# Our Cosmic History*

Lecture #3 - April 15, 2010

## "Structure: The Formation of Galaxies, Stars, & Planets"

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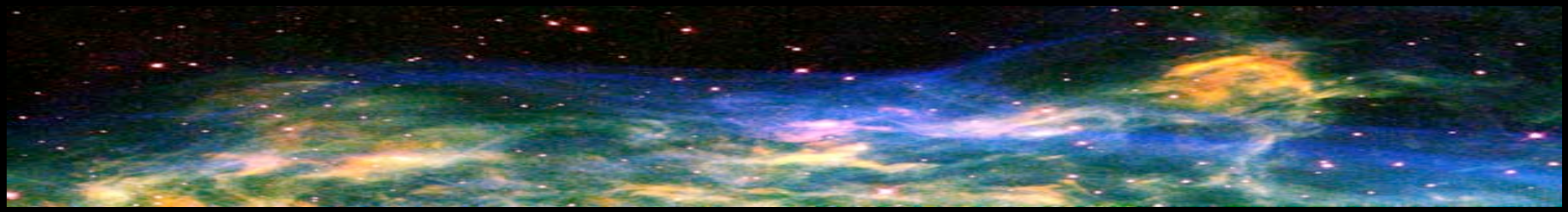
(with slides from Aparna Venkatesan, USF & Melinda Hutson, PSU)

** Lecture series sponsored by the PSU Center for Science Education & the Science Integration Institute, and made possible by a generous grant from the Oregon Dept. of Education*



# Themes of the series…

- Reflecting on what it means to be *you*, in this moment, within the context of the universe as we currently understand it. What is the cosmic *story* we are part of?
- Gaining perspective on how we connect to the universe: we are children of the *whole cosmos*, not just our immediate surroundings
- Framework for teachers and students to see how the details of science fit into a big picture that gives meaning and context to those details

# Series Web Site…

…for schedule, resources, & continuing discussion…

http://oregonteacherscholars.pbwiki.com/Our-Cosmic-History

(or link from www.scienceintegration.org)

Upcoming…

Lecture #4:

"Chemistry & Life on Earth"

April 22nd at 7 pm

(same location - 71 Cramer)

# How shall we understand the essence of Earth?

• Simplicity - Empty our minds, clear away clutter and reflect very deeply on a rock or a bit of earth - our home that gives us life - and the pure, simple awareness of that moment…

"To see a world in a grain of sand…."

"Nothing is nothing."

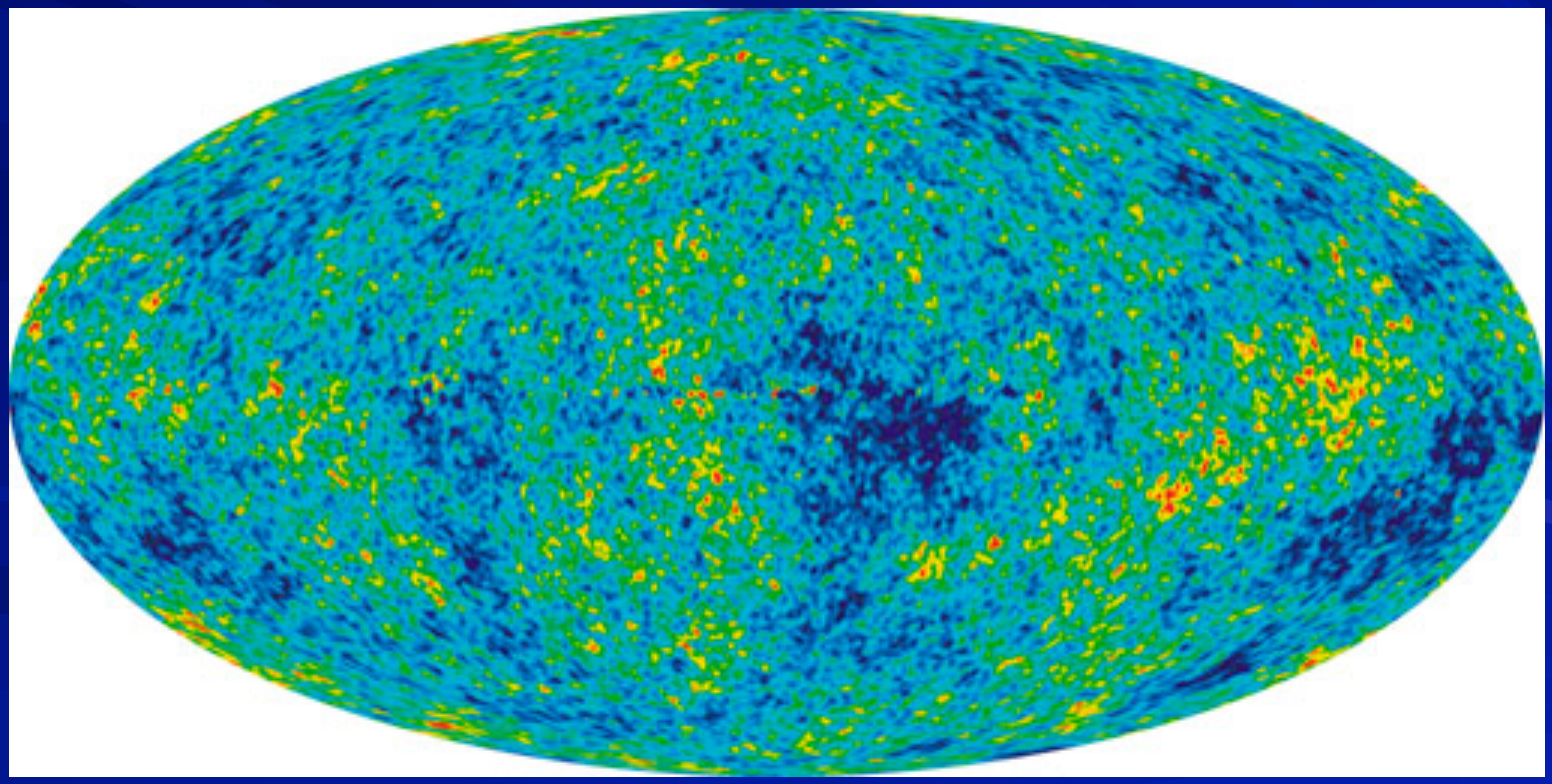
• Complexity - Scientific story contains many details that clutter and distract our minds in a way, but also deeply enrich our awareness of what we see.

# Balance…

“Precisely when we grasp the vastness of the universe we also grasp an equally vast interior, the enormous geography of the soul, so to speak. Words may fail afterward, forcing us to rely on hackneyed descriptions that emphasize our insignificance, but what we actually sense, if only for an instant, is largeness of spirit.”

~ Edwin Dobb

A snapshot of infant universe: Patterns of structure in the CMB observed by WMAP show us the “seeds” of galaxies in universe today; these seeds were only ~1 part in 100,000 different from the average at cosmic age 380,000 yr, but this was enough to make everything we see!



From Aparna Venkatesan

# Gravity: driving force for structure formation

Newton's simple idea with powerful consequences for the universe:

"Every piece of matter attracts every other piece of matter, with a force that is proportional to the product of the 2 masses and inversely proportional to the square of the distance between them."

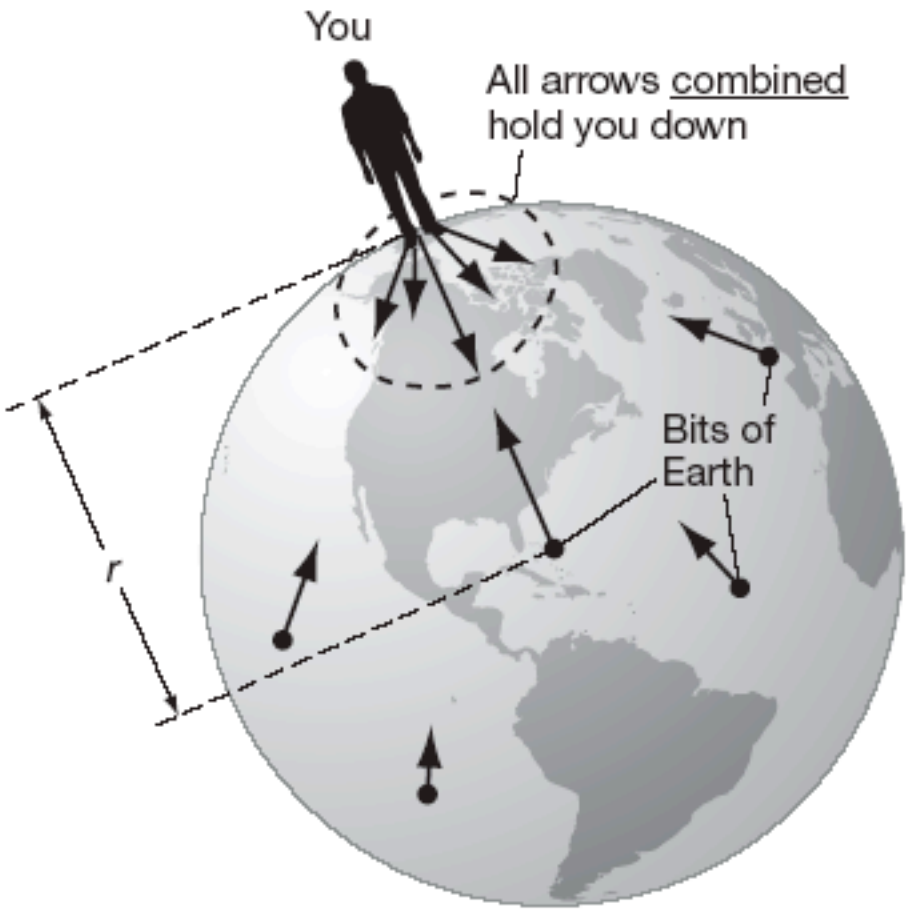



**FIGURE 4.6 Gravity at the Earth's Surface** You are pulled toward the center of the Earth with a force that is due to the combined forces of all the bits of mass that make up the Earth.

Source: Duncan & Tyler, *Your Cosmic Context*, ©2009 Pearson Addison-Wesley

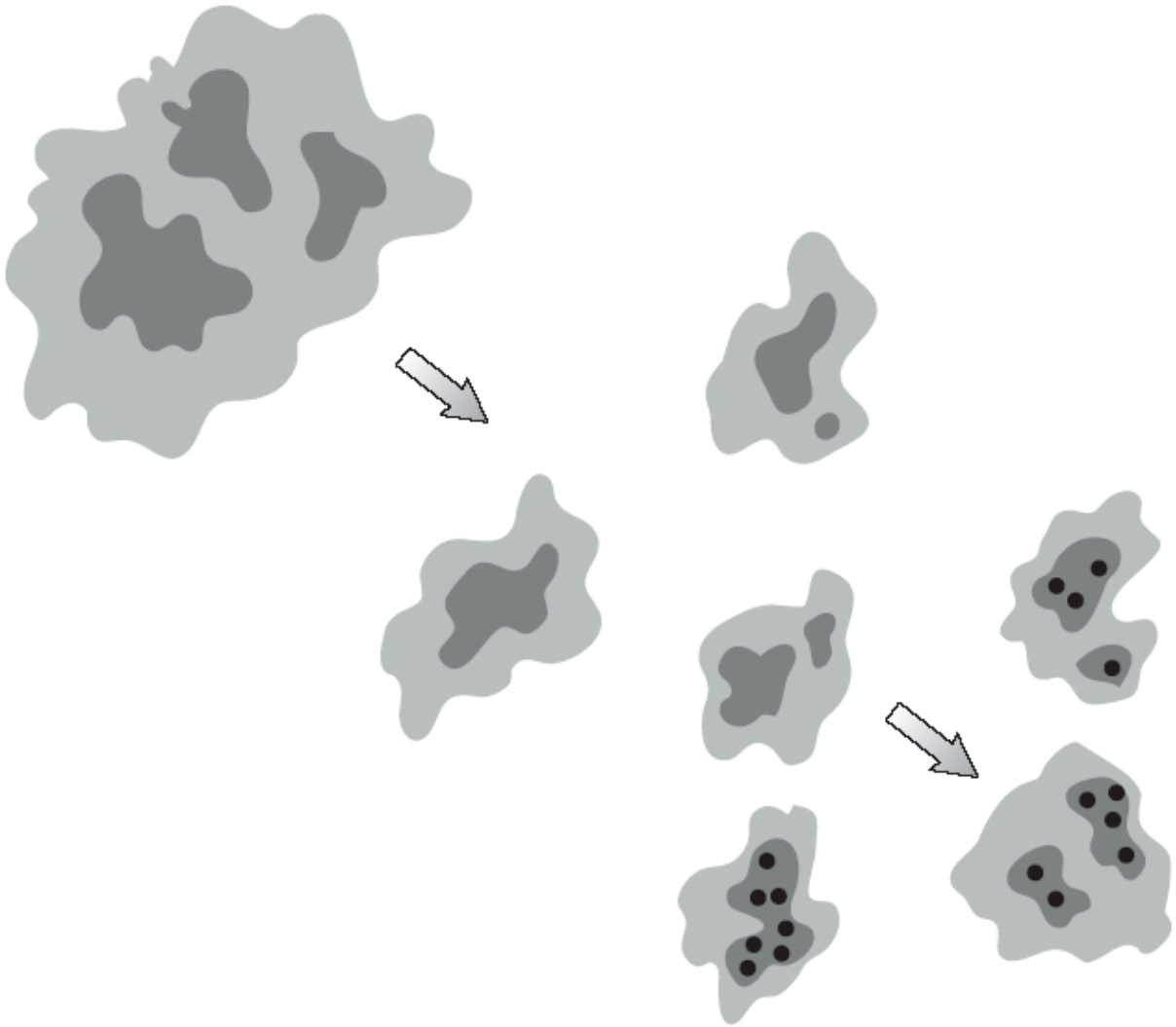


**FIGURE 11.9 Structure Formation** Dark matter halos (clumps of dark matter held together by their own gravity) gravitationally pull in clouds of baryonic matter (hydrogen and helium gas). In time, the baryons clump together, too, enabling pockets of particularly compressed gas to form stars. On larger scales, you can imagine networks of these halos and galaxies beginning to assemble into clusters, walls, and voids (more on this in Chapter 12).

