# Wed. Aug. 30, 2017
# Reading:

- Reading for Fri.:
  - Wood Ch. 1 (solar system overview)
- Reading for Wed.
  - Wed. Wood Ch. 6 & 8 (Asteroids & Meteorites, Solar Nebula)
- Reading for Fri. Sept. 8. Rozel et al. (link on-line)

- Discuss plans for class during the Rocky Mountain Field Trip

# Solar System Overview + Asteroids

- Today
  - Solar system overview
  - Begin Asteroids and Meteorites

- Complications:
  will address later after presenting the "classical" view
    - Many extra-solar planetary systems look VERY different that ours (many Jovian planets found in small orbits)
    - Jovian planets may "migrate" during formation,
    - The above migration can affect terrestrial planets and other objects too, mixing material from different locations in the solar system

# Relative Size of the Planets

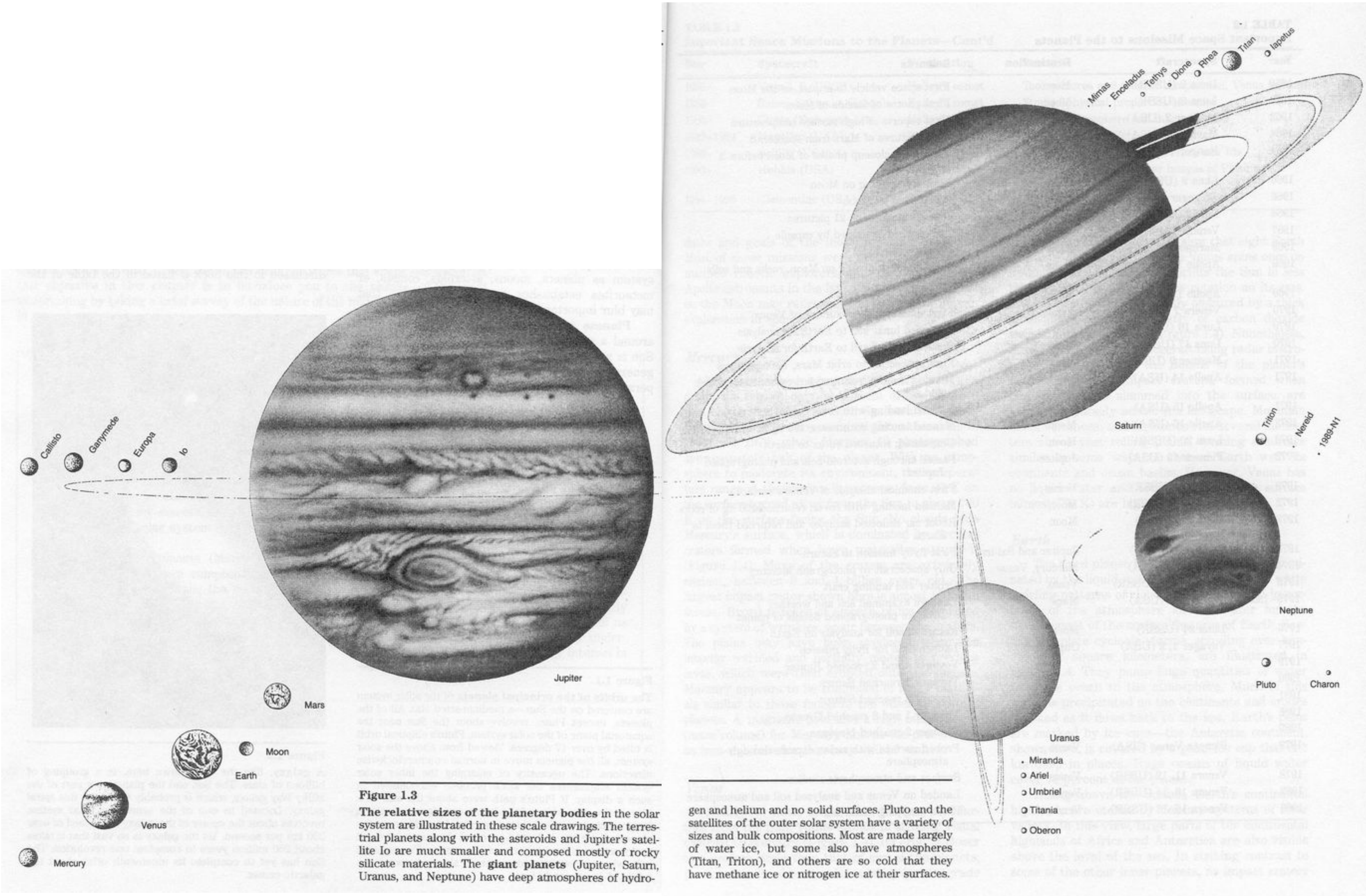
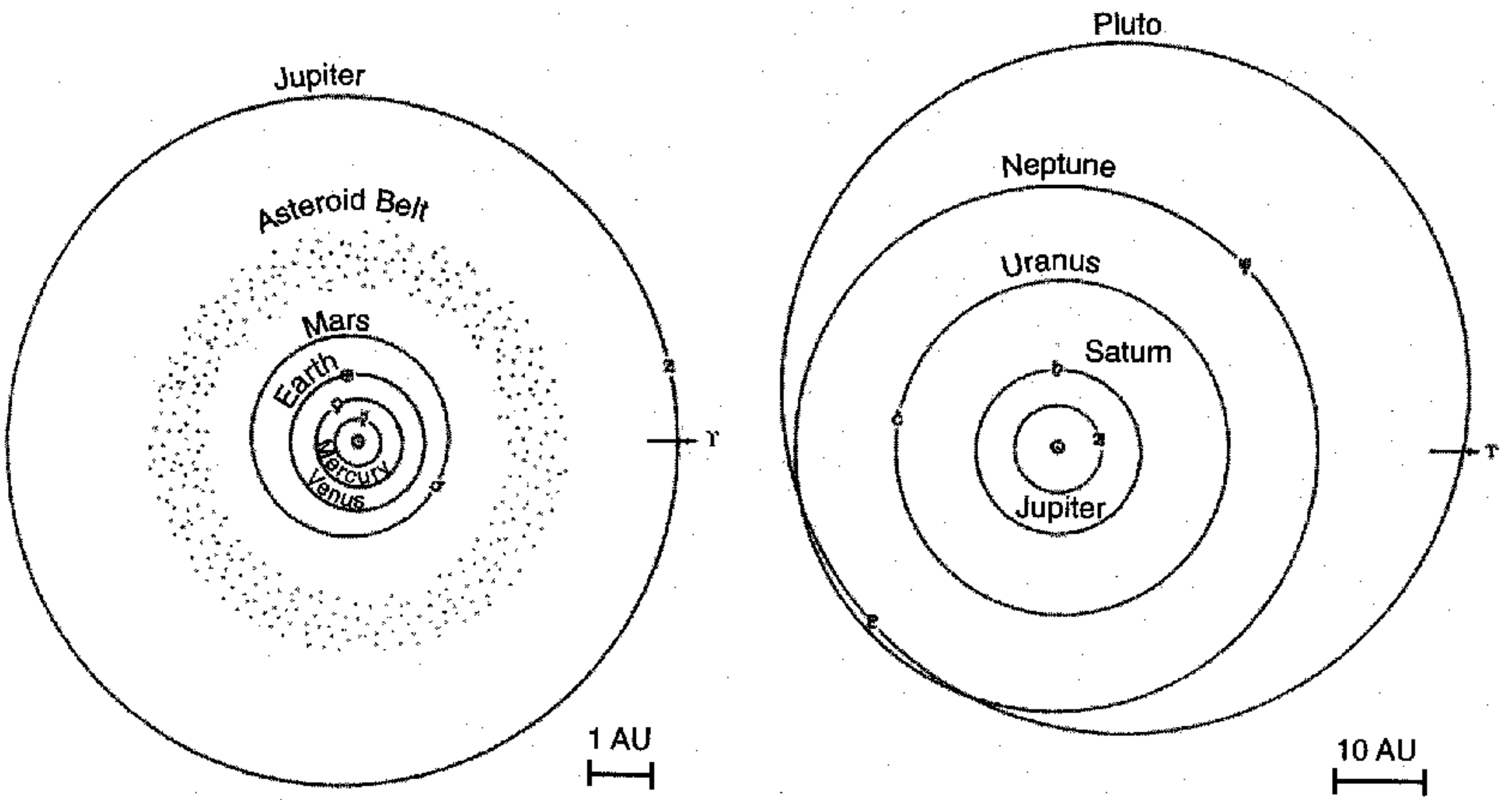



**Figure 1.3**
**The relative sizes of the planetary bodies** in the solar system are illustrated in these scale drawings. The terrestrial planets along with the asteroids and Jupiter's satellite Io are much smaller and composed mostly of rocky silicate materials. The **giant planets** (Jupiter, Saturn, Uranus, and Neptune) have deep atmospheres of hydrogen and helium and no solid surfaces. Pluto and the satellites of the outer solar system have a variety of sizes and bulk compositions. Most are made largely of water ice, but some also have atmospheres (Titan, Triton), and others are so cold that they have methane ice or nitrogen ice at their surfaces.

