Origin of heavier elements, origin of universe

Like we said earlier…

- It takes higher and higher temperatures to make larger and larger nuclei fuse together
- What happens when a star cannot maintain fusion reactions?
- Planetary nebulae
- "Neutron capture" (nucleosynthesis paths)

Name of Process	Fuel	Products	Temperature
Hydrogen burning	H	He	10,000,000 K
Helium burning	He	C, O	100,000,000 K
Carbon burning	C	O, Ne, Na, Mg	>500,000,000 K
Neon burning	Ne	O, Mg	1,200,000,000 K
Oxygen burning	O	Mg, to S	2,000,000,000 K
Silicon burning	Mg to S	Elements ~ Fe	2,700,000,000 K To 3,500,000,000

Star of ~10 Solar Masses:

- **$^{12}C \rightarrow {}^{16}O \rightarrow {}^{20}Ne \rightarrow {}^{24}Mg$**
- Once carbon is burned, collapse, heating, and about 6 months of ^{28}Si production - and then about a day of:
- **$^{28}Si \rightarrow {}^{32}S \rightarrow {}^{36}Ar \rightarrow {}^{40}Ca \rightarrow {}^{44}Ti \rightarrow {}^{48}Cr \rightarrow {}^{52}Fe \rightarrow {}^{56}Ni$**
- Once this sequence is over, the star cannot initiate new fusion reactions by compressing, and it's all over:
- Gravitational collapse (neutron star, or black hole if massive enough), or Supernova (final collapse involves extreme heating resulting in explosion)
- ^{56}Ni decays in a few months to ^{56}Fe

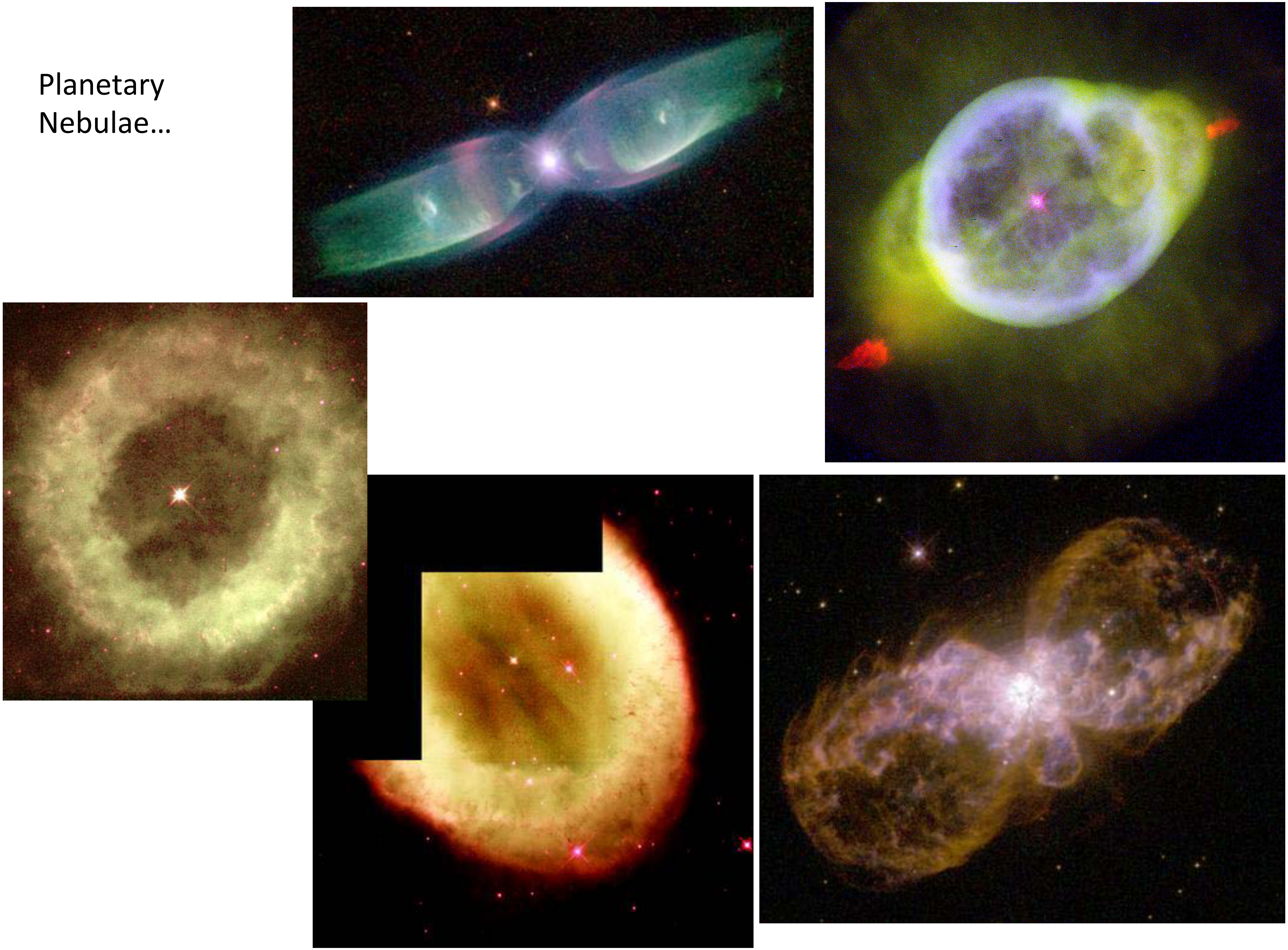
If you can’t make elements heavier than ^{56}Fe by fusion in stars…where did they come from?