Source: Duncan & Tyler, *Your Cosmic Context*, ©2009 Pearson Addison-Wesley

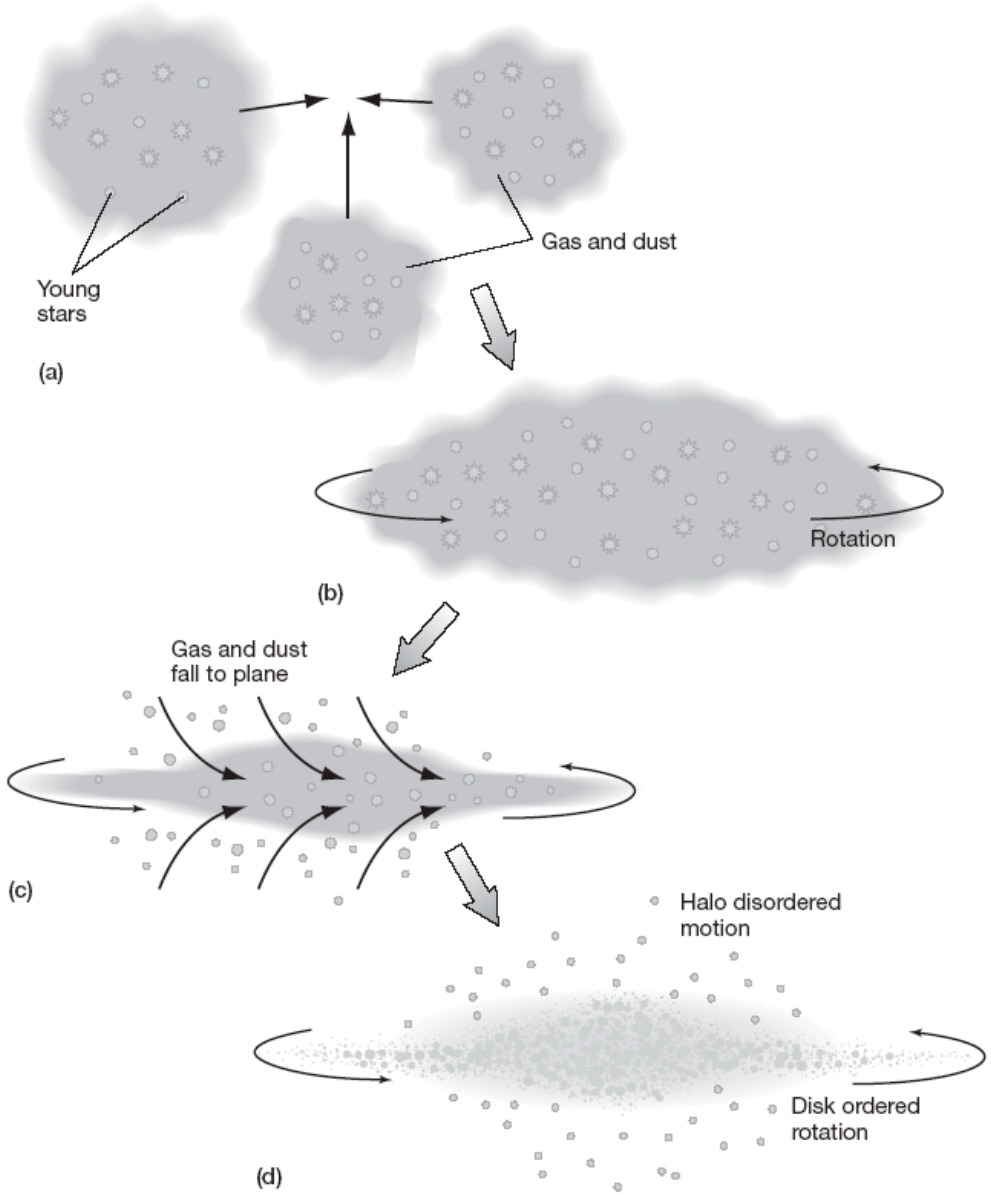



**FIGURE 4.15 Spiral Galaxy Formation** The formation of spiral galaxies under the influence of gravity and rotation generates separate components. Shown here, the disk forms from a rotating gas cloud, which later fragments into stars. The halo appears to be composed of stars that formed prior to the disk; now the swirling gas in the disk is not able to "push" halo stars into flat orbits.

Source: Duncan & Tyler, *Your Cosmic Context*, ©2009 Pearson Addison-Wesley

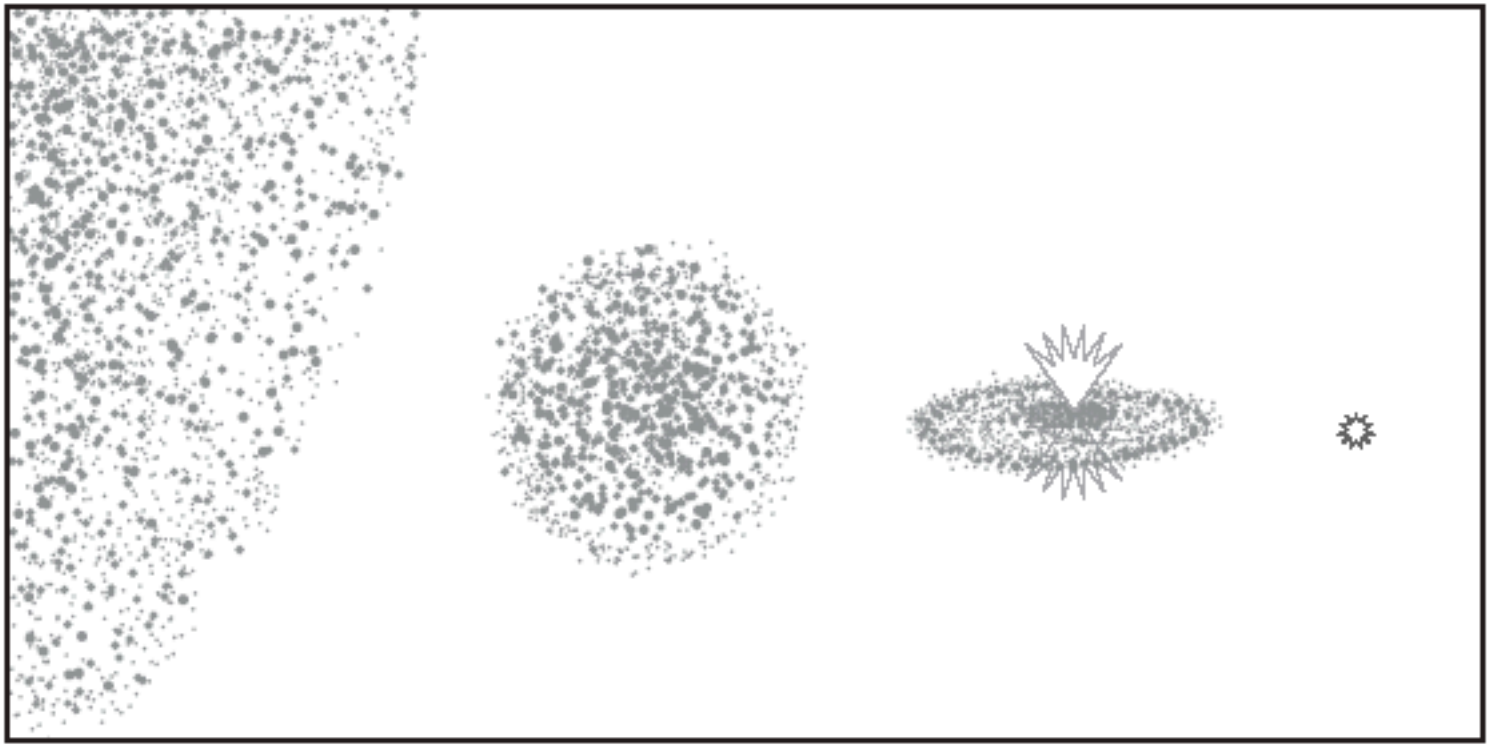
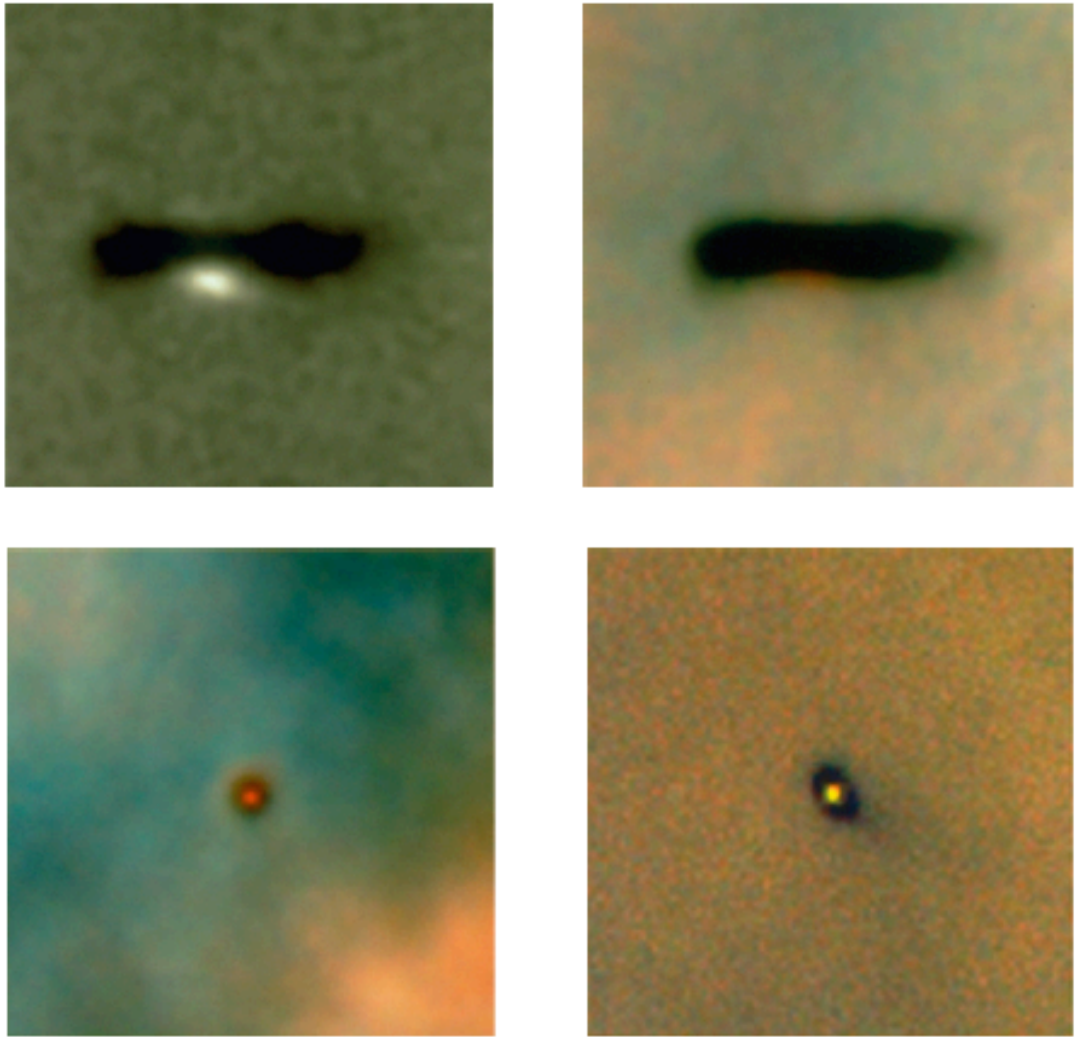


**FIGURE 9.4 Star Formation** Evolution of an interstellar cloud as it compresses by its own gravity, flattens into a spinning disk, and spawns a star at the center, possibly with orbiting planets forming within the disk.



**COLOR FIGURE 21 Infrared Images of Stars Forming in the Orion Region** The glow observed from the centers appears to be that of small stars forming. The dark, dusty disks, seen approximately edge on in the two upper frames, are about 400 AU thick (about 7 times the diameter of our solar system). Therefore, if this system is to evolve into a planetary system like ours, the disk will need to slim down dramatically. In the two lower frames, the same situation is seen in a "top view" (we happen to view these from "above" rather than edge on).