From Christiansen & Hamblin Fig. 1.3

# Division into inner (terrestrial) and outer (jovian) planets




A B

Figure 1.3 Map of the Solar System, to two scales. (A) Orbits of Jupiter and the terrestrial planets interior to it, and position of the asteroid belt. (B) Orbits of Jupiter and the giant planets exterior to it. ♈ is the direction of the vernal equinox, a reference axis in our galaxy. The astronomical symbol for each planet is entered at the perihelion of its orbit.

From Wood: Fig. 1.3

# Regular Spacing in Distance from Sun

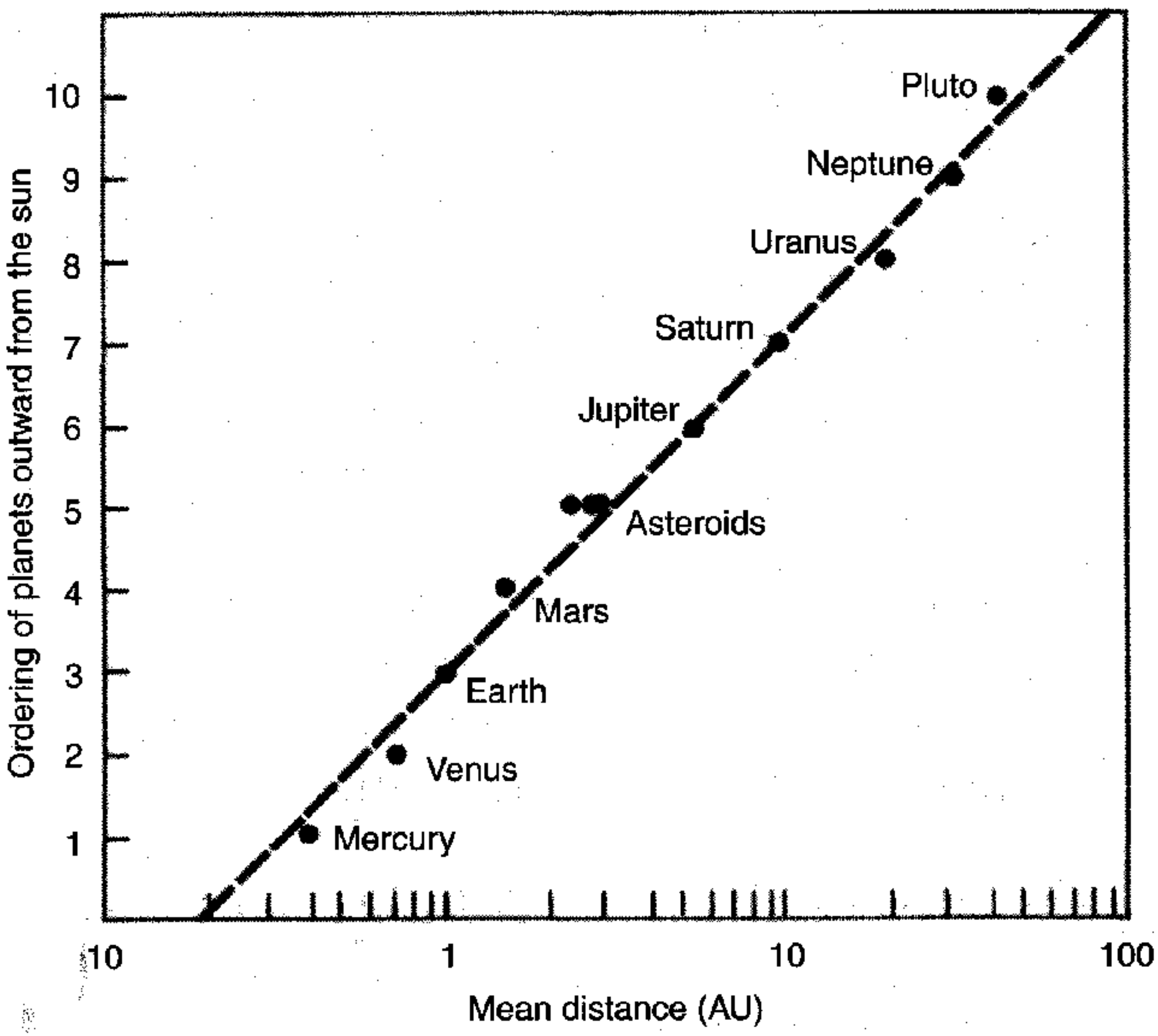



Figure 1.5 The spacing of planets in the Solar System appears fairly regular if a logarithmic scale of mean distances is used, and if the asteroids collectively are considered to be a planet. The dashed line corresponds to a spacing law such that each planet's orbit is 75% larger than the next inner one.

From Wood: Fig. 1.5

# Properties and Patterns

**Table 1.1 THE PLANETS OF THE SOLAR SYSTEM: ORBITAL, ROTATIONAL, AND BODY PROPERTIES.**

| Planet | Mean distance from the sun, AU[a] | Orbital eccentricity[b] | Orbital inclination, degrees from Earth's orbit | Orbital period, Earth years | Radius at equator, km | Mass, $10^{24}$kg | Mean density, g/cm$^3$ | Rotation period, Earth days | Mean orbital velocity, km/sec | Velocity of escape from planet surface[c], km/sec |
|---|---|---|---|---|---|---|---|---|---|---|
| Mercury | 0.39 | 0.206 | 7.0 | 0.24 | 2440 | 0.33 | 5.43 | 58.8 | 47.9 | 4.4 |
| Venus | 0.72 | 0.007 | 3.4 | 0.62 | 6052 | 4.87 | 5.20 | 243.7[d] | 35.0 | 10.4 |
| Earth | 1.00 | 0.017 | (0.0) | (1.00) | 6378 | 5.97 | 5.52 | (1.0) | 29.8 | 11.2 |
| Mars | 1.52 | 0.093 | 1.8 | 1.88 | 3396 | 0.64 | 3.91 | 1.03 | 24.1 | 5.0 |
| Jupiter | 5.20 | 0.048 | 1.3 | 11.86 | 71,492 | 1898 | 1.33 | 0.41 | 13.1 | 59.5 |
| Saturn | 9.54 | 0.056 | 2.5 | 29.46 | 60,268 | 568 | 0.69 | 0.43 | 9.7 | 35.5 |
| Uranus | 19.18 | 0.046 | 0.8 | 83.91 | 25,559 | 86.8 | 1.32 | ~0.75[d] | 6.8 | 21.3 |
| Neptune | 30.06 | 0.009 | 1.8 | 164.8 | 24,766 | 102 | 1.64 | 0.78 | 5.5 | 23.5 |
| Pluto | 39.53 | 0.249 | 17.1 | 247.7 | 1150 | 0.013 | ~2.0 | 6.40 | 4.7 | 1.1 |

a. 1 AU = $1.496 \times 10^8$ km (Sec. 1.4)
b. Section 2.1
c. Section 2.2
d. Retrograde rotation.
(Data from *The New Solar System*, Eds. J. K. Beatty, C. C. Petersen, and A. Chaikin, 1999. Cambridge, Massachussetts: Sky Publishing Corp.)