- ^{62}Ni actually the most stable element, but the pathway to making it involves an “uphill” step
- You need “extreme” conditions with lots of extra neutrons released so that something called “neutron capture” can take place

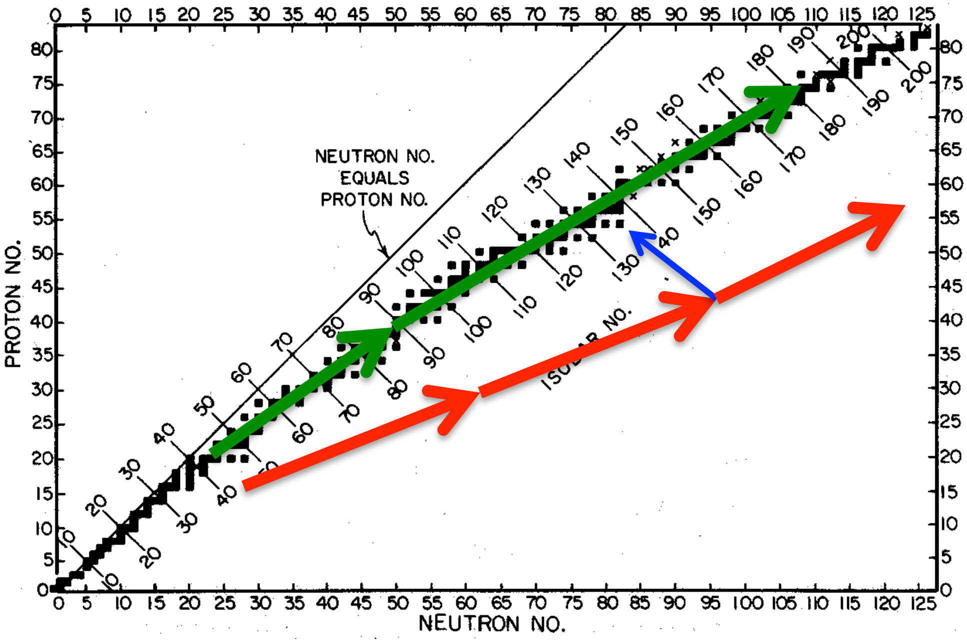
Ejection of elements into space

- Red giant star is so large that gravitation is weak for the outermost layers – they can be ejected into space (planetary nebulae)
- Supernova: if core gets too massive and gravity too strong, heat cannot prevent collapse
- Collapse leads to sudden increase in temperature, outer parts blown away, inner part becomes dense neutron star or black hole

Planetary
Nebulae…

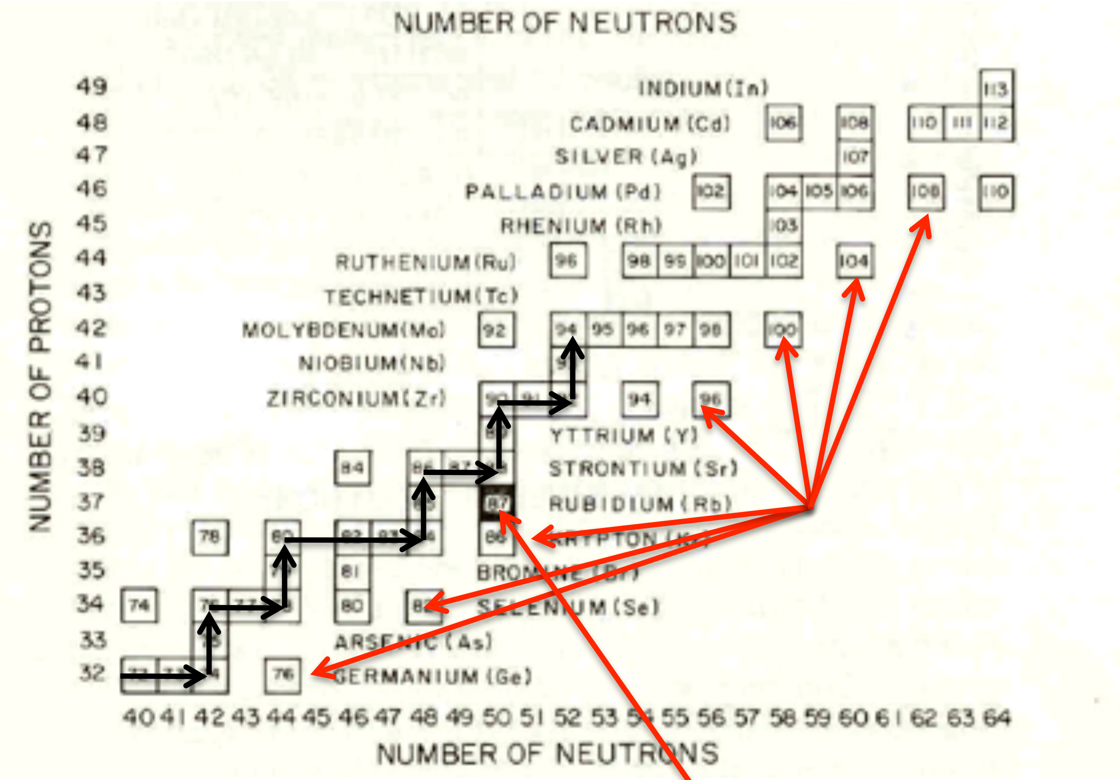


Where did all these isotopes come from?