# Galaxy formation begins…

simulation courtesy C. Ma (UC Berkeley) and collaborators

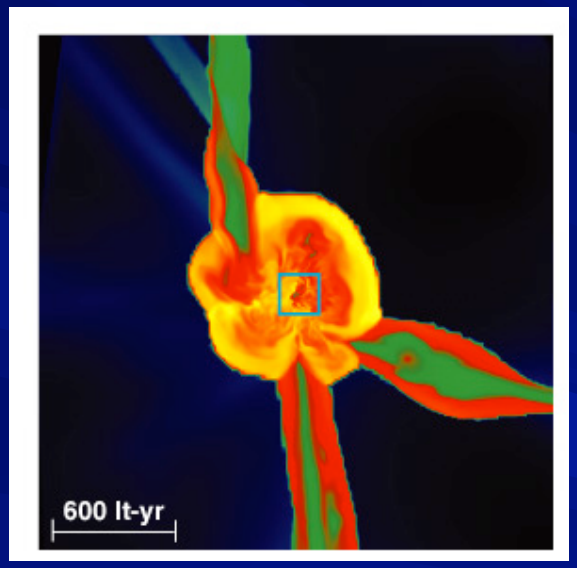
From Aparna Venkatesan

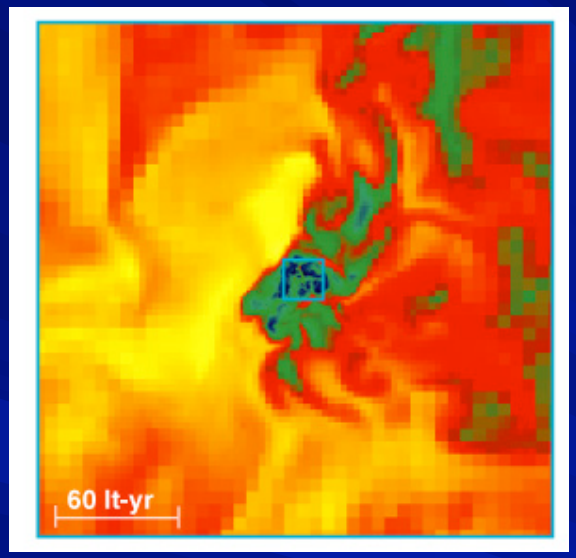
# First Stars: End of the dark ages

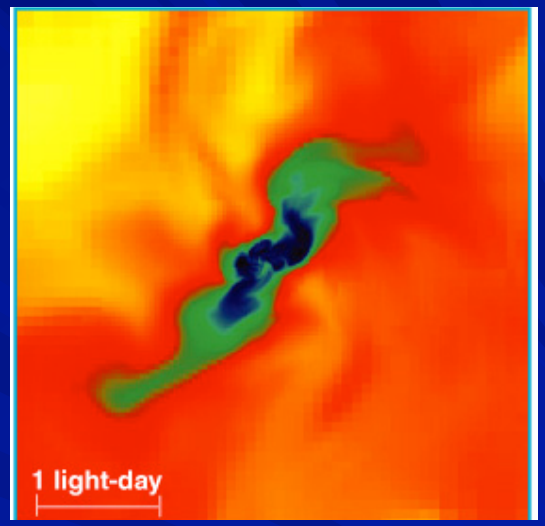
- The first stars are believed to have formed when the universe was about 100-500 million years old
- Note they would have been made only of H & He so different than stars forming today
- First sources of light (stars and quasars) important for “reionization” of universe - and enriching universe with heavier elements

From Aparna Venkatesan

# Simulation of the First Star




- Simulations of early star formation suggest the first molecular clouds never cooled below 100 K, making stars of > 10 $M_{Sun}$, possibly up to ~100-300 $M_{Sun}$

From Aparna Venkatesan

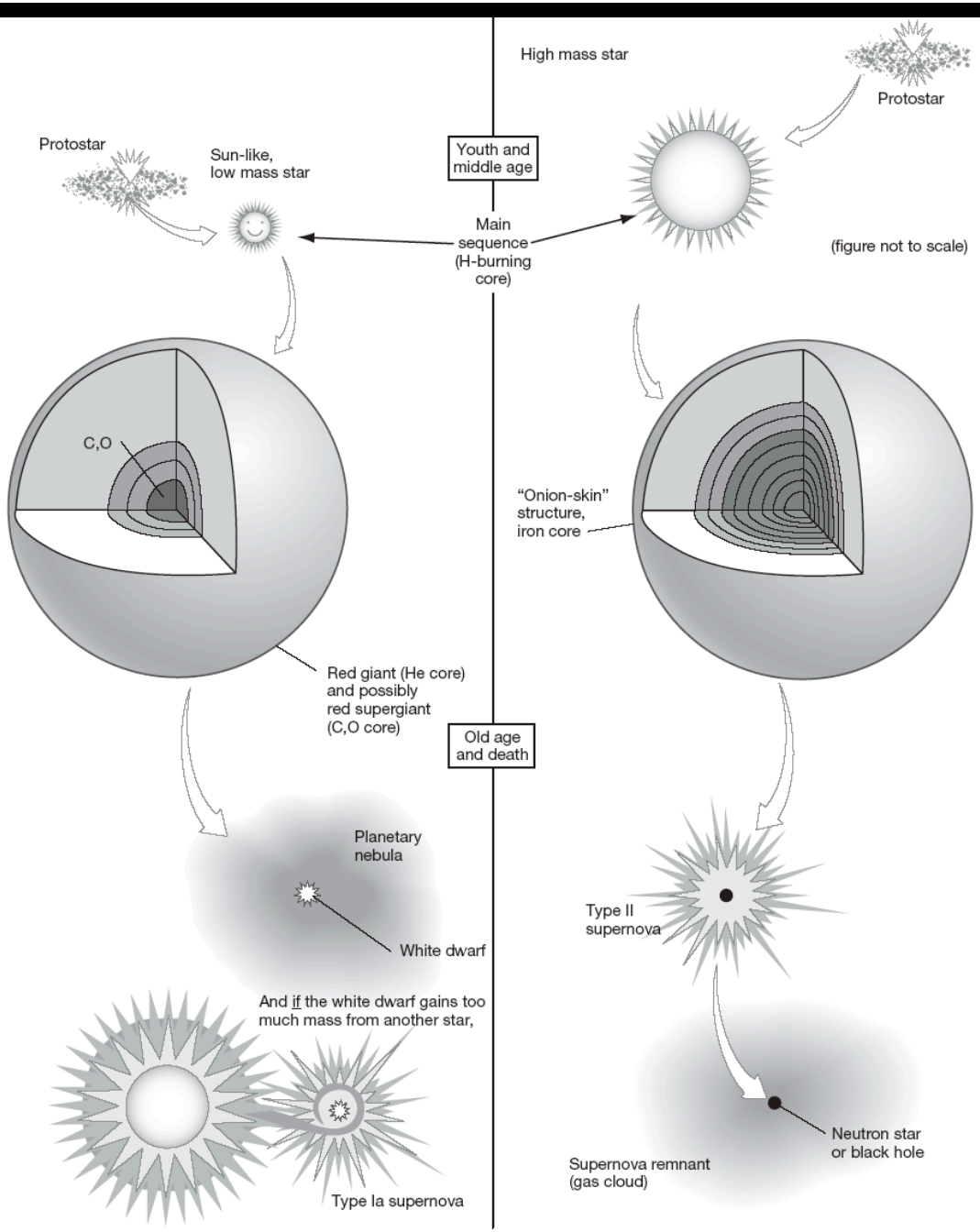



**FIGURE 9.8 Stellar Evolution** The left side summarizes the evolution of a low-mass star, such as the Sun; this summary is valid for a star that's less than about 10 solar masses. The evolution of more massive stars is summarized on the right side. (See the text for details.)

Source: Duncan & Tyler, *Your Cosmic Context*, ©2009 Pearson Addison-Wesley

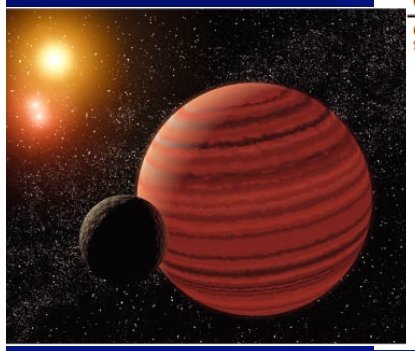
# Lifetimes of Stars

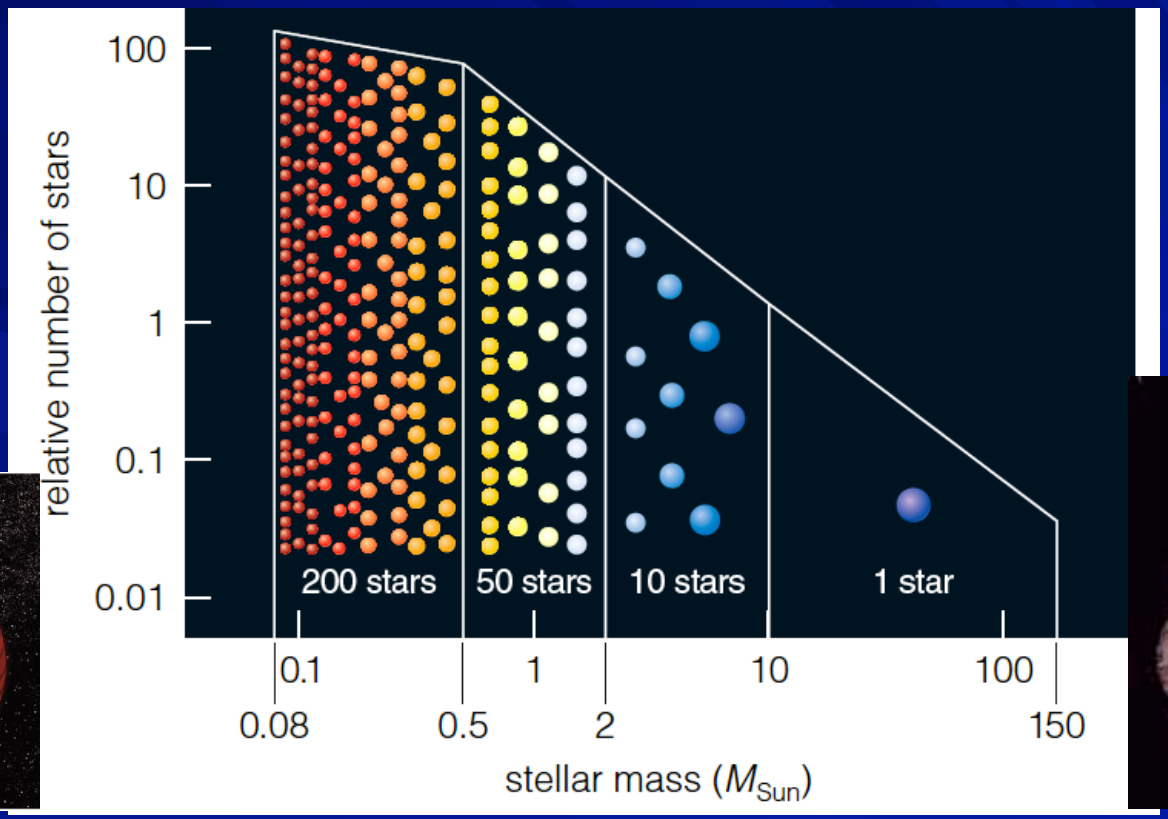
- Rock-star analogy: high-mass stars are hotter and more luminous – BUT they burn through the available fuel MUCH faster, leading to early burnout

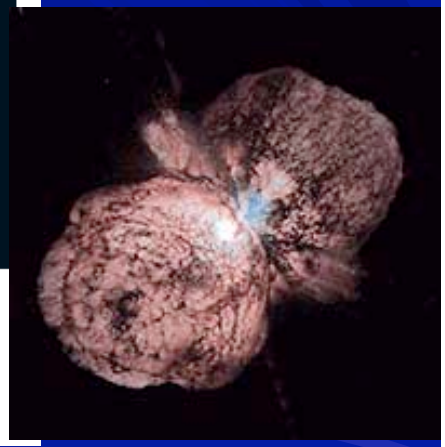
- Such stars are rare but have enormous impact on cosmic history

From Aparna Venkatesan

# Demographics of Stars





- Observations of star clusters show that star formation TODAY makes many more low-mass stars (dominate overall mass) than high-mass stars (dominate overall light)