From Wood: Table 1.1

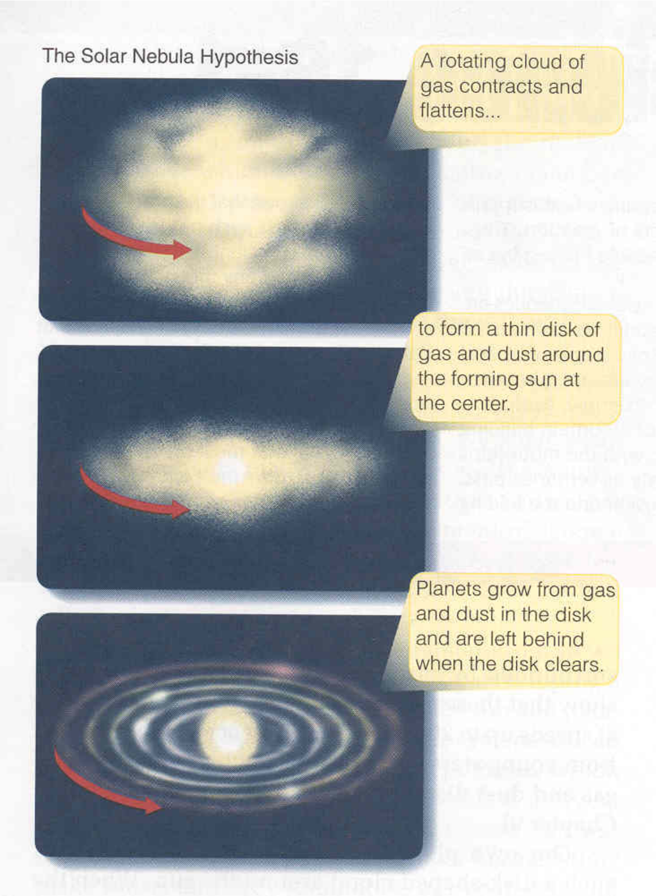
# Patterns in the solar system

- Composition of planets
  - Inner terrestrial planets: rocky worlds
  - Outer Jovian planets: H, He rich "gas giants"
  - More subtle trends within groups
    - Higher density in close to sun for terrestrial planets
    - Higher density out farther from sun (less H, He) for jovian planets
- Motion of planets
  - All in ~ circular, low eccentricity, "prograde" orbits
  - All regular satellite systems of Jovian planets similar to this
  - Planetary orbits "regularly" spaced
  - Rotation less regular, but most prograde and "low inclination"
- Patterns in activity
  - Large terrestrial planets more geologically active
  - Small bodies less active and will preserve more of original conditions

# Solar nebula explains patterns

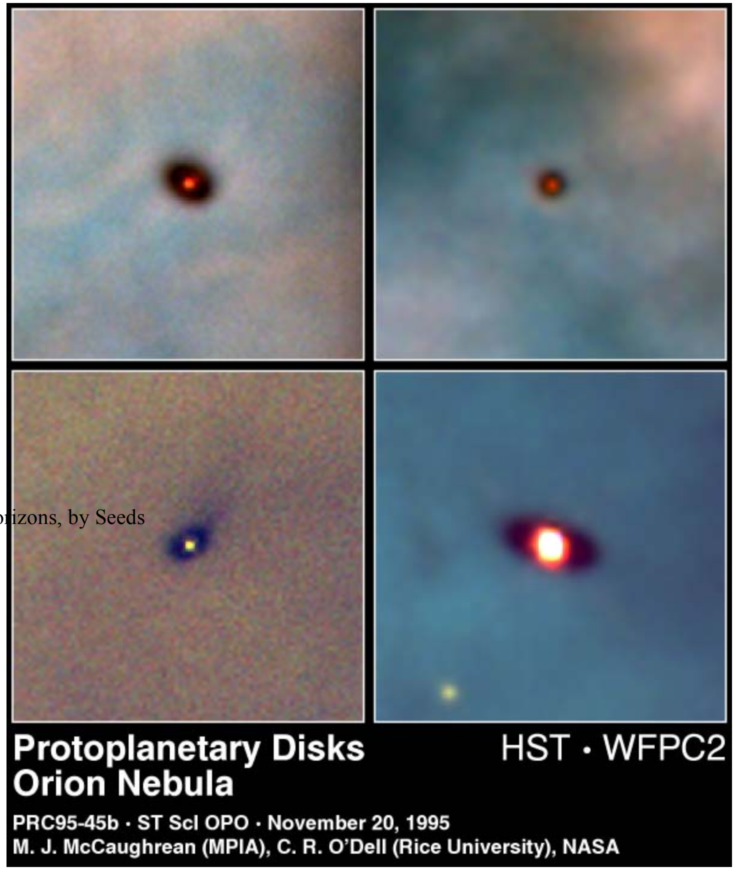
- "Disk like orbits" explained by solar nebula
  - Original proposals by Kant, Laplace and others
  - Problem with angular momentum
    - Sun contains 99.9% of mass of solar system
    - Planetary orbital motion holds most of the angular momentum
      - (Sun takes 27 days to rotate – slow compared to what you would expect)
  - Angular momentum "loss" controls evolution of disk
- Chemical models of nebula (from 1960's, 1970's) explains compositional trends in planets
  - Grossman 1972 (and earlier Anders' and other papers)
  - Jovian planets tied to "snow line"
  - More subtle trends also explained
  - Meteorites are "fossils" from time of formation
    - Use them to test detailed predictions
- Growing evidence of role of disks in formation of other stars (and now planets)

# Protoplanetary Disks




From Horizons, by Seeds

our text: Horizons, by Seeds




- Hubble images of "proplyds" in the Orion nebula
- Seen in silhouette against glowing gas clouds
- Central star just visible shining through dust at long (red) wavelengths