- Add neutrons **s**lowly, they convert to protons before you get the next neutron. This keeps you following the **GREEN** path (S process).
- …called the “valley of stability”
- Some isotopes cannot be made this way
- **R** vs. **S** process!

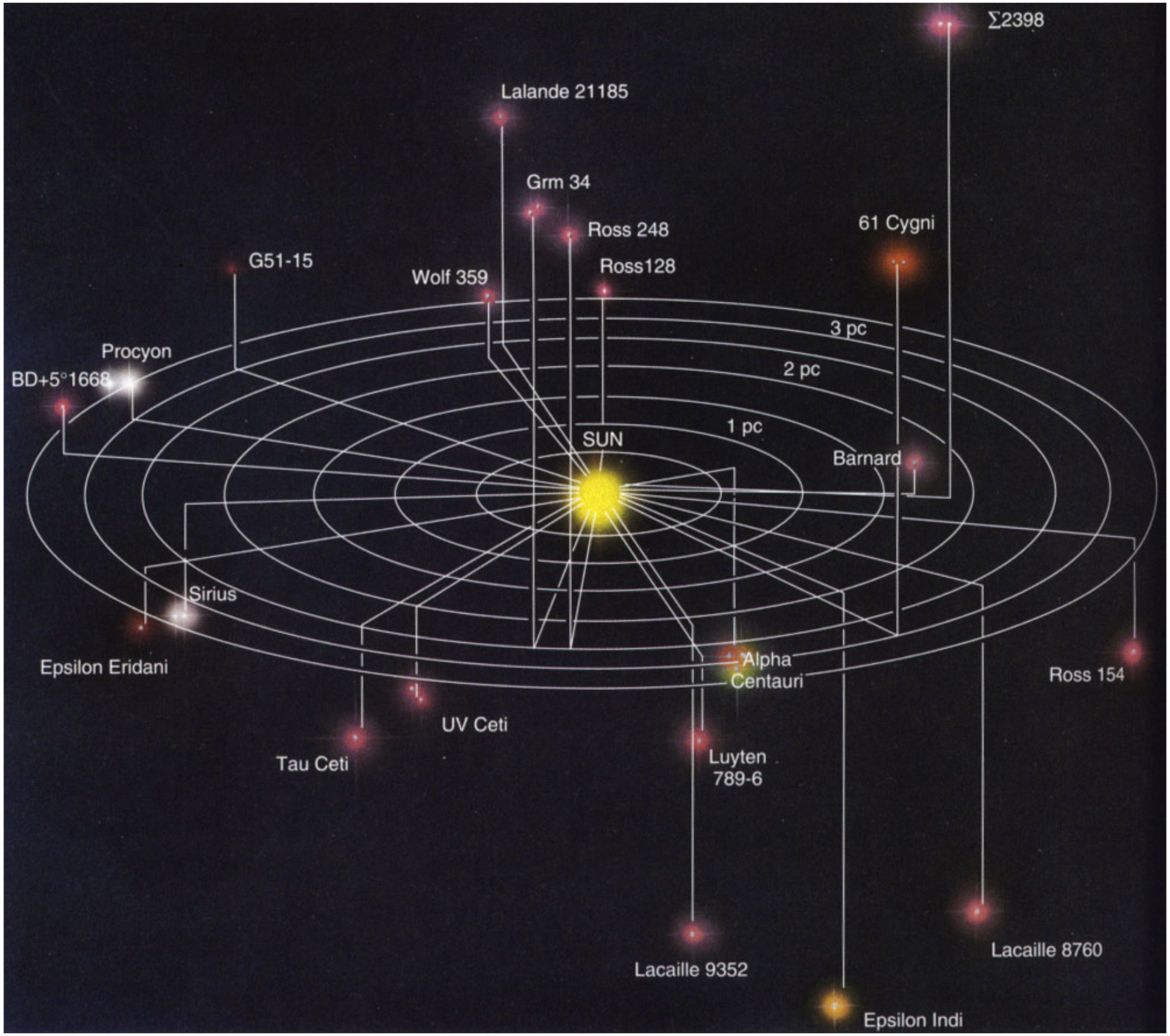
- Add neutrons extremely **r**apidly, they cannot convert to p fast enough and you’re following the RED path (neutron rich)
- **Blue** arrow shows that come isotopes can only be made this way

