ASTM001/MAS423 Solar System
Solar Nebula & Planet Formation

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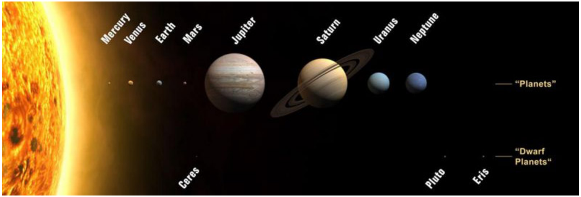
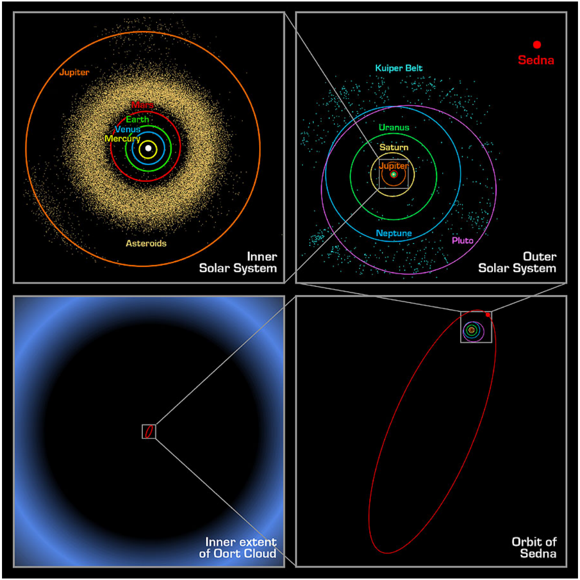
Outline

- The solar system we have today
  (what we have to explain).
- Review basic ideas of solar nebula.
  The so-called *Minimum Mass Solar Nebula* or (MMSN)
- Derive mass accretion rate of a solid planet.
  - 'Orderly' accretion.
  - 'Runaway' accretion
- Discuss implications



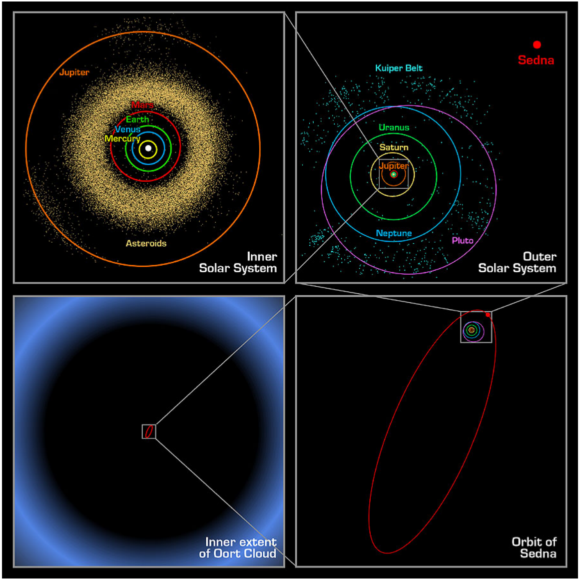
Solar system structure: Inner system

- Terrestrial Planets
  - Mercury 0.39 AU
  - Venus 0.72 AU
  - Earth 1.00 AU
  - Mars 1.52 AU
- Asteroid belt
  - Thousands of bodies
  - Dynamical clusters in a, e, I. Collisional Families
  - Sizes: Dust $\rightarrow$ $R \sim 500$ km (Ceres)