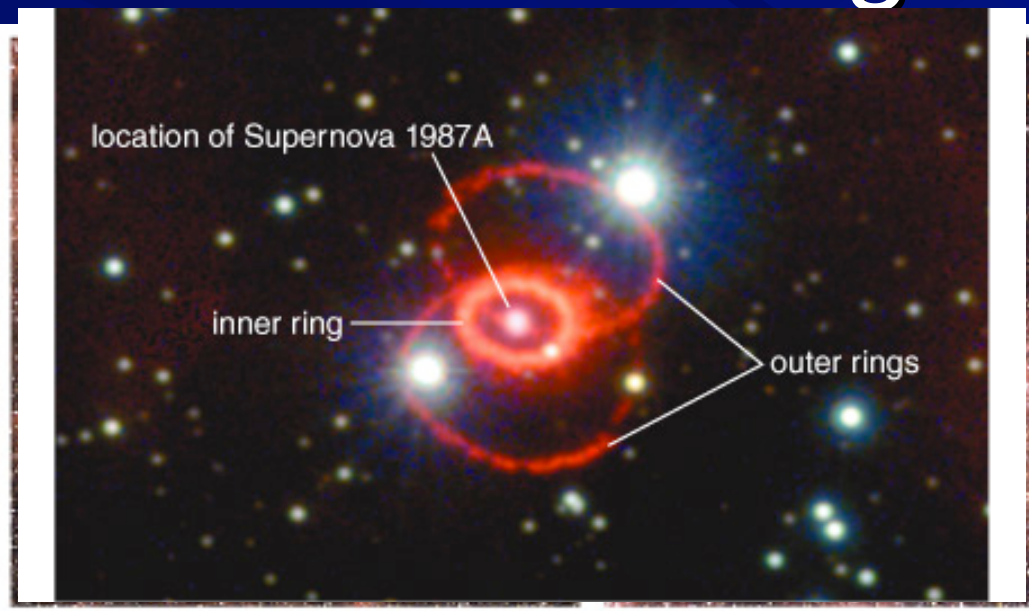
From Aparna Venkatesan

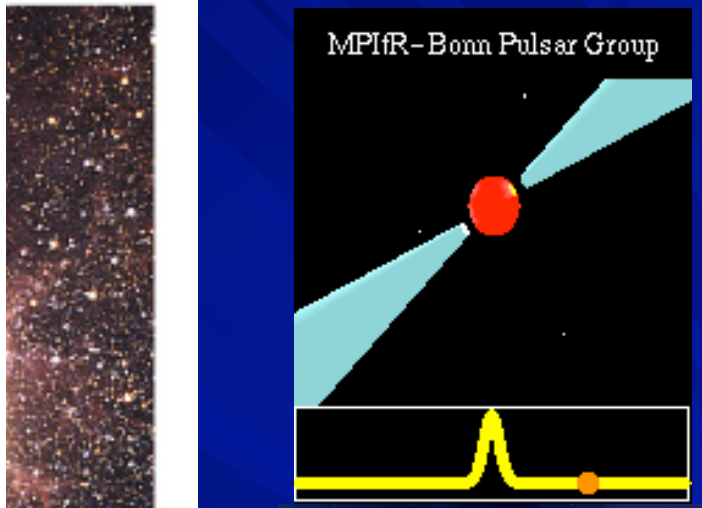
# The First Stars: Masses

- Without any heavy elements or molecules to provide cooling, the clouds that formed the first stars may have been considerably warmer than today's molecular clouds
- The first stars may therefore have been more massive than most of today's stars, in order for gravity to overcome pressure in parent cloud. This would explain why we have not observed such primordial stars to date (they didn't live very long), BUT THIS IS STILL AN UNRESOLVED ISSUE!

From Aparna Venkatesan

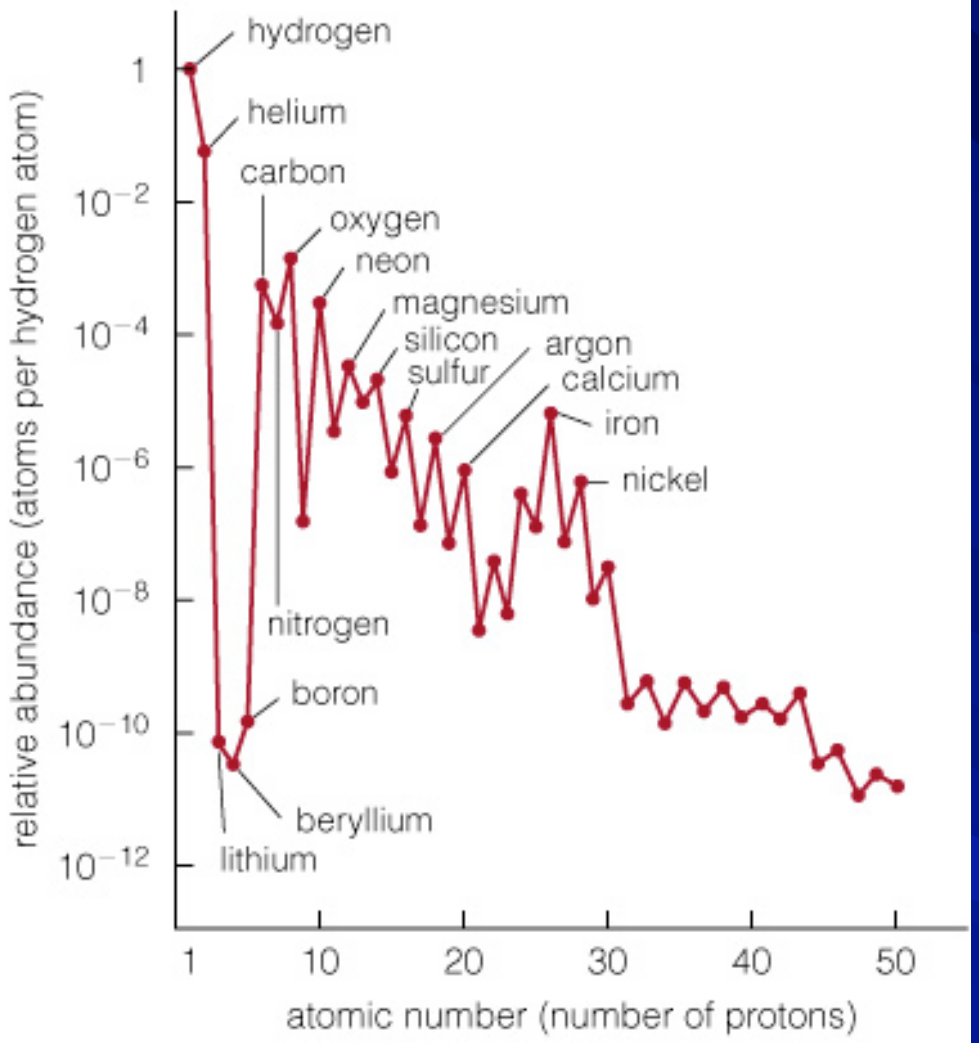
# Death of high-mass stars




End their lives as supernovae leaving behind a pulsar or black hole. The closest supernova in the last four centuries was seen in 1987 in the Large Magellanic Cloud (closest small galaxy)

From Aparna Venkatesan



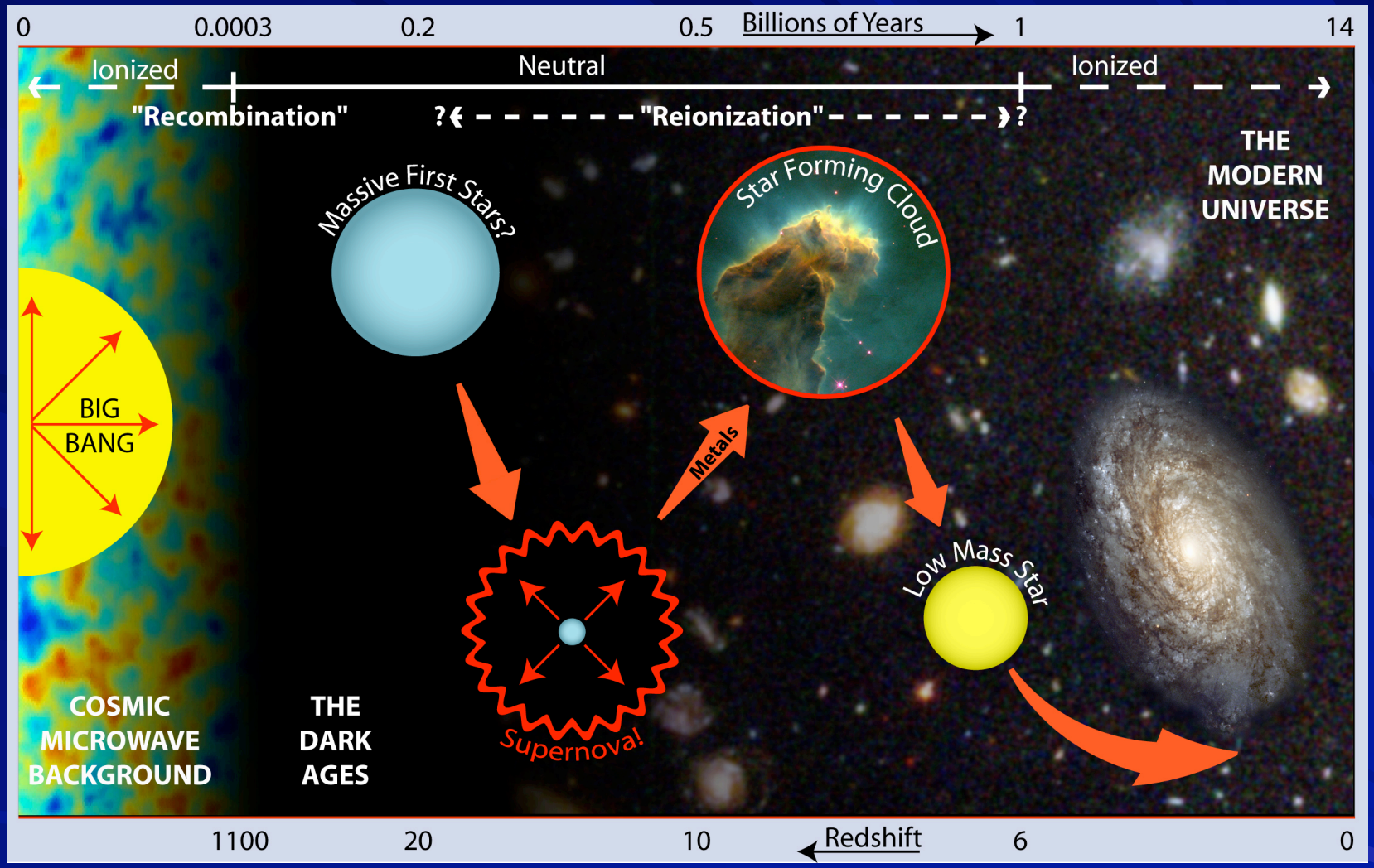

Observed composition of the universe today (note H & He MUCH more common than everything else).

From Aparna Venkatesan

# Element Genealogy:

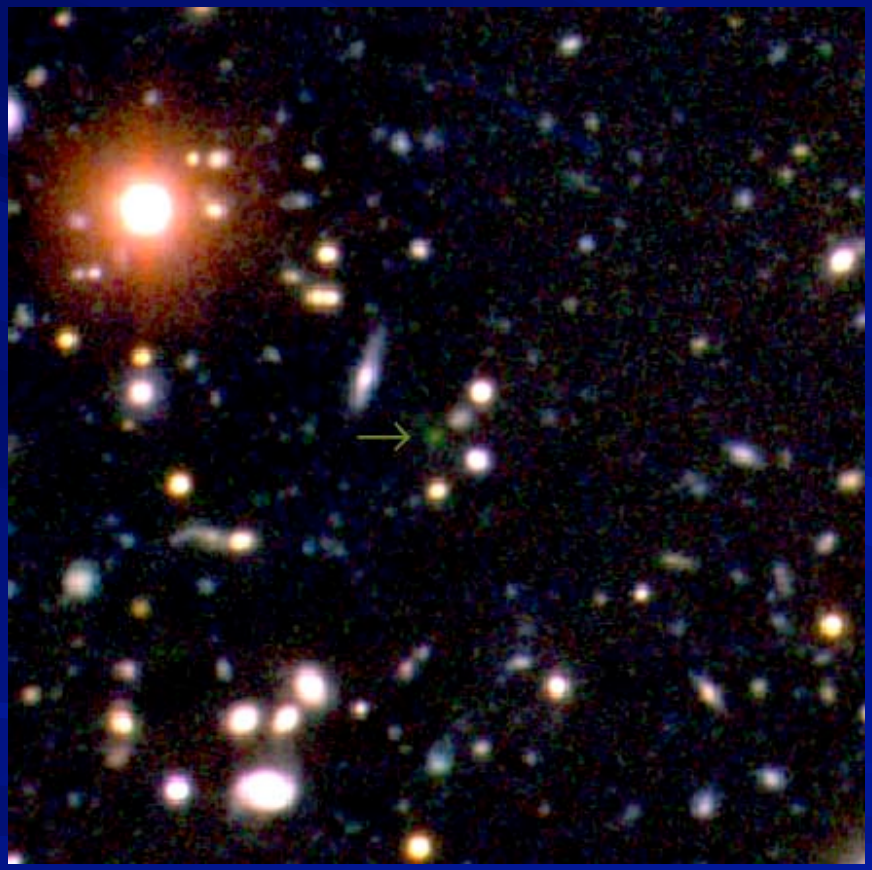
- Low mass: < 2 times the Sun
  make elements up to carbon
- Intermediate masses: 2-8 times the Sun
  make elements beyond carbon, like nitrogen up to oxygen, and no more
- High masses: > 8 times the Sun
  end as supernovae, make elements up to iron and beyond