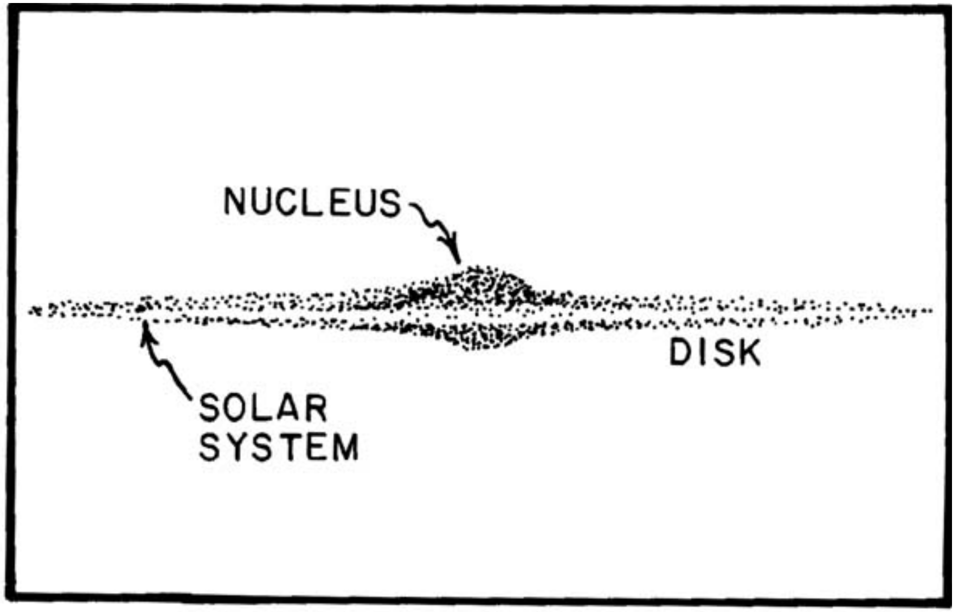


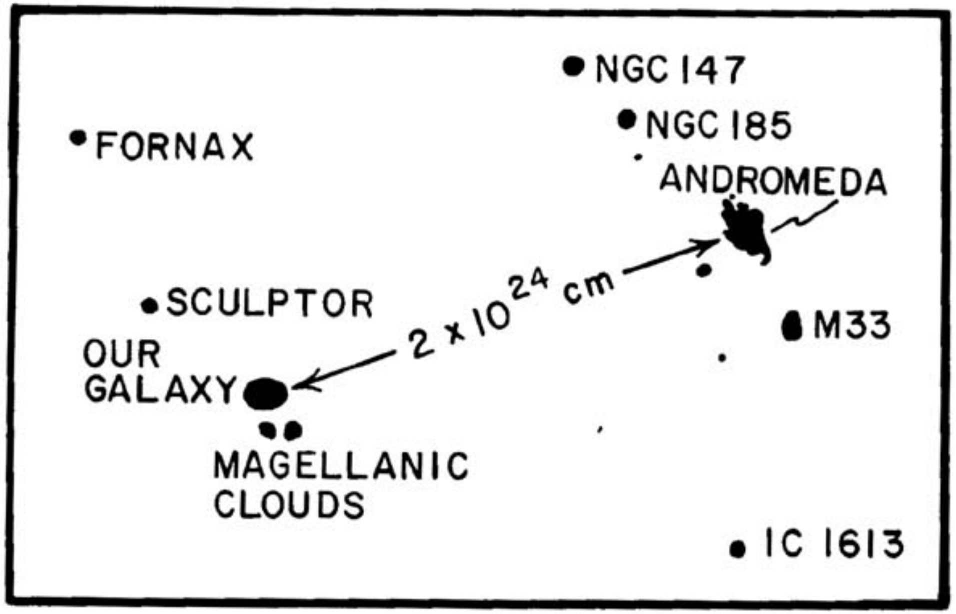
From "How to Build a Habitable Planet"
by Broecker

- S process is the "center path" isotopes (**black**)
- Isotopes to the right of the "center path" are **R** process elements (e.g., ^{87}Rb)
- Isotopes to the left of the "center path" stem from rapid proton capture or (photo)disintegration

A quick look at the universe…


Σ2398
Lalande 21185
Grm 34
Ross 248
61 Cygni
G51-15
Wolf 359
Ross128
3 pc
Procyon
2 pc
BD+5°1668
1 pc
SUN
Barnard
Sirius
Epsilon Eridani
Alpha
Centauri
Ross 154
UV Ceti
Tau Ceti
Luyten
789-6
Lacaille 8760
Lacaille 9352
Epsilon Indi


