra outside and during a planet transit.

The absorption due to planet's atmosphere causes 2.3×10^{-4} difference in spectral features.

Needs a spectrograph with very stable and pure optics.

Distinction between brown dwarfs and planets

Formation mechanism:

- BD is formed from collapse of a cloud

- Planets are formed in accretion disks of stars

Mass criterion, burning of deuterium

- BD mass range $13 - 75 M_J$

- Planets mass $< 13 M_J$

The latter is preferred.