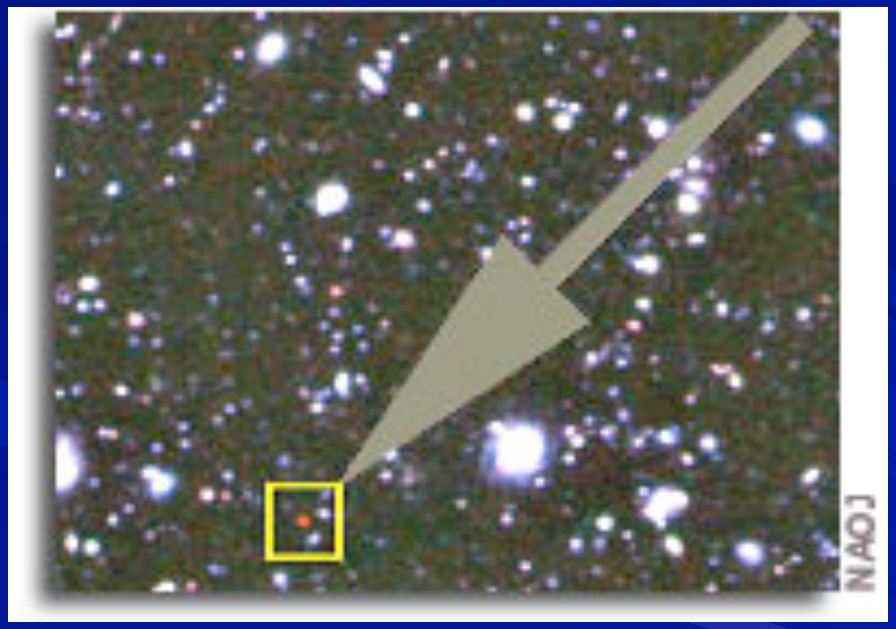
From Aparna Venkatesan




**Source: Tumlinson, Venkatesan & Shull 2004, Sky and Telescope**

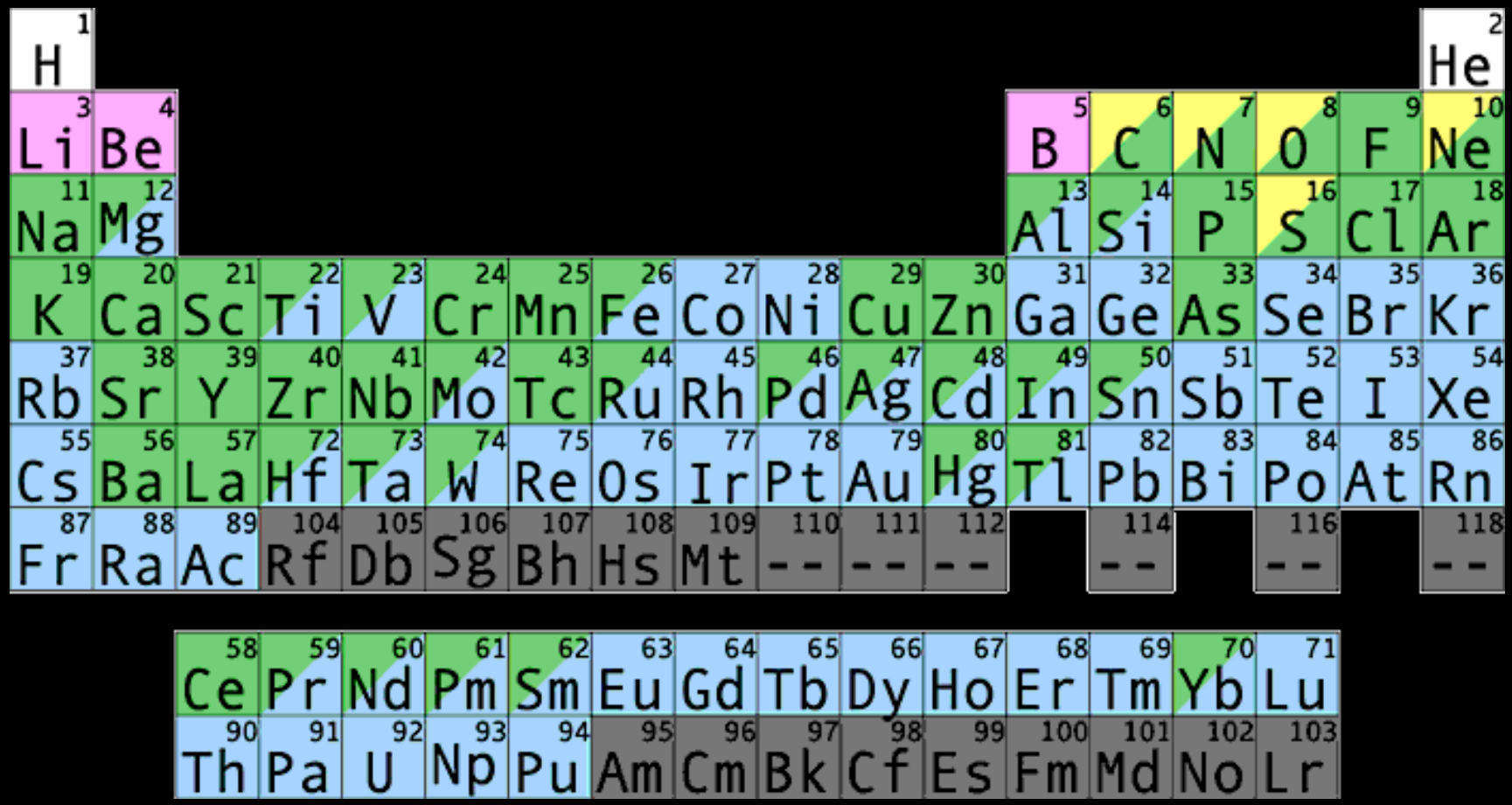
# Distant galaxies in emission at cosmic age 0.8 billion yr





*Source: NASA Imagine the Universe project*

http://imagine.gsfc.nasa.gov/docs/teachers/elements/elements.html




White - Big Bang

Pink - Cosmic Rays

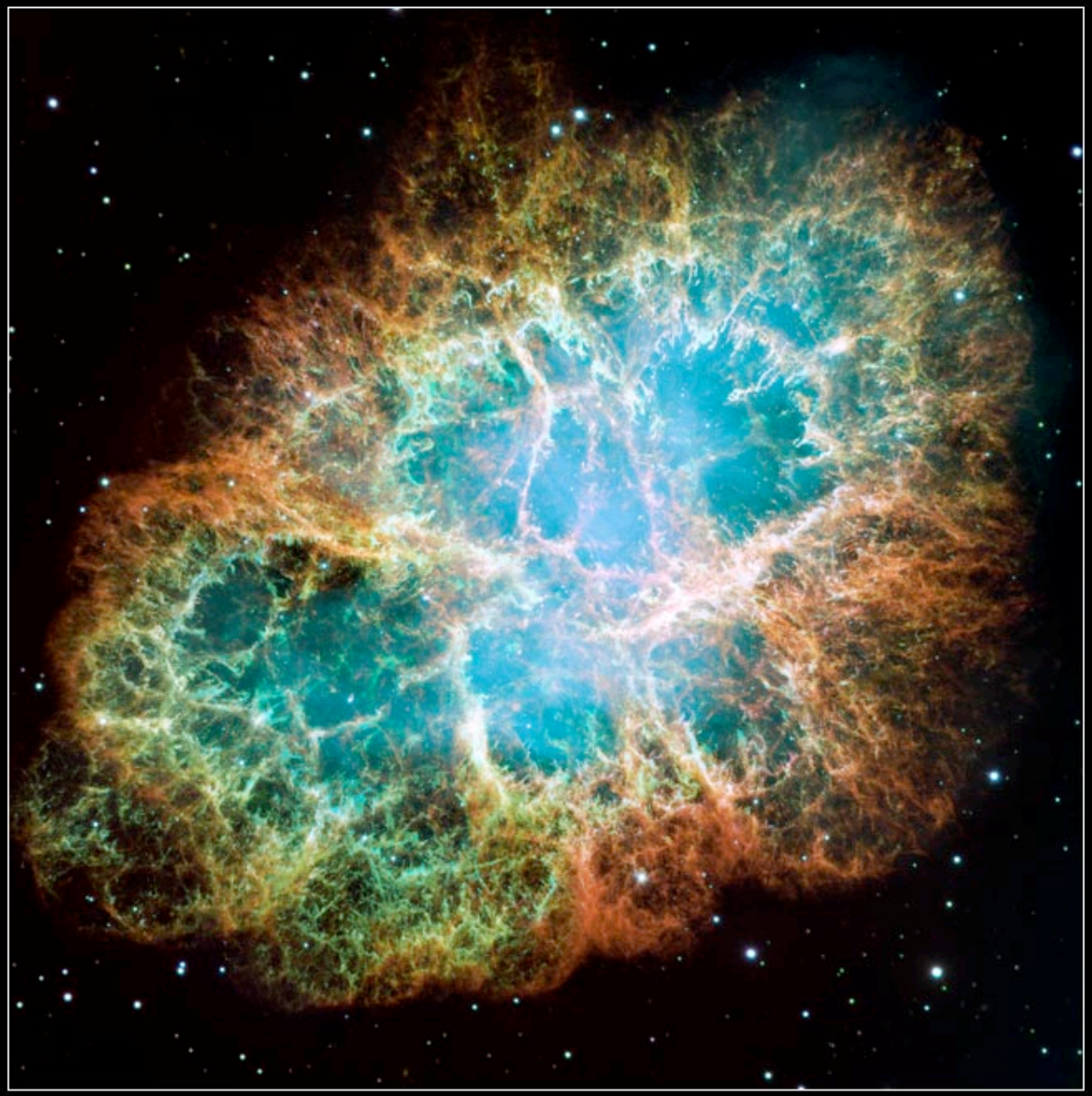
Yellow - Small Mass Stars

Green - Large Mass Stars

Blue - Supernovae

Crab Nebula ▪ M1

*HST* ▪ WFPC2



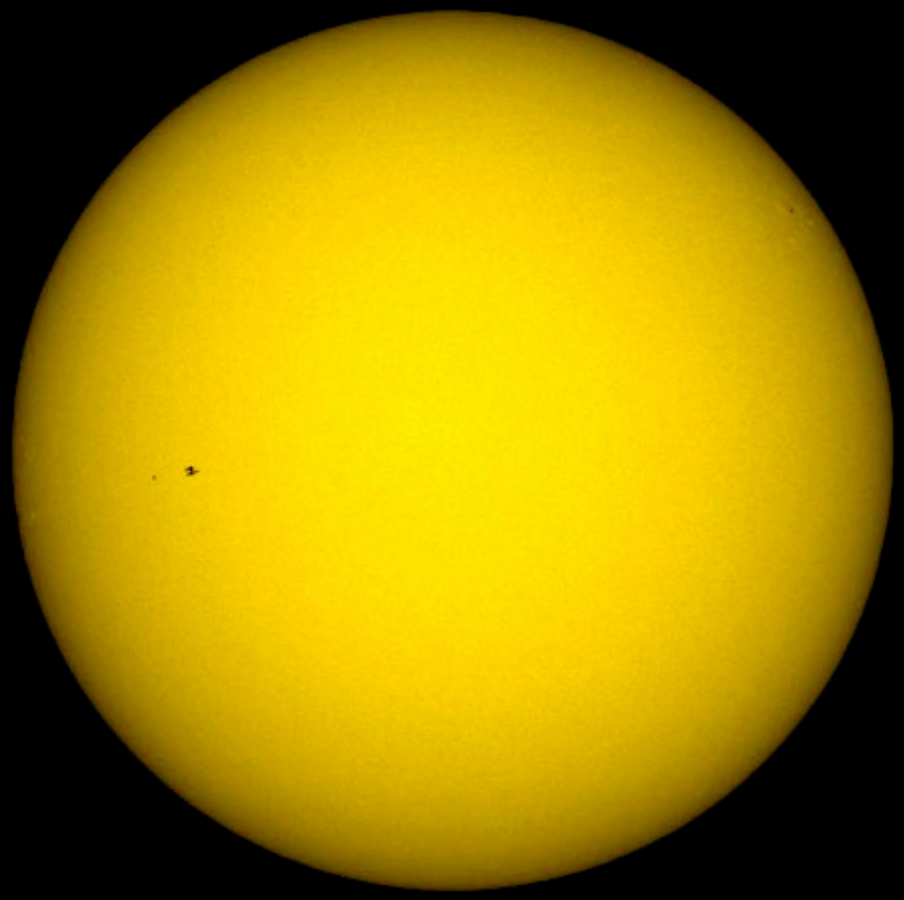
NASA, ESA, and J. Hester (Arizona State University)