NUCLEUS
DISK
SOLAR SYSTEM

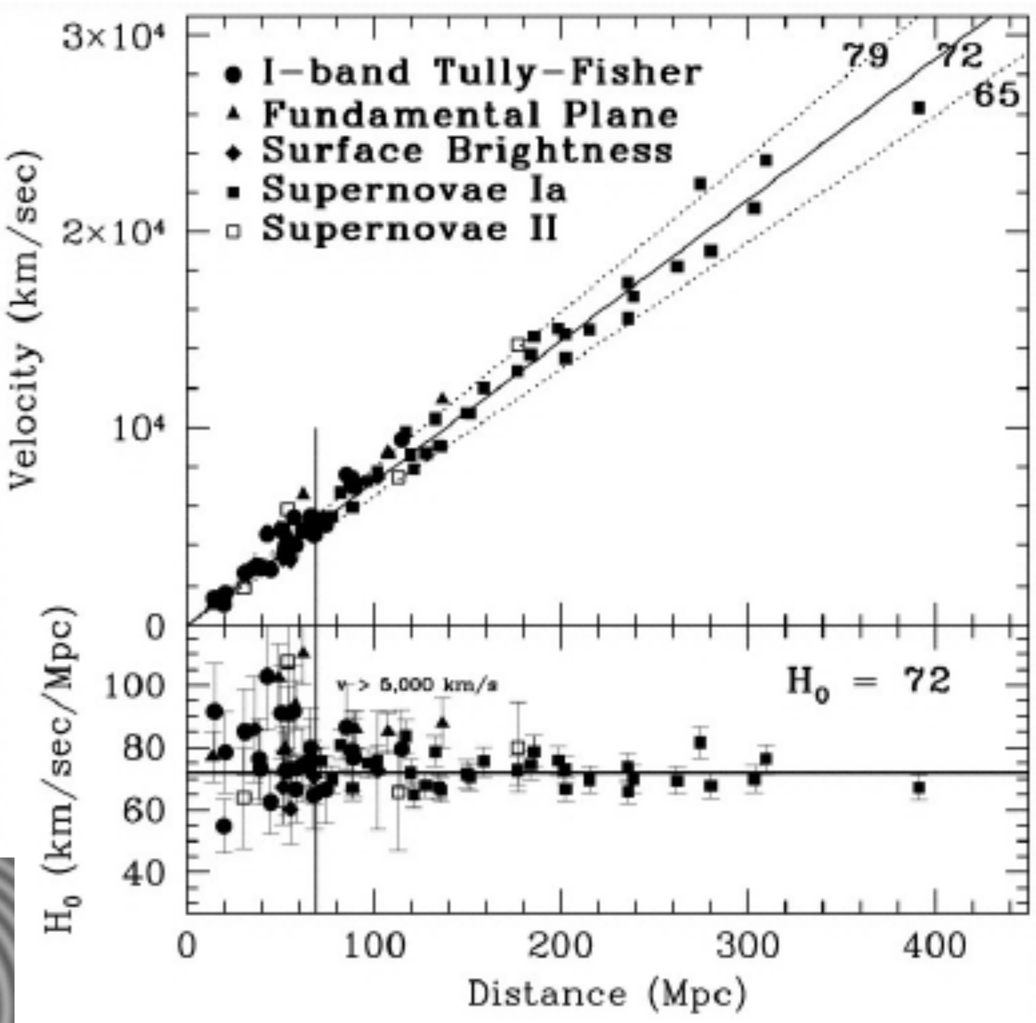

NGC 147
NGC 185
FORNAX
ANDROMEDA
SCULPTOR
2×10^{24} cm
M33
OUR GALAXY
MAGELLANIC CLOUDS
IC 1613

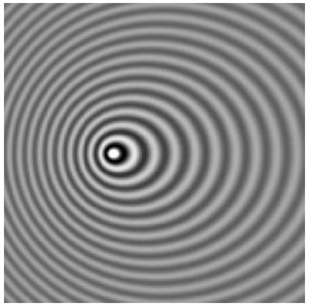
Gravitational Lens in Abell 2218 HST • WFPC2

PF95-14 • ST ScI OPO • April 5, 1995 • W. Couch (UNSW), NASA

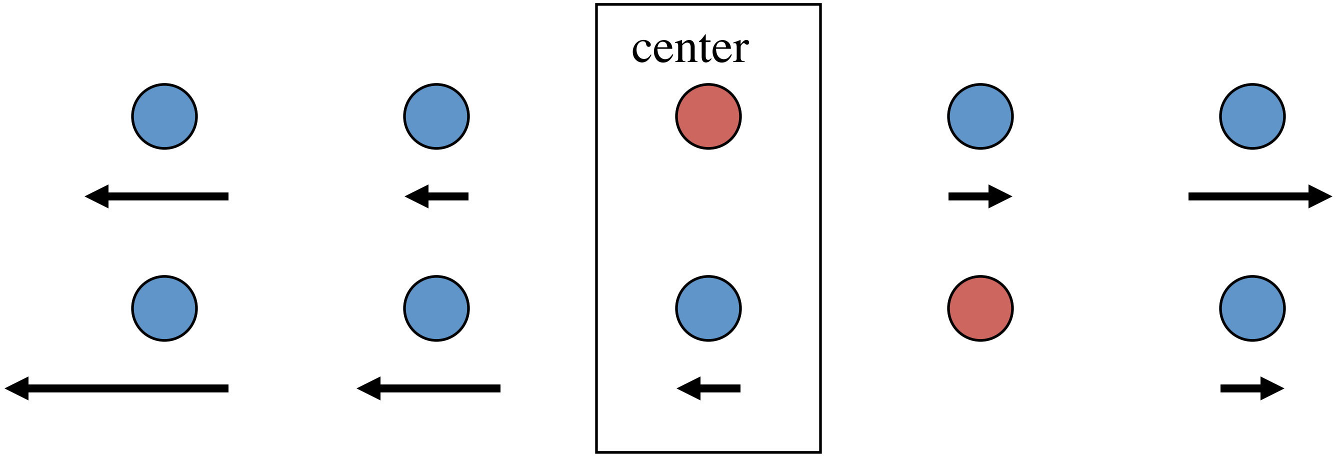
The Big Bang

- 1920's: Edwin Hubble discovered that all distant galaxies are moving away from us (can tell from Doppler Effect).
- Velocity is proportional to distance!





- Velocity = (H_0)(distance) (H_0=71 km/sec/Mpc)
- Time = (distance)/(velocity) = $1/H_0$
- Age of universe is roughly 13.6 x 10^9 years!
- We cannot tell whether we're near the center or not:

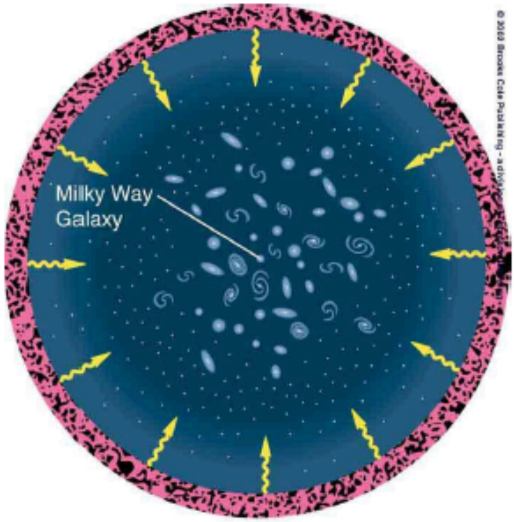


- Of course, initial "event" had monumental heat and density
- Universe expanding, cooling

Timepoints:

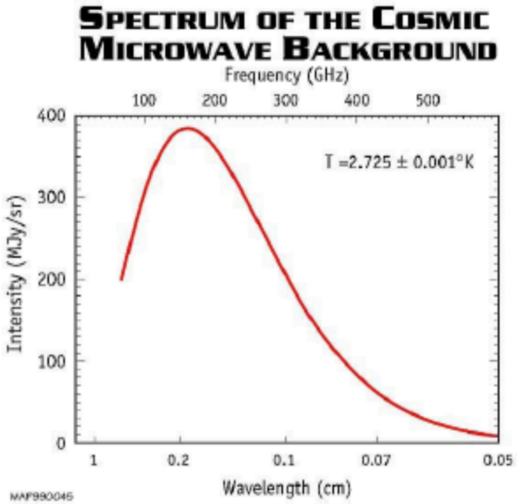
- 10^{-34} sec: 10^{26}K Nuclear strong force, electroweak force separate
- 10^{-7} sec: 10^{14}K Protons, antiprotons – photons
- 10^{-4} sec: 10^{12}K Number of protons frozen
- 4 sec: 10^{10}K Number of electrons frozen
- 2 min: ^{2}H (deuterium) nuclei begin to survive
- 3 min: Helium nuclei begin to survive
- 30 min: Frozen 2H, He nuclei (critical prediction)
- 300,000 yr: H atoms begin to survive
- 10^{9} yr: Galaxies begin to form

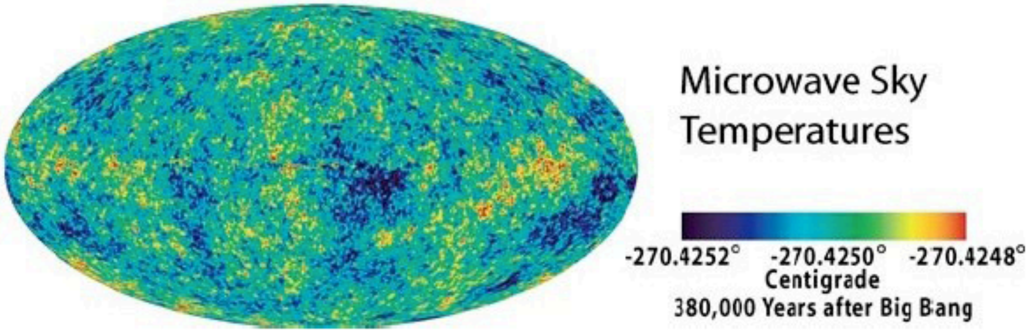
First prediction from Big Bang model:
Cosmic Microwave Background (CMB)



The present universe as it appears from our galaxy

From: Horizons, by Seeds





"WMAP" observations of CMB

Contrast stretch whole sky image of CMB to show <u>very subtle</u> variations.

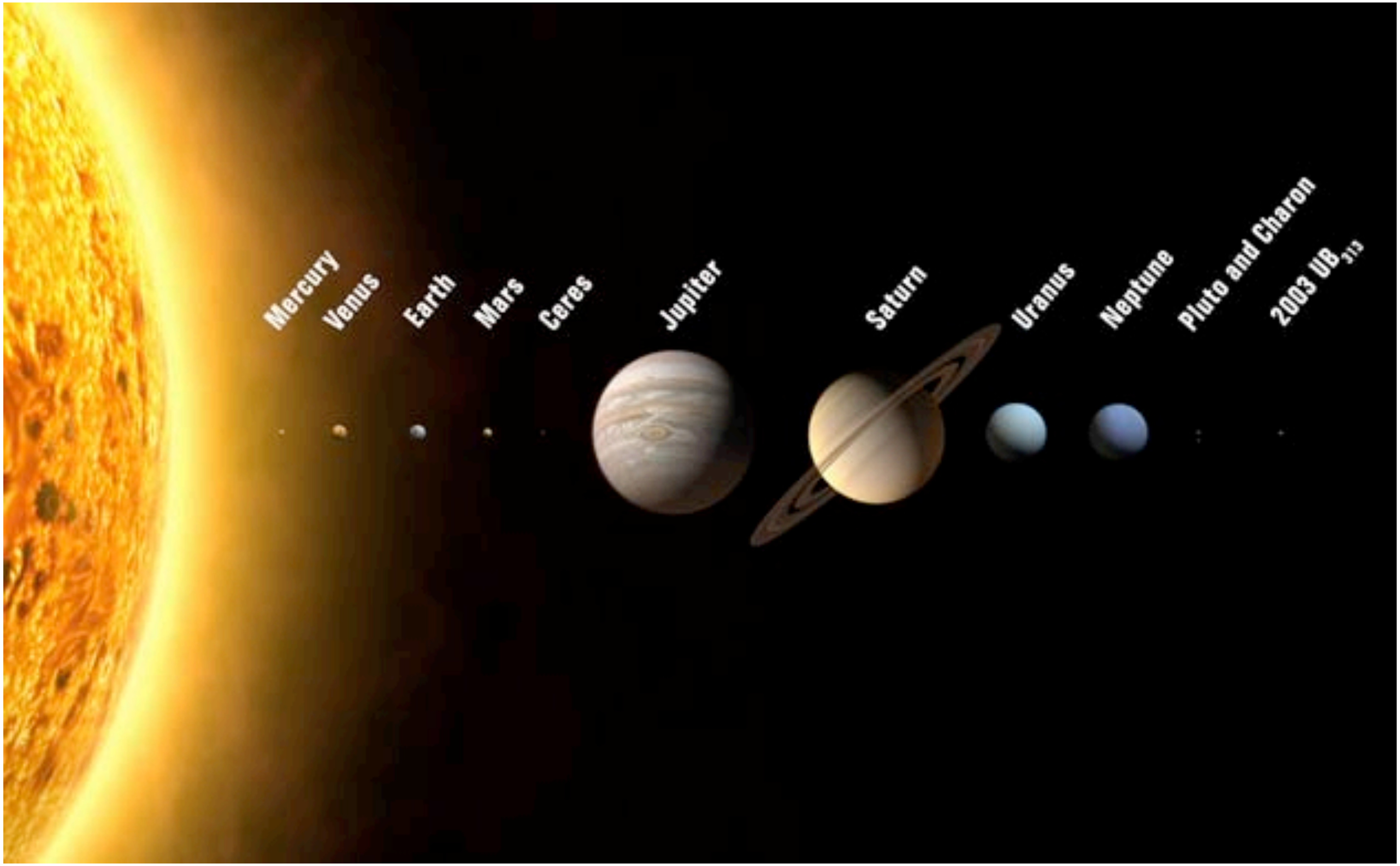
See early "clumpiness" which eventually grows into current galaxies and clusters of galaxies. Lets you measure density of universe – and determine other parameters.