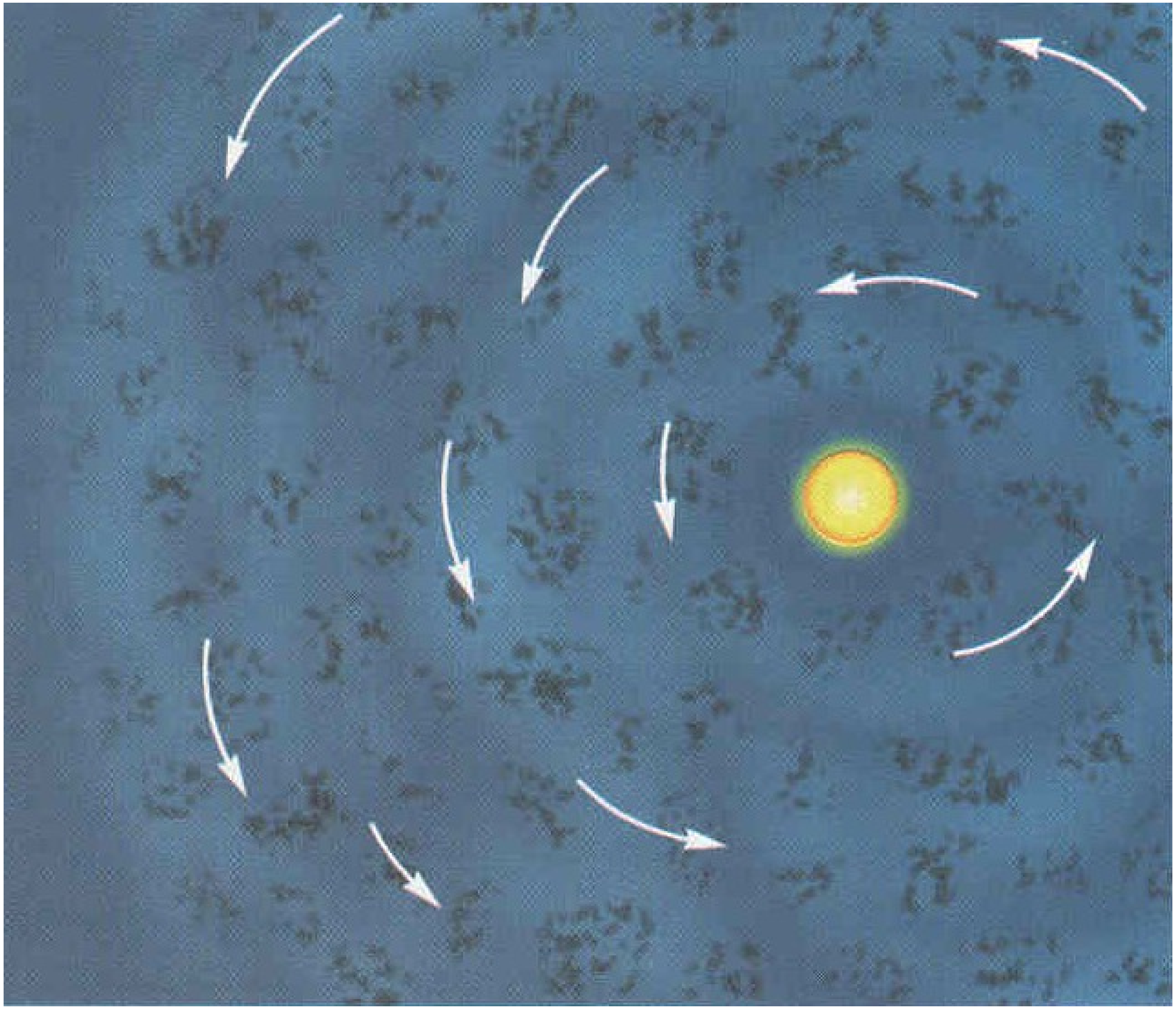
# Equilibrium Condensation Model

- Start with material of solar composition material
  - (H, He, C, N, O, Ne, Mg, Si, S, Fe ...)
- Material starts out hot enough that everything is a gas
  - May not be exactly true but is simplest starting point

- As gas cools, different chemicals condense
  - First high temperature chemicals, then intermediate ones, then ices
- Solids begin to stick together or accrete
  - snowflakes ⇒ snowballs
- Once large enough gravity pulls solids together into planetesimals
  - planetesimals grow with size

- At some point wind from sun expels all the gas from the system
  - Only the solid planetesimals remain to build planets
  - Composition depends on temperature at that point (in time and space)
  - Gas can only remain if trapped in the gravity of a large enough planet

# Growth of the Planetisimals



From Horizons by Seeds

- Once planetisimals reach critical size gravity takes over

# Small “planets” show evidence of the assembly process – partly erased in places

# Later evolution of the planets

- Geologic activity on planet related to heat flow (Watts/m$^2$) $\propto$ Volume/Area $\propto R^3/R^2 \propto R$
  - Large planets more active than small ones
    - They simply have more volume to generate heat compared to surface area
  - They also take longer to lose initial heat of formation
    - They may also have more initial heat – more gravitational energy released assembling them

| | |
|---|---|
| • Large objects (Earth, Venus?) | still active |
| • Intermediate objects (Mars) | active for much of its lifetime |
| • Small objects (Moon) | active for first ~1 billion years |
| • Very small objects (asteroids, comets) | may preserve original material |

# Small "planets" show evidence of the assembly process – partly erased

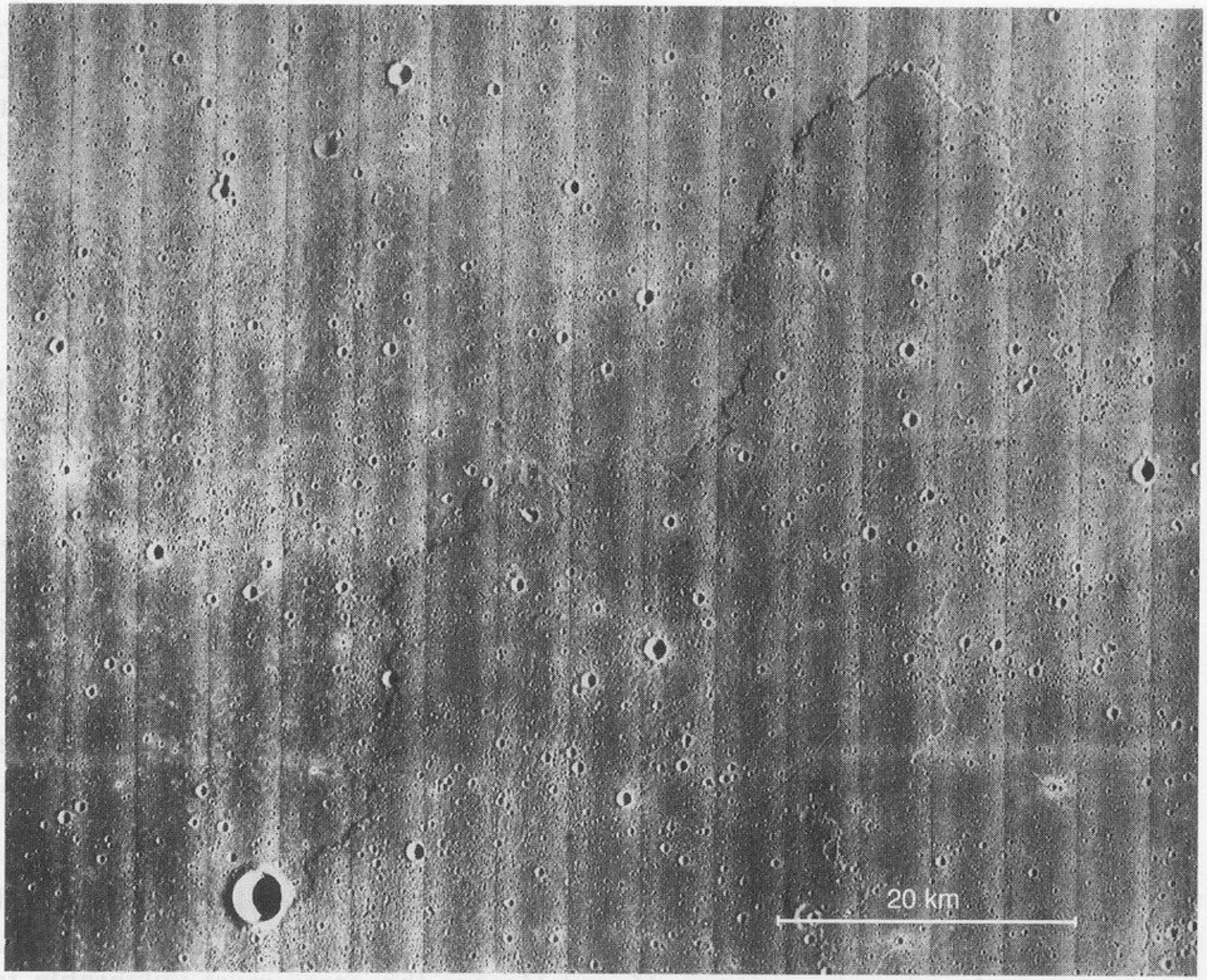



Figure 1.10 A portion of the surface of Mare Imbrium on the moon. Lava flowing in a sheet from south to north ~3 Ga ago got no farther than this area, where it solidified. The frozen lava flow front is still visible as an irregular scarp tens of meters high. (NASA photograph)