STScI-PRC05-37


Microwave Popcorn

**How does the formation of our own solar system and Earth fit into this general picture?**

**The key point to remember – the solar system formed as a byproduct of the formation of our sun**



http://img.dailymail.co.uk/i/pix/2006/09/sun290906_468x460.jpg

From Melinda Hutson

**Question:**

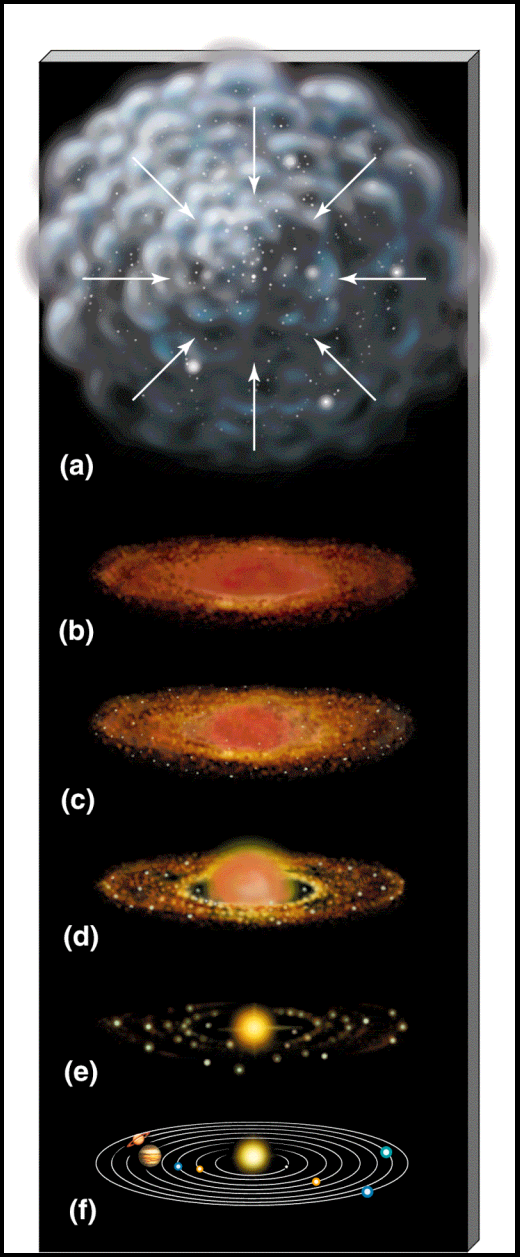
When did the solar system and the Earth form?

**Answer:** Between 4.5 and 4.6 billion years ago

**Question:**

How can we tell this?

Answer: Radiometric dating of meteorites, the oldest rocks on the Moon, and a zircon grain on the Earth




From Melinda Hutson

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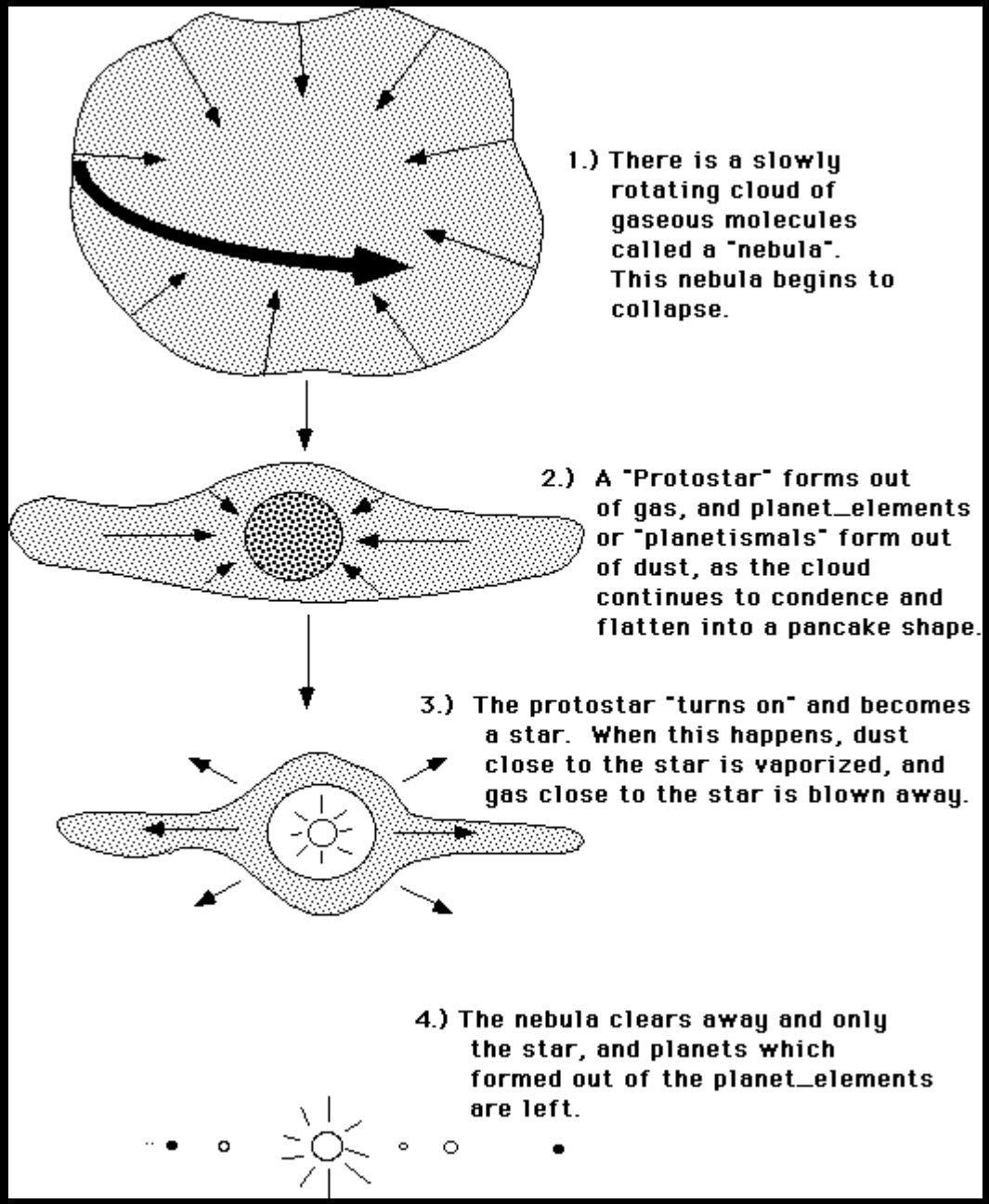


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## The simple model:

**Step 1: A portion of a huge "molecular cloud" collapses – as it collapses it forms a disk of gas and dust called a nebula.**

**Step 2: Most of the gas and dust migrates inward to create a hot luminous center = "protostar"**

**Step 3: The star "turns on" and the "protoplanetary nebula" dissipates leaving behind leftover building material that didn't make it into the star (planets, moons, asteroids and comets)**

From Melinda Hutson

**Question:**

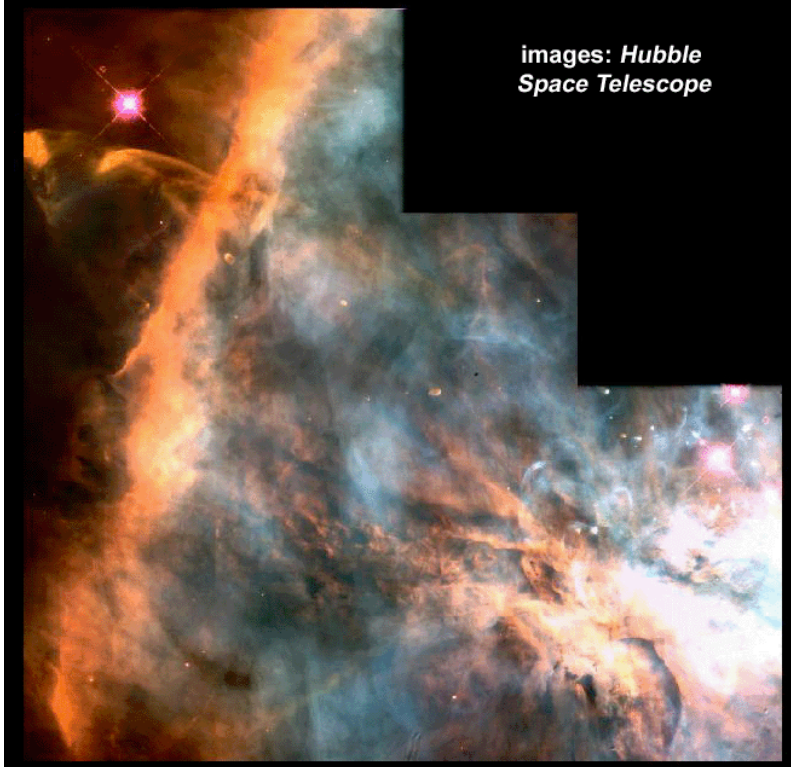
**Do we see any evidence to support our simple model?**

**Answer:**

**Yes, at least on a large scale**

From Melinda Hutson

# The Orion Nebula



images: *Hubble Space Telescope*

**We see ovoid- and disk-shaped protoplanetary nebulae inside star-forming regions such as the Orion Nebula.**

proplyds in the Orion Nebula

images: *Hubble Space Telescope*

From Melinda Hutson

We see light from protostars, some of which have strong magnetic fields, inside some protoplanetary nebulae.

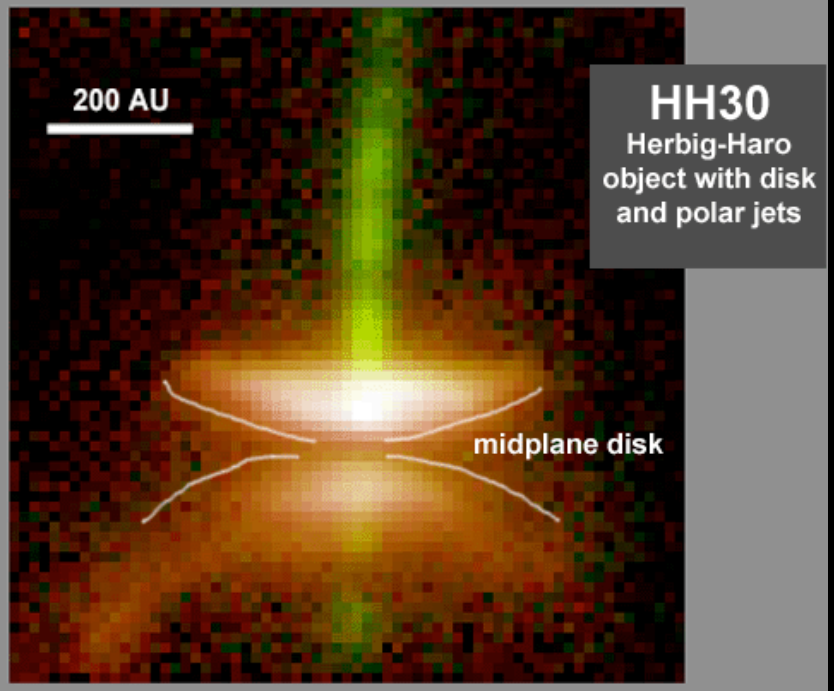
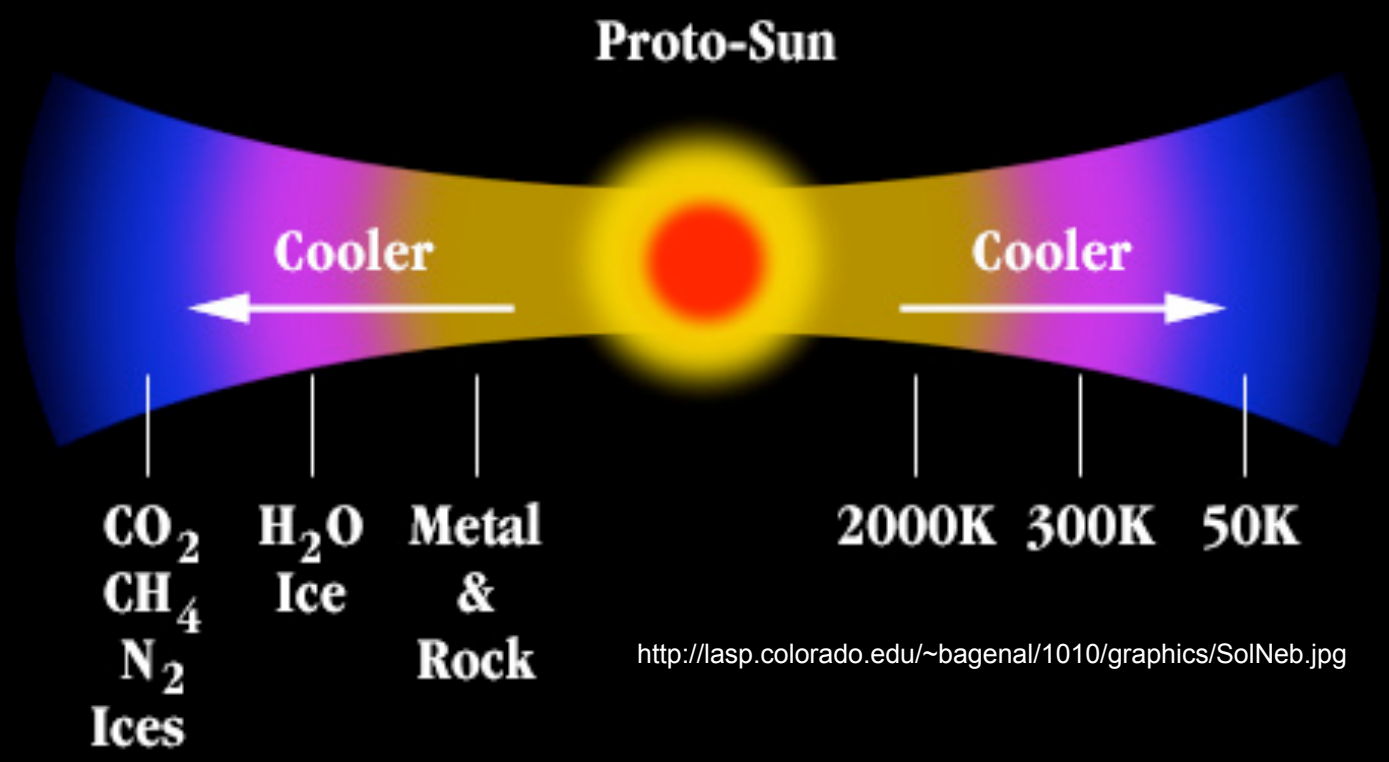




image: *Hubble Space Telescope*

Midplane of disk is opaque (blocks light from newly forming star) because of solid material in disk – why solid?