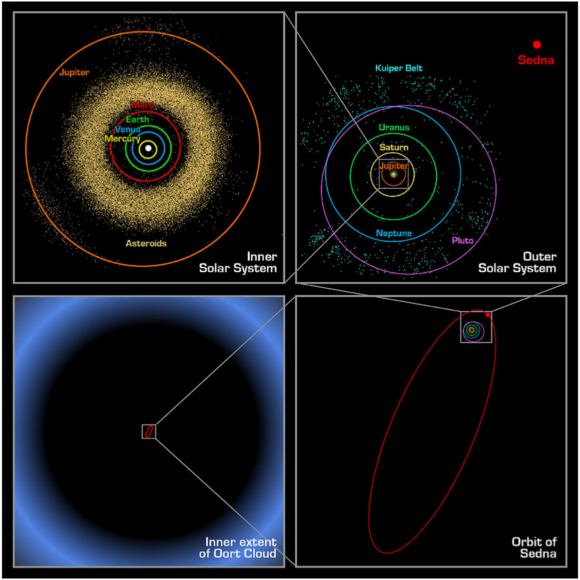
Solar system structure: the giants

- Gas giant planets
  - Jupiter 5.2 AU
  - Saturn 9.6 AU
- Ice giant planets
  - Uranus 19.2 AU
  - Neptune 30.1 AU



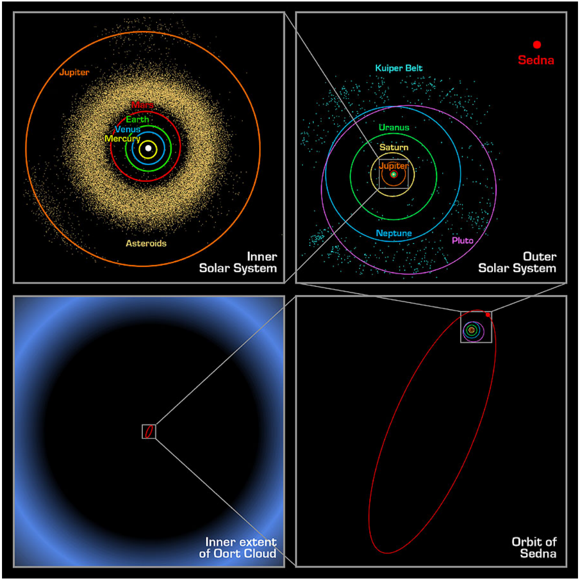
Solar system structure: the dark cold depths

- Kuiper belt (30 AU - 50ish AU)
  - Now over 1,000 known objects (KBOs)
  - Several dynamical and spectral groupings. Collisional families?
  - *Ice dwarf* planets (Eris, Pluto, Sedna ...).
  - Sizes: Dust $\rightarrow R \sim 1200$ km (Eris)
  - Largest seem to have satellites (are binary).

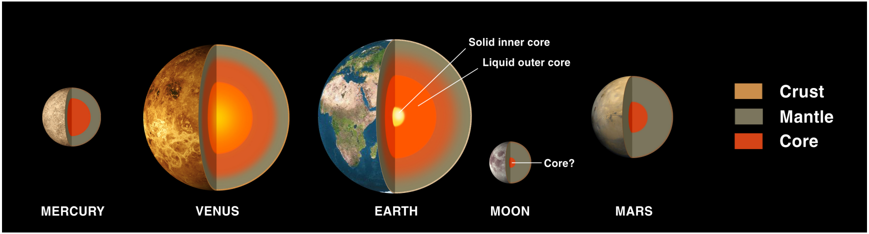


Solar system structure: the dark cold depths

- Oort cloud
  - Long period comet reservoir
  - Roughly spherical cloud
  - Inner edge: $\sim 2 \times 10^3$ AU
  - Outer edge: $\sim 50 - 100 \times 10^3$ AU
  - Ejected debris from planet formation?



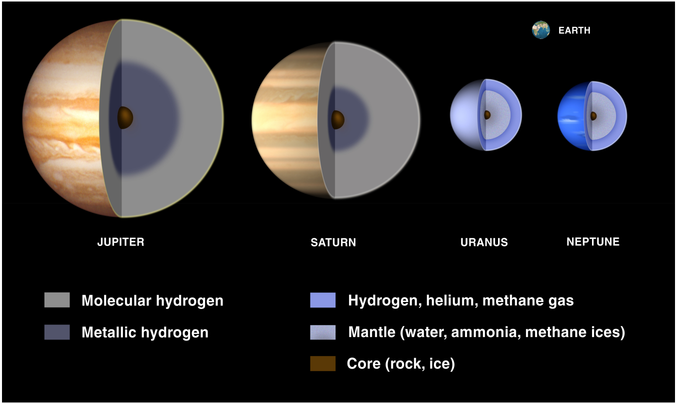
Planetary Composition: Terrestrial planets



- Surfaces/mantles appear rich in silicates
- Iron/Nickel rich cores
- Mercury has large density, suggesting a large core
- Earth has an abnormally large Moon, $(m_m/M_\oplus \sim 10^{-2})$
- Moon may have no core at all?