Wood Fig. 1.10

# Solar System Timeline

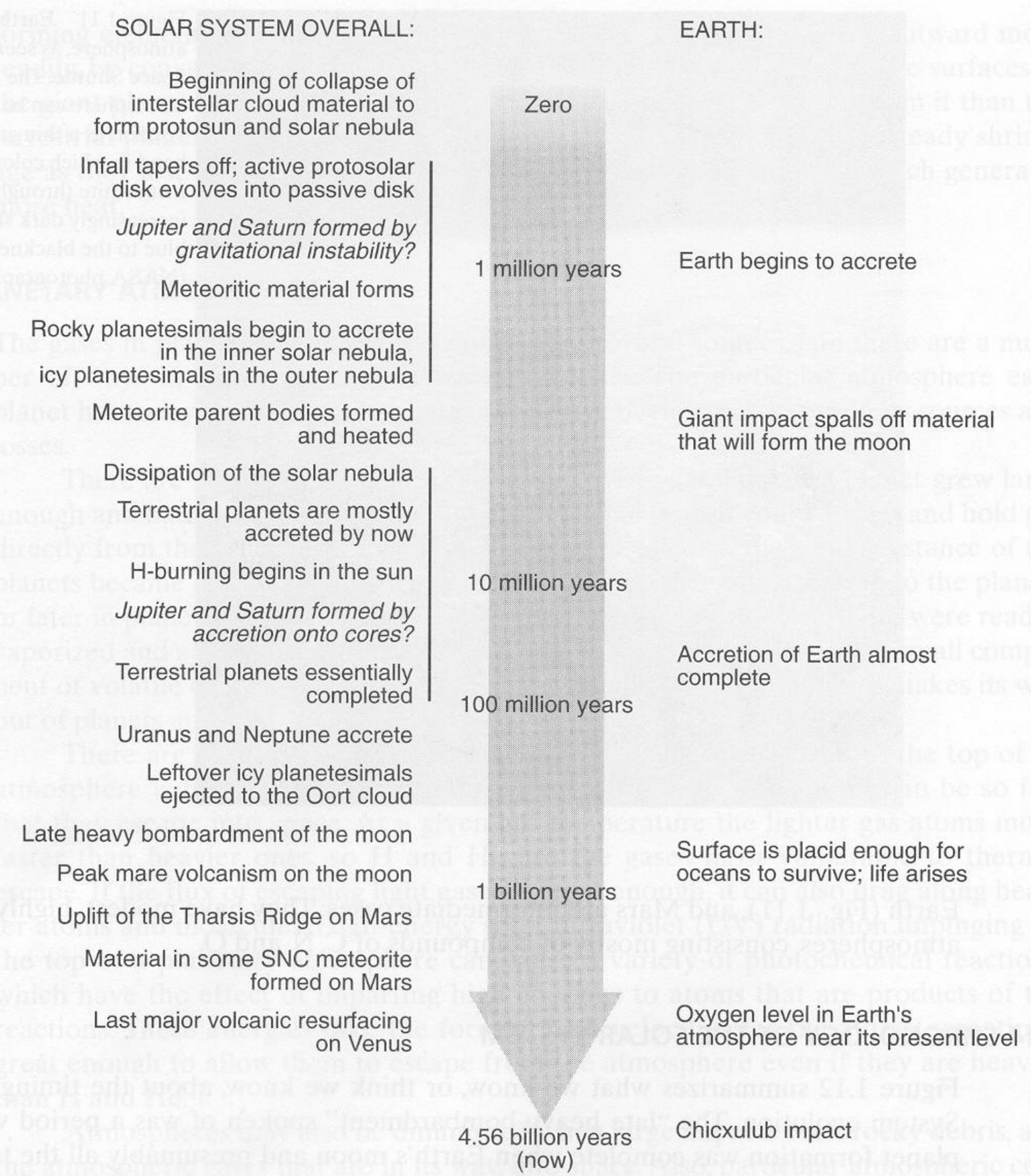



Figure 1.12 An approximate time line for the history of the Solar System. The time scale is not linear; it is greatly compressed at the bottom and expanded at the top. See also Figure 6.16, a time line for meteorites.

Wood Fig. 1.12

# How can we test the condensation model?

- Bulk composition of major planets
  - But geologic activity has reprocessed material so only "elemental" abundances are preserved

- Samples of primitive material surviving from early history of solar system
  - Need to find places where there has been "no" geologic activity
  - That means look for small bodies which cooled quickly
    - Asteroids (and meteorites which come from them)
    - Comets

# Asteroids / Meteorites are the "fossil" record left from the nebula

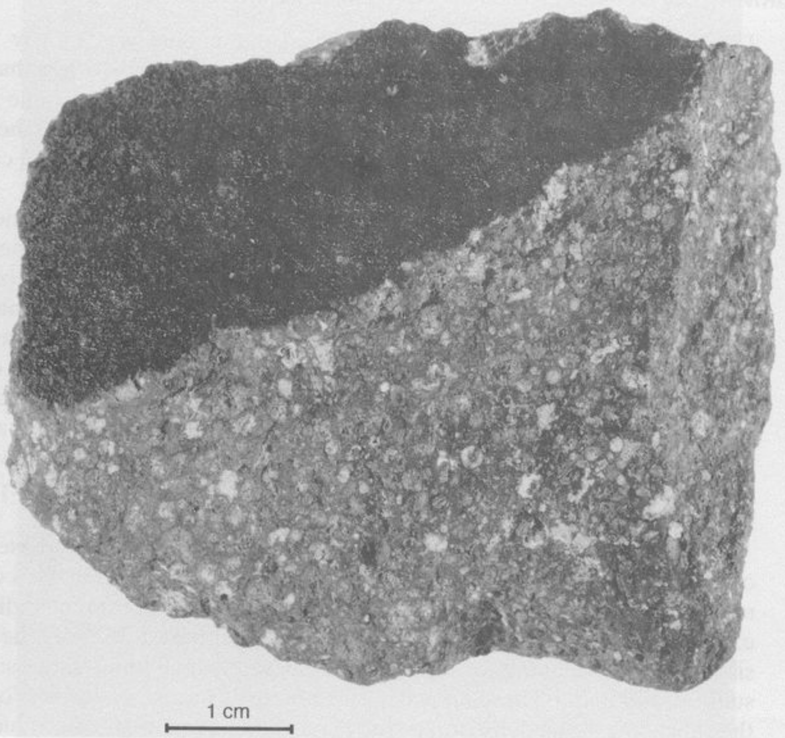
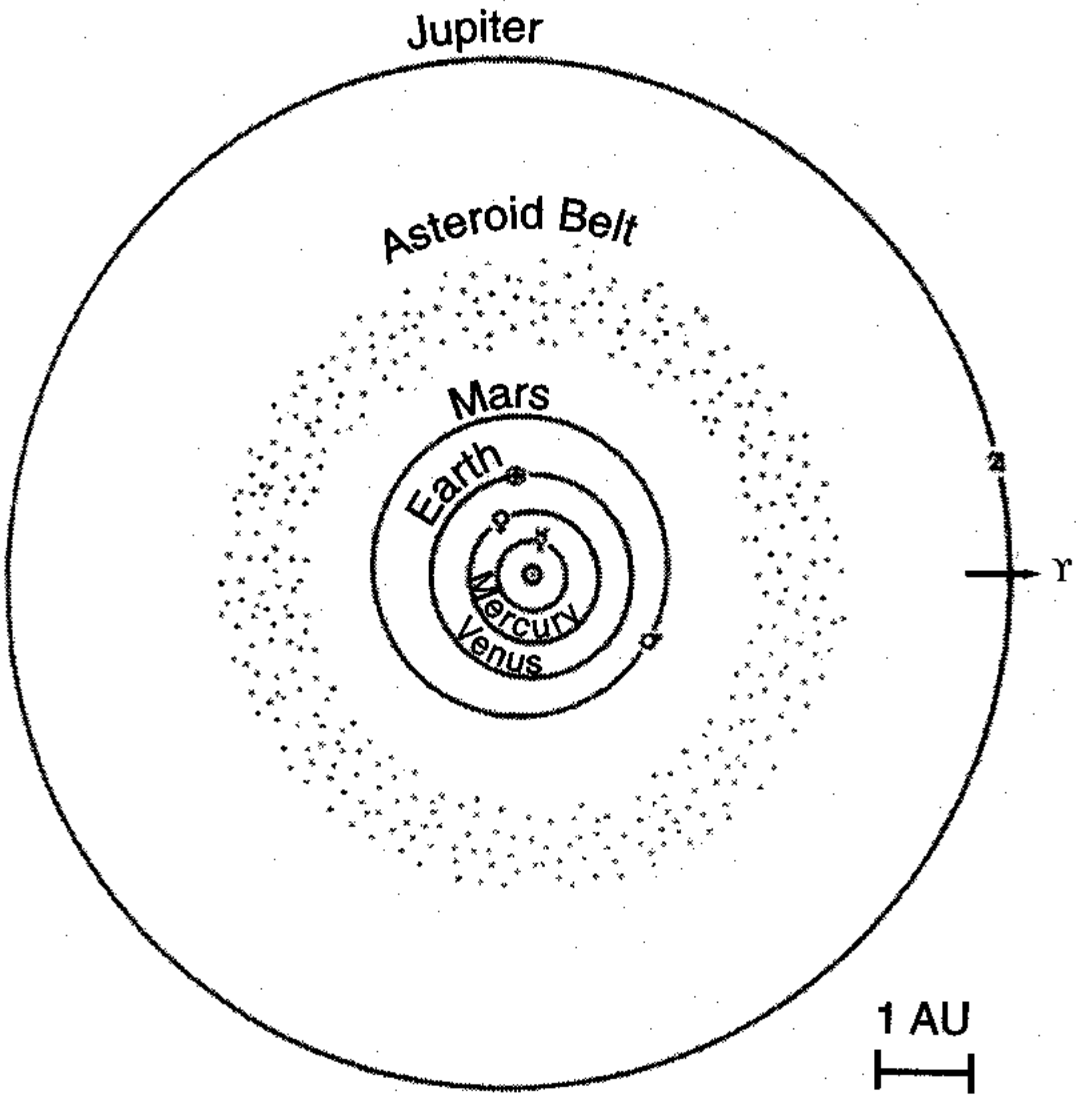