From Melinda Hutson



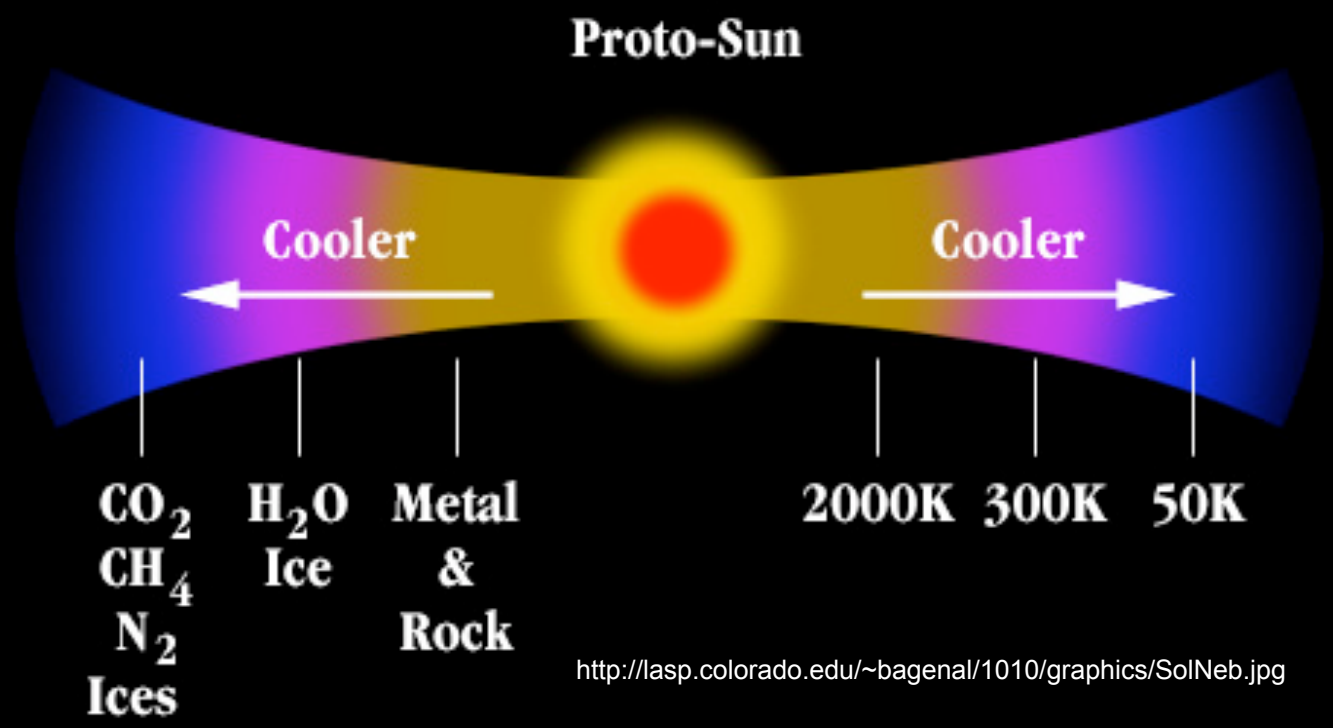

http://lasp.colorado.edu/~bagenal/1010/graphics/SolNeb.jpg

**We know that molecular clouds are very cold before they begin to collapse.**

**The surface of the sun today is 5700K, and the interior has to be over 10,000,000K (to be a star).**

**We also know from looking at disk-shaped nebulae in space that the disk is densest in the center and less dense the farther one gets from the protostar**

From Melinda Hutson



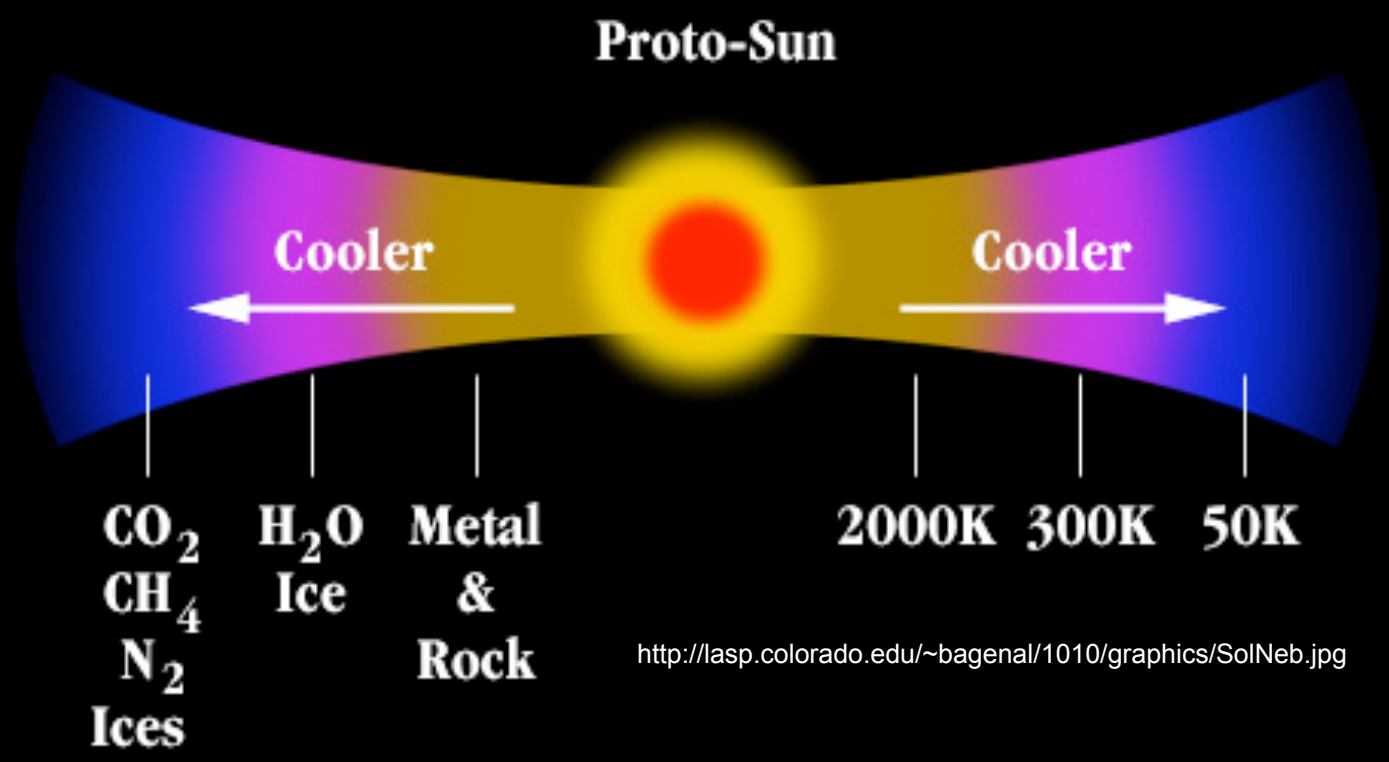

http://lasp.colorado.edu/~bagenal/1010/graphics/SolNeb.jpg

**Our simple model looks at a snapshot in time and assumes that only rock and metal were solid and available to build planets and asteroids in the inner solar system**

**The model also assumes that the outer solar system had both the inner solar system solids as well as solid ices, and so could build more massive planets, icy moons and comets .**

**The model predicts that the most massive planets would be able to gravitationally "grab" nebular gas, and so become gas giants.**

From Melinda Hutson




http://lasp.colorado.edu/~bagenal/1010/graphics/SolNeb.jpg

**Our simple model predicts:**

**Planets all formed in the same plane orbiting the sun in the same direction.**

**Rocky/metallic planets should be smallest closest to the sun and largest just before the location where ice becomes solid.**

**The largest gas giant planets form where ice becomes solid and gas giant planets become smaller the farther you get from the sun.**