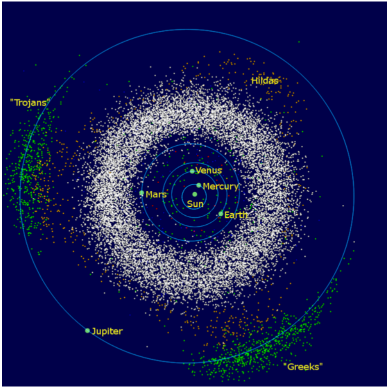
What drove settling of iron to the centers of the terrestrial planets?

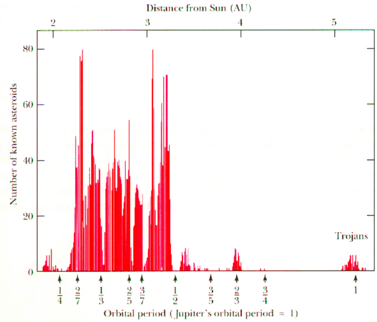
Planetary Composition: Giant planets



- Rock/ice cores of $\sim 10 M_\oplus$ are inferred.
- Jupiter and Saturn have large gaseous envelopes of H_2
- Uranus & Neptune have a few $M_\oplus$ of gas.
- All have extensive systems of satellites
  - Close-in large regular satellites
  - Distant smallish irregular satellites

Asteroids





- Planetary building blocks that . . .
  - never grew up
  - have been steadily ground down
- Perturbations from Jupiter tend to excite e and I
- Appear devoid near mean motion resonances.
- Compositions vary; rock, ice and mixtures
- Meteorite record suggests a few have differentiated. (how?)

Dynamical state of solar system

Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Nept
7°	3.4°	0°	1.85°	1.3°	2.49°	0.77°	1.7
0.2	0.0068	0.0167	0.0934	0.0485	0.0532	0.0429	0.0

- Small eccentricities and prograde inclinations suggest a disk.

  So we start with a nebular disk.
- Basic ideas of ‘nebular theory’ go back to I. Kant and P.S. Laplace (contemporary versions by V.S. Safronov).
- Adjustments come from numerical modeling.
- Major re-assessment necessary in light of extrasolar planets.

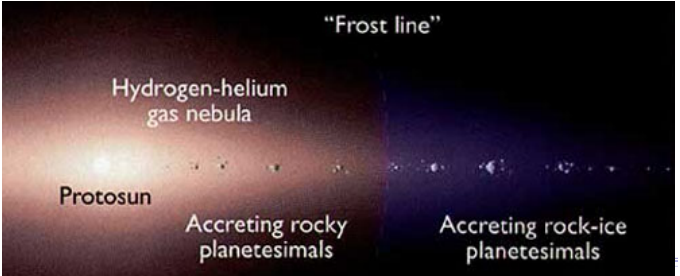
. . . but what might this disk have looked like?

Solar System Formation Overview

- Some event (e.g. nearby supernova) triggers gravitational collapse of a cloud (nebula) of dust and gas
- As the nebula collapses, it forms a spinning disk (angular momentum conservation)
- The collapse relases gravitational energy, which heats the center; the central hot portion forms the star.
- The outer, cooler particles suffer repeated collisions, building planet-sized bodies from dust-grains (this collisional accumulation is called *accretion*)
- Young stellar activity (T-Tauri phase) blows-off any remaining gas (after $\sim 1 - 10$Myr), leaving embryonic solar system.
- The nebular hypothesis suggests that the planets and Sun should all have about the same composition.
- Comets and meteorites are important because they are relatively pristine remnants of the original nebula (they are sometimes referred to as *primitive bodies*).