Figure 1.8 A fragment of a chondritic meteorite that fell in Allende, Mexico, in 1969. The black coating at the top of the specimen is fusion crust, melted by atmospheric friction as the meteorite streaked through Earth's atmosphere. The near face of the specimen is a broken surface, exposing the unaltered chondritic material inside the fusion crust. The chondrite is an aggregate of small bodies (chondrules, refractory inclusions) that formed in earliest times, in the primitive solar nebula. (Smithsonian Astrophysical Observatory photograph)

- Allende meteorite
- Fall on Feb. 8, 1969 near Pueblito de Allende in Mexico
- Carbonaceous chondrite (most primitive)
- Age ~ $4.5 \times 10^9$ years

Wood Fig. 1.8

# Why is there an asteroid belt?  Resonant Perturbations




- Resonance with Jupiter orbital period

Wood  Fig. 1.8

# Why is there an asteroid belt?  Resonant Perturbations

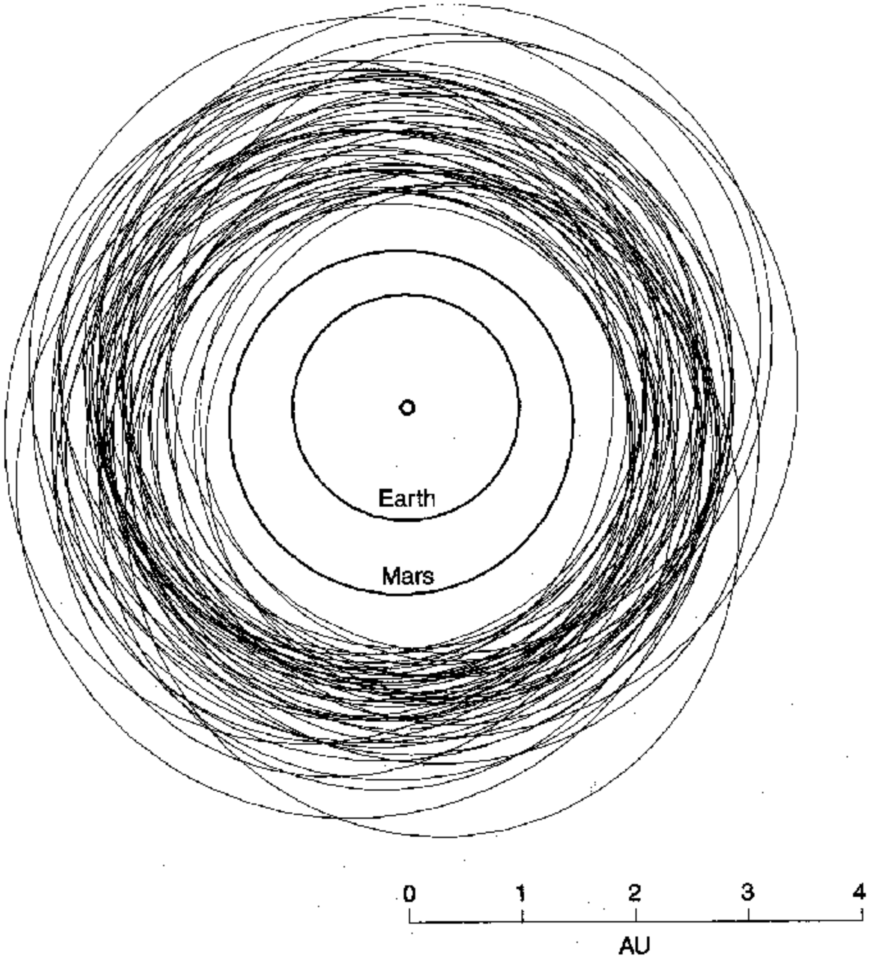
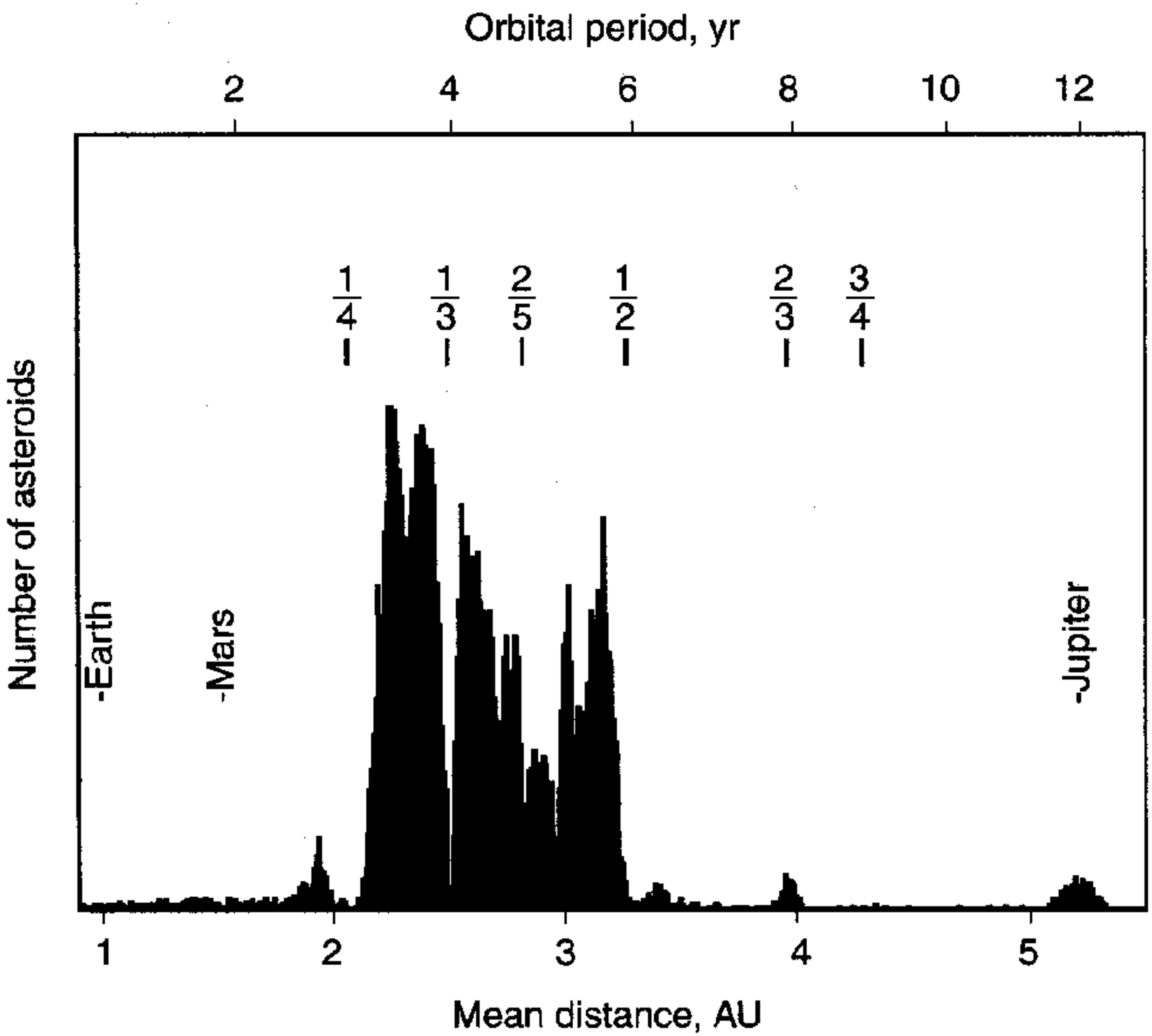