Another prediction: Abundance of light elements

- In Big Bang, T and ρ dropping very rapidly with expansion
- Only about 30 min before T is too low for element formation
- Only have time for H, He, a bit of Li
- Amount of ^{2}H depends on exact density
- ^{4}He is stable, most neutrons end up in ^{4}He
- Models predict about 25% He, which is close to observation

A quick look at our solar system

Planet Sizes



Division into inner (terrestrial) and outer (Jovian) planets

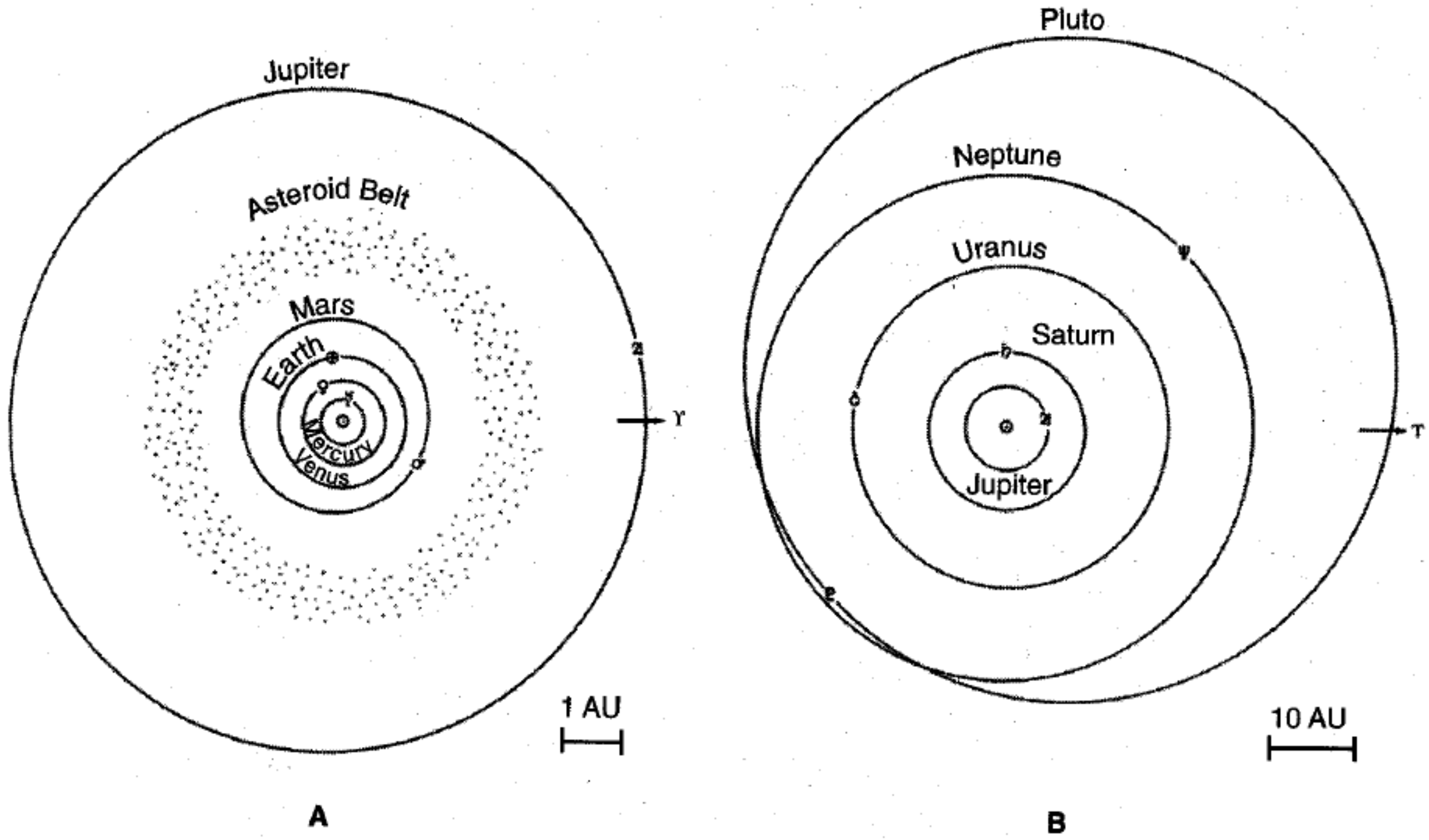


Figure 1.3 Map of the Solar System, to two scales. (A) Orbits of Jupiter and the terrestrial planets interior to it, and position of the asteroid belt. (B) Orbits of Jupiter and the giant planets exterior to it. ♈ is the direction of the vernal equinox, a reference axis in our galaxy. The astronomical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