Minimum Mass Solar Nebula

- Oldest meteorites appear to have similar composition to the Sun's photosphere.
- So, we grind up the planets and spread them out in a disk near their current orbits.
- We 'reconstitute' them to solar abundances (mainly to get the gas:solids ratio) and examine the radial distribution of material.
- Because we're examing a flattened system, we then describe the mass distribution of the disk in terms of a mass surface density, or mass per unit area in the disk.



Minimum Mass Solar Nebula

- The surface density profile takes the form of a power-law

$$\Sigma_{solid} = \Sigma_o \eta_{ice} \left(\frac{r}{1AU}\right)^x$$
$$\Sigma_{gas} = \Sigma_o \eta_{gas} \left(\frac{r}{1AU}\right)^x$$

where

- x is the power-law exponent. Commonly set to -3/2 in MMSN. This is an empirical fit to the smoothed data.
- Σ_o is the surface density of solid material at 1AU (about 8-10 g cm^-2)
- $\eta_{gas} \approx 200$, from solar composition.
- Beyond the frost-line ($\sim$ 2.5-3AU) the solid material is enhanced by condensation of ices.

$$\eta_{ice} \sim 3 \text{ outside frost-line } \eta_{ice} = 1 \text{ inside frost-line}$$

Minimum Mass Solar Nebula - Assumptions

This basic framework is the starting point for most studies of planetary formation.
The MMSN assumes:

- Formation is 100% efficient at transfering mass from the disk to the planets. *More mass was likely needed*.
- Formation occurred locally, in *feeding zones*, and is a sort of inverse of the mass-smearing process that was used to construct the MMSN.

Numerical work suggests that the *feeding zone* concept is useful during some aspects of particle accumulations.
Also, short period extrasolar giant planets suggest they have migrated $\rightarrow$ accretion need not be local.

Stages of Planet Formation

1. Nebular disk formation
2. Condensation of dust, settling to the mid-plane, accumulation into ∼1-10km planetesimals, $\sim 10^4$ yr
3. Collisional accumulation of planetesimals into $\sim 10^3$km planetary embryos. $\sim 10^5$ yr. (*Runaway Growth*).
4. Orderly growth, embryos sweep up remaining planetesimals. Reach ∼Mars mass, $\sim 10^6$yr.
5. Collisions between embryos, Moon-forming collisions, $\sim 10^7 - 10^8$ yr. Sometimes called the 'Late stage'

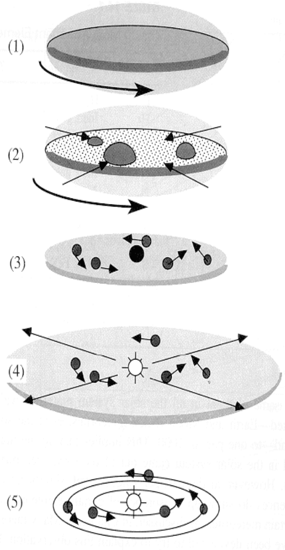


FIGURE 14.3 Five stages in the evolution of the solar nebula. (1) Starting as a disk-shaped cloud of gas and dust. . . (2) the cloud collapsed into fragments. . . (3) that began to orbit about the largest fragment, the proto-

What controls accretion rate?

- Collision Rate = (Number density) $\times$ (Collision Cross-section) $\times$ (velocity through the population).
- Mass accretion rate

$$\frac{dM}{dt} = \rho \pi R^2 \left(1 + \left[\frac{v_{esc}}{v_r} \right]^2 \right) v_r$$

- Here $v_r \sim v_{circ}(e^2 + I^2)^{1/2}$ (from CW#3)
- The escape velocity $v_e = (2GM/R)^{1/2}$
- The mass density can be written in terms of the surface density

$$\rho = \frac{\Sigma}{H} = \frac{\Sigma n}{v_r} \tag{1}$$

where $H = v_r/n$ is the disk scale height.

The Accretion Rate?

- The mass accretion rate is then

$$\frac{dM}{dt} = \Sigma n \pi R^2 \left(1 + \left[\frac{v_{esc}}{v_r}\right]^2\right) \tag{2}$$

- What happens when $v_r \gg v_e$?
- What happens when $v_r \ll v_e$?
- How does accretion rate vary with a?
- What determines the effective width of the *feeding zone*?