Figure 6.2 Orbits of the first 50 numbered asteroids. This set does not include Mars- or Earth-crossing asteroids; all remain in the asteroid belt. (Data from the JPL Database of Asteroids and Comets; courtesy of NASA/JPL/Caltech)

- Resonance with Jupiter orbital period
- $P^2 \propto a^3$
  - $P = \frac{1}{2} P_{Jupiter}$ at
  - $a = (1/2)^{2/3}\ a_{Jupiter}$
    $= 0.63 \times 5.2$ AU
    $= 3.27$ AU
- Non-resonant perturbations tend to cancel out over time
- Resonant perturbations keep adding up
- During formation period, collision velocities got too high to allow accretion

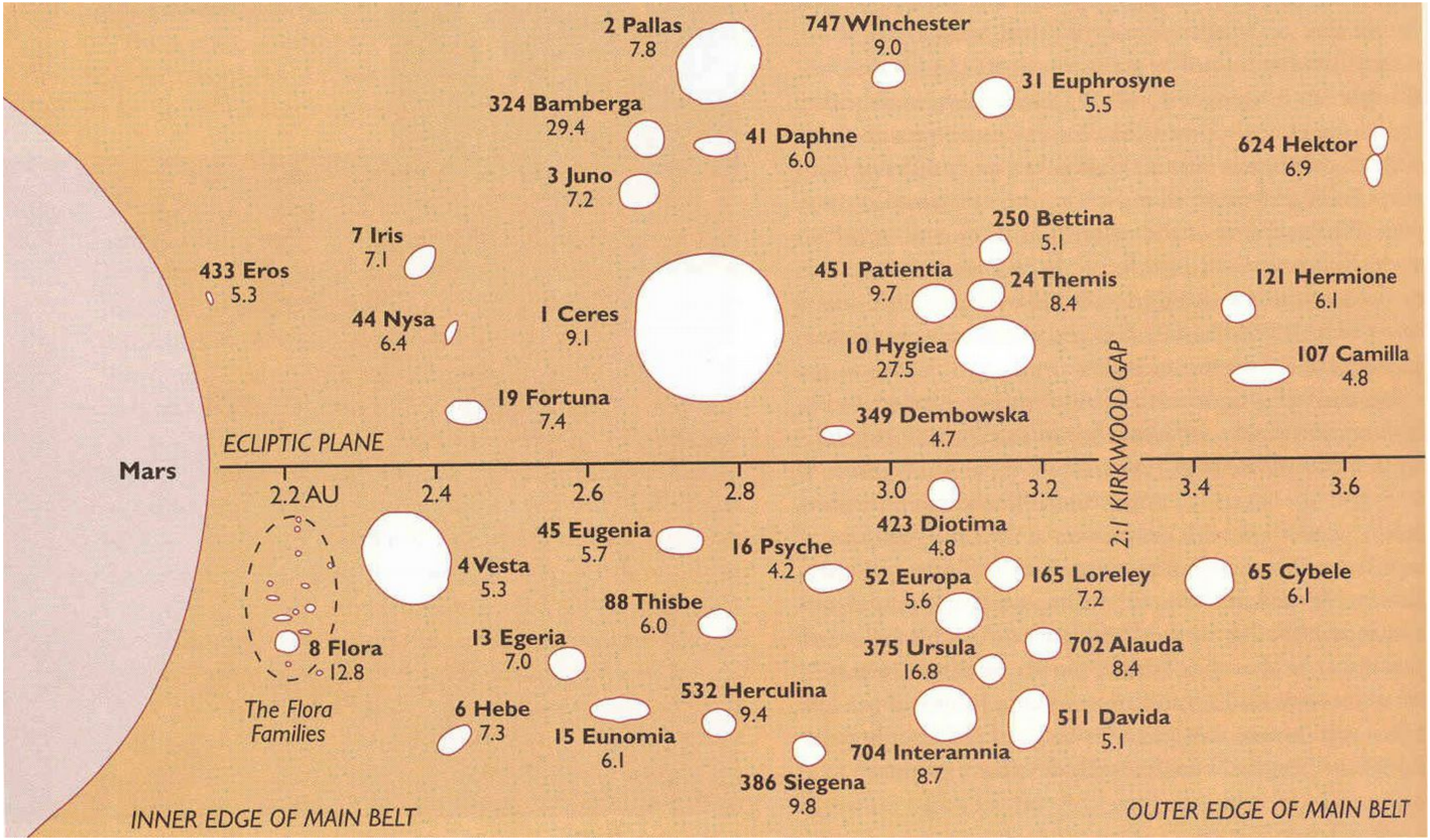
Wood Fig. 6.2

# Kirkwood Gaps




Wood Fig. 6.5

# The larger asteroids




The New Solar System, Beatty et al.

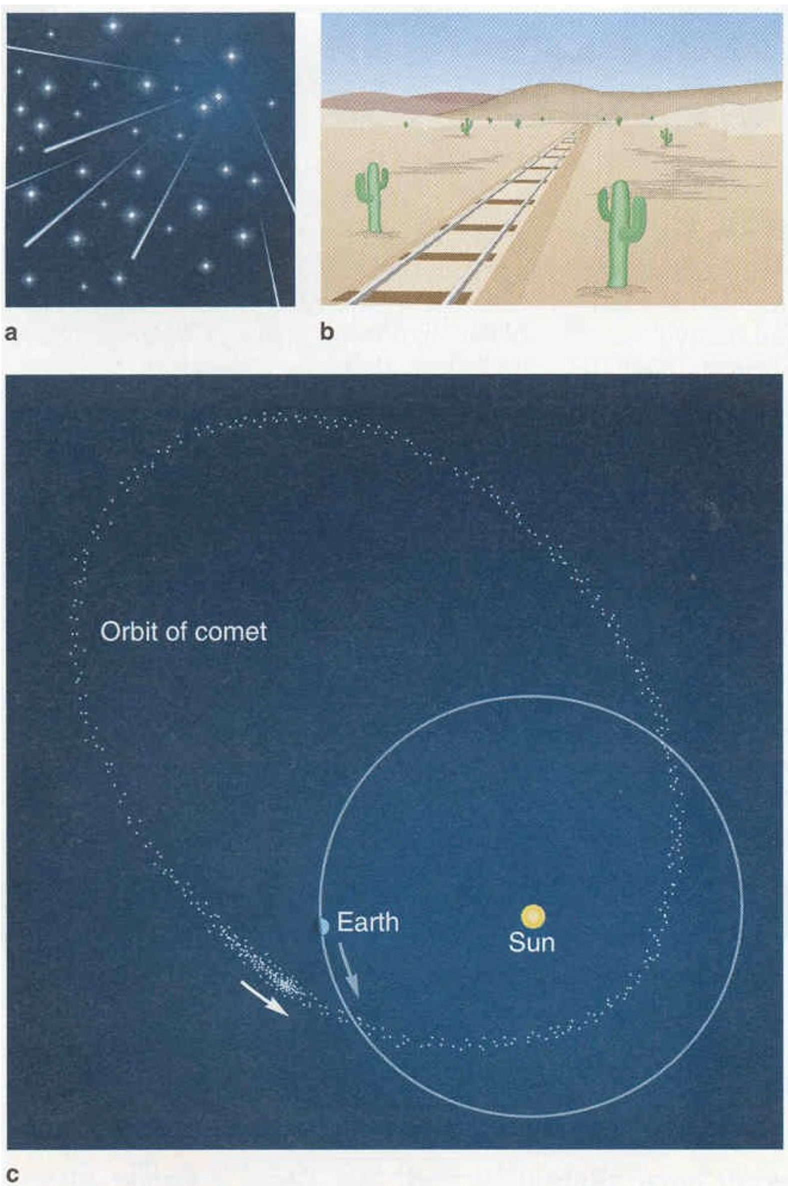
# Meteors vs. Meteorites

- Meteor is seen as streak in sky
- Meteorite is a rock on the ground
- Meteoroid is a rock in space