From: Wood Fig. 1.3

Regular Spacing in Distance from Sun

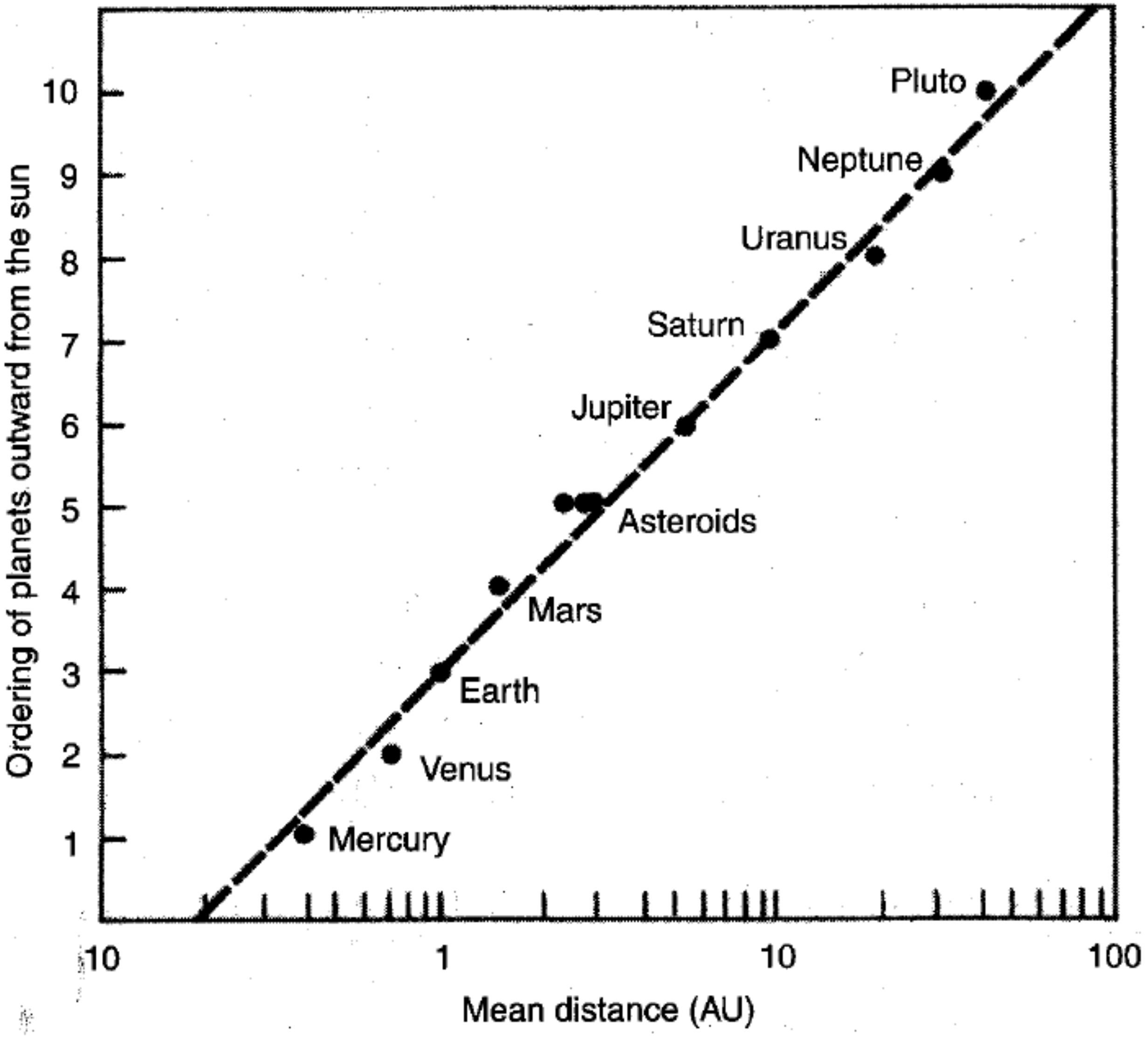


Figure 1.5 The spacing of planets in the Solar System appears fairly regular if a logarithmic scale of mean distances is used, and if the asteroids collectively are considered to be a planet. The dashed line corresponds to a spacing law such that each planet's orbit is 75% larger than the next inner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

From: Wood Fig. 1.5

Patterns in Planets

- Terrestrial planets are small, dense, rocky. Si, O, Fe, Mg – perhaps with Fe cores (H_2O only a very small fraction)
- Jovian planets are large, low density (Saturn is less dense than water), mostly H and He with traces of CH4, NH3, H_2O – they also have lots of moons (many of which have frozen H_2O).

Inner planets have…

- Higher density the closer to Sun (after correction for gravitational compression)

Planet	Density	Uncompressed Density
Mercury	5.44	5.30
Venus	5.24	3.96
Earth	5.50	4.07
Mars	3.36	3.40

- (Units in g/cm^3)

Orbits:

- All close to circular
- All in close to the same plane
- All in the same direction
- More later on meteorites, but the plot shows that the most “primitive” (unaltered by collisions and heating) have the same composition as the solar atmosphere