- Meteor showers (related to comet orbits) rarely produce meteor<u>ites</u>
  - Apparently most comet debris is small and doesn't survive reentry

- Meteorites can be "finds" or "falls"
  - For a fall – descent actually observed and sometimes orbit computed
  - "Finds" <u>were</u> heavily biased towards most recognizable (so unusual) meteorites – but discovery of Antarctic meteorites has produced a large "unbiased" sample
  - Most measured meteorite orbits have aphelion in asteroid belt

# Meteor Showers and Comets




- Meteor showers caused by large amount of <u>small</u> debris spread out along comet orbits
- Almost none makes it to the ground – no meteor<u>ites</u>
- Occur each year as earth passes through orbit of comet
- Appears to come from "radiant point" in sky
- Leonids: Mid November

From the Astro 1050 text Horizons, by Seeds

# Meteorites as samples of asteroids

- Meteorites (which survived) are not associated with comets
- They seem to come from the asteroid belt

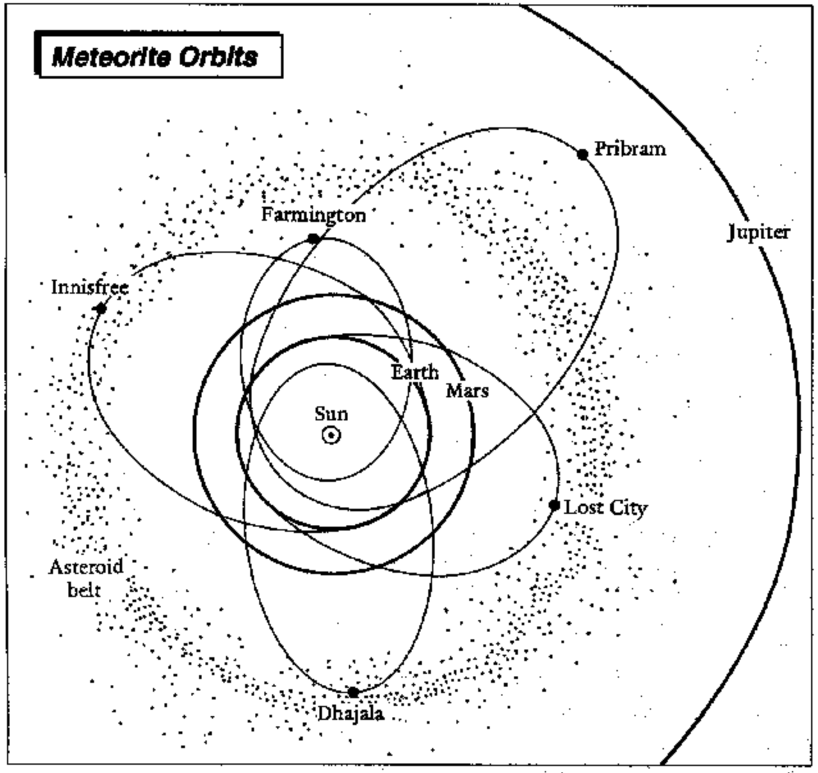



Figure 3.2: The calculated orbits of recovered meteorites provide information on the sources of these objects. Five recovered ordinary chondrites had highly elliptical orbits. All of these had aphelia, the approximate locations of which are illustrated by small dots in this figure, within or near the asteroid belt between Mars and Jupiter. This suggests that chondrites may be fragments of asteroids. The orbits are drawn to scale, but their orientations are chosen for clarity of illustration.

# Common Classification of Meteorites

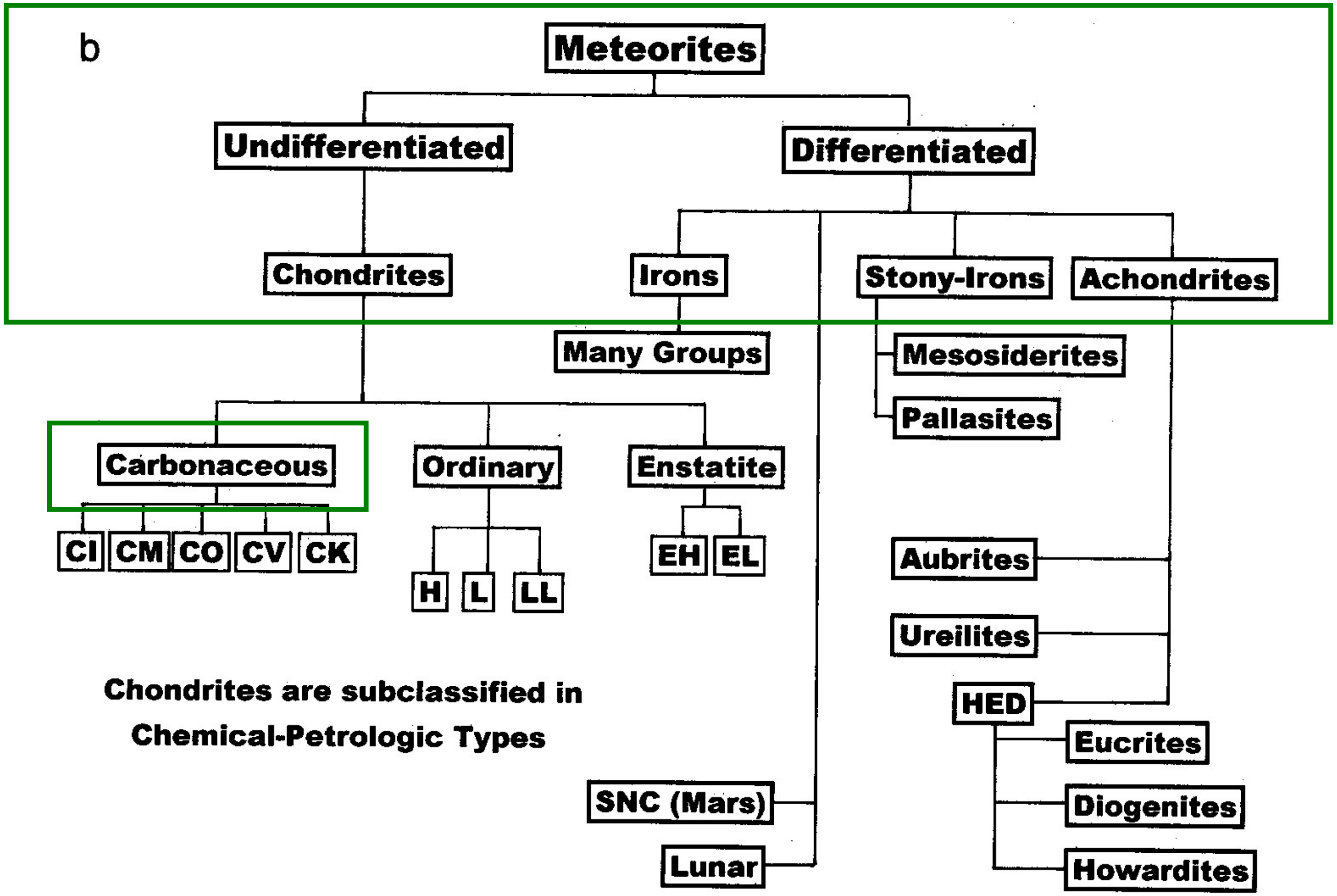
- Simplest classification is
  - Stones     Stony-Irons     Irons

  - But there are two very different types of stones
    - Stones that look like "ordinary" igneous rocks
    - Stones that are strange assemblages of very primitive components

- Better classification based on how "altered" they are – then with subdivisions based on details of composition

# Types of Meteorites

- Many fine divisions, we'll only care about the main ones



# Future Topics

- Further overview of Asteroids, Meteorites
- More details on Equilibrium Condensation Model

- Complications in the above simple picture
  - Details of meteorite composition/processing
  - Unusual exoplanets
  - Subtle composition effects in major planets
  - Theoretical models