From Melinda Hutson

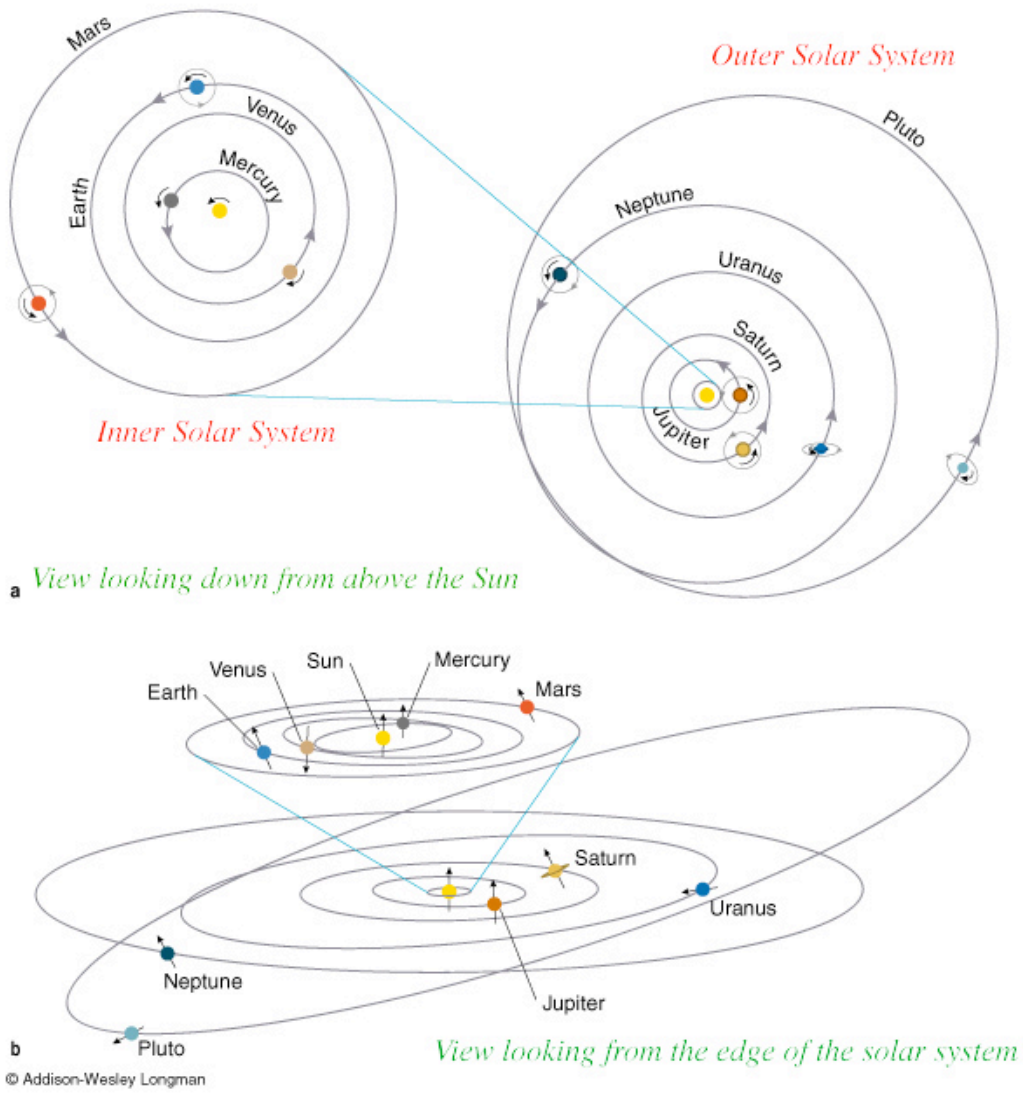
**Question:**

**Do we wind up with exactly the sort of solar system predicted by our simple model?**

**Answer:**

**Not quite, but close for our solar system and not at all for recently discovered solar systems around other stars**

From Melinda Hutson



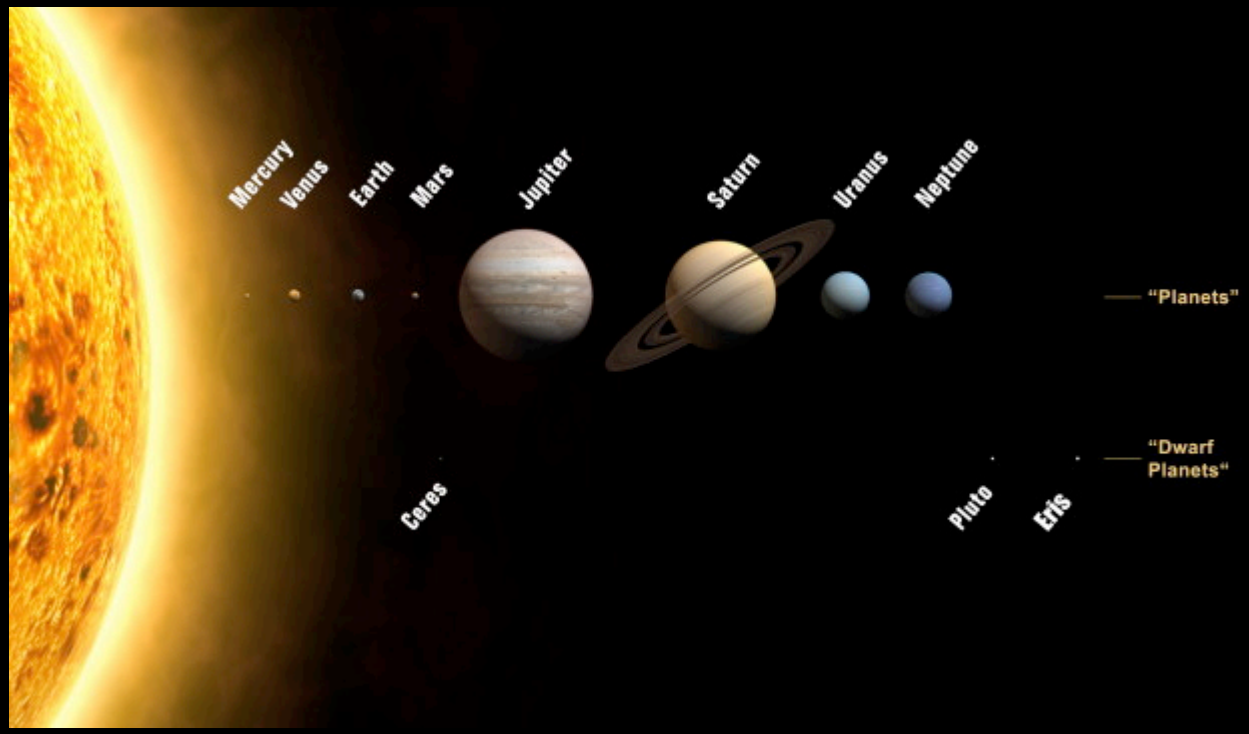

**The planets in our solar system do orbit the sun in a plane with all of the planets going around the sun the same direction.**

http://www.astro.psu.edu/users/niel/astro1/slideshows/class43/slides-43.html

From Melinda Hutson

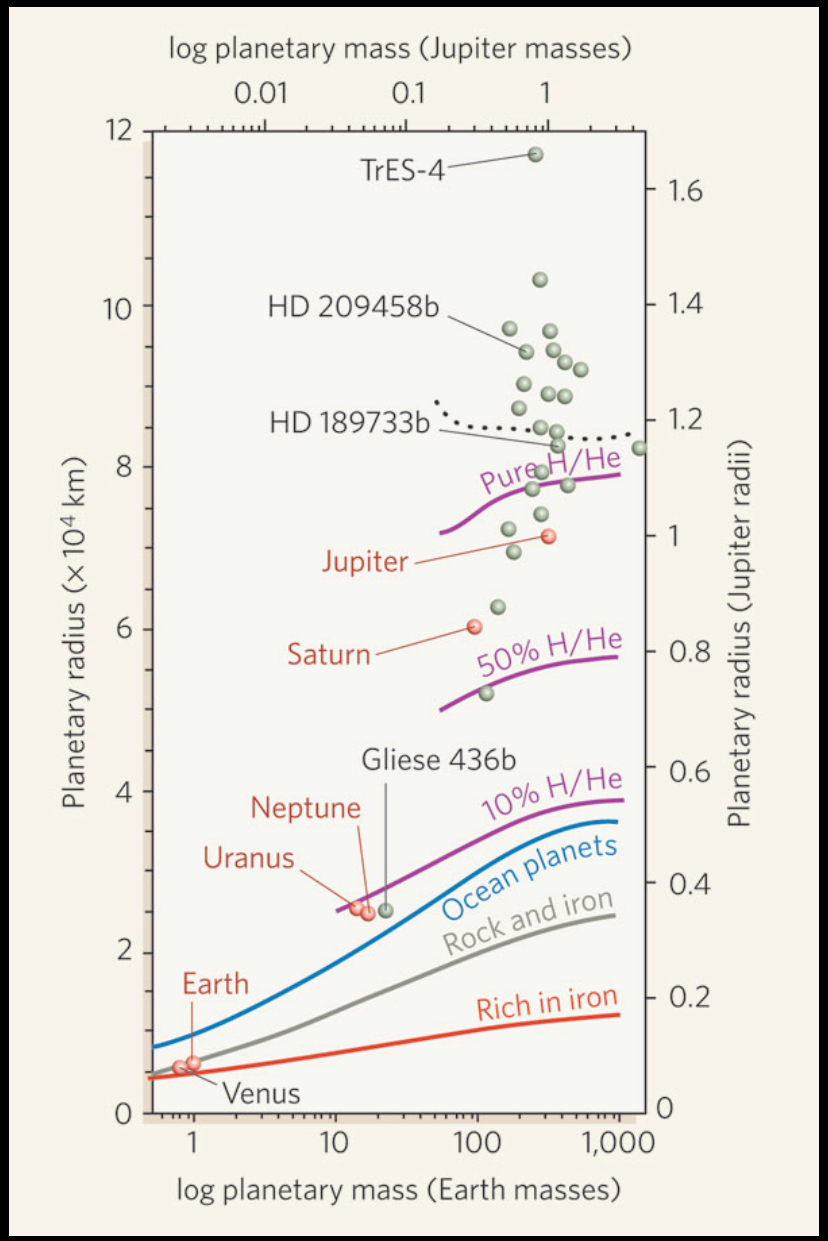
**The terrestrial planets (rocky/metallic) do get bigger going from Mercury to the Earth, but then Mars is smaller and there is an asteroid belt instead of a planet between Mars and Jupiter.**

**Jupiter is the largest gas giant and the gas giants do get smaller the farther you get from the sun.**




Solar System diagram. The planet sizes are to scale, the distances between them are not.
**Credit: The International Astronomical Union / Martin Kornmesser**

From Melinda Hutson



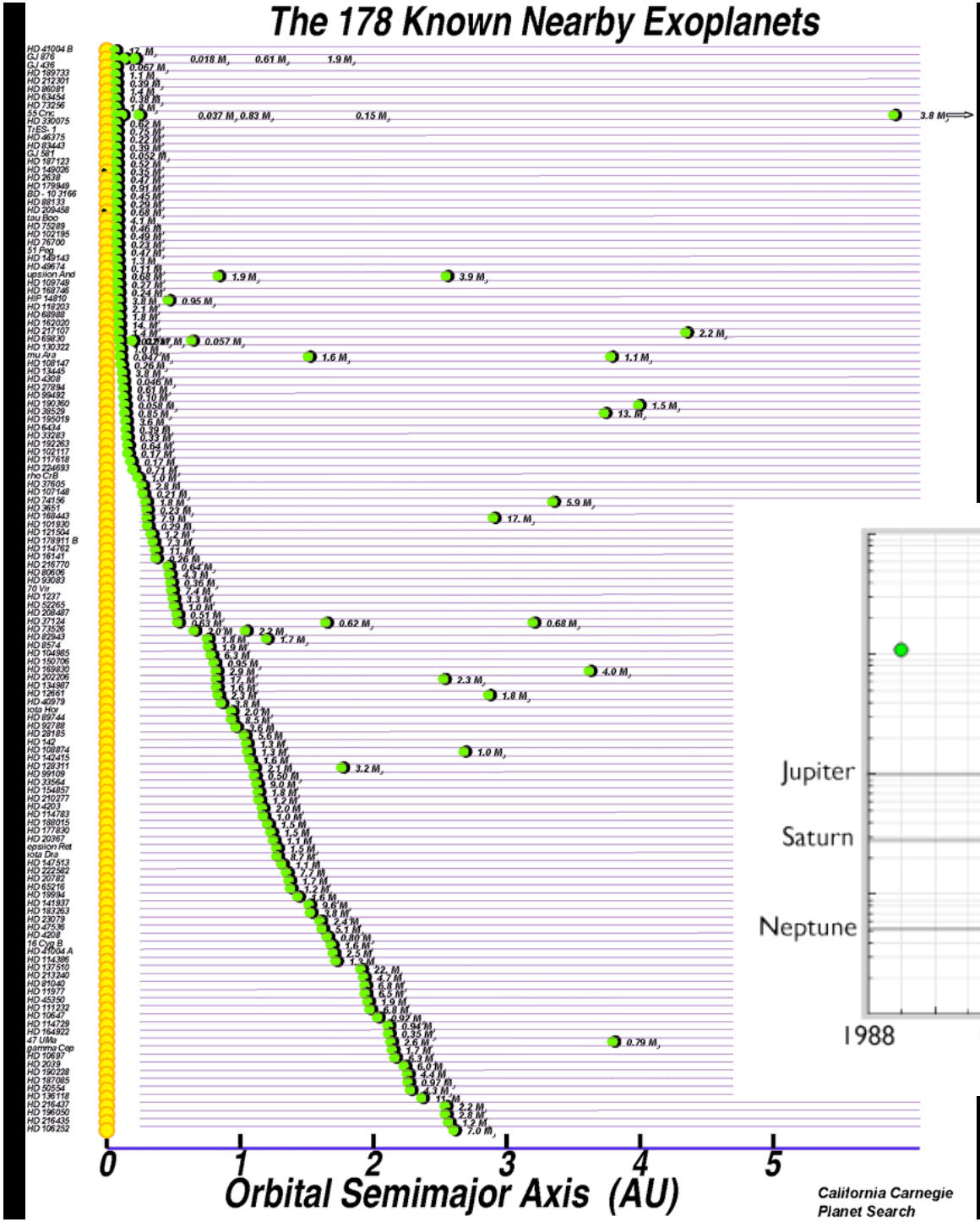

http://www.nature.com/nature/journal/v451/n7174/images/451029a-f1.0.jpg

**Figure to left from 2008**

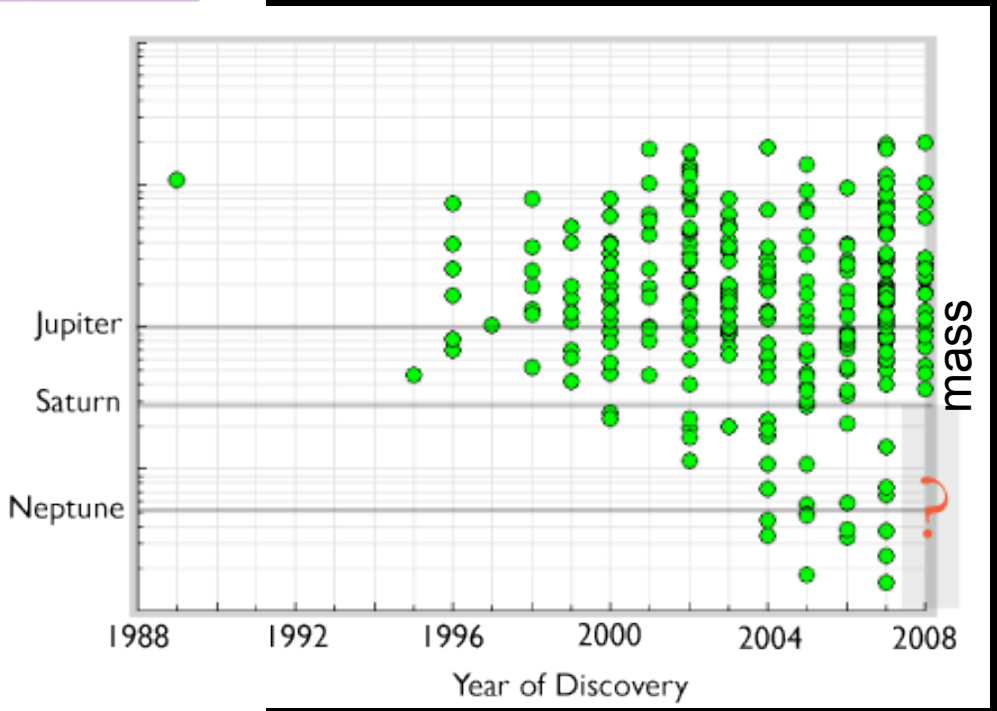
**We've now discovered that when a planet reaches a critical size/mass, it rapidly becomes Jupiter-sized or larger and is essentially star-like (almost entirely H and He) in its composition.**

**We think that Jupiter became huge before the terrestrial planets finished forming and that Jupiter's gravity "pulled" material out of the region where Mars and the asteroid belt are, causing Mars to be small and preventing a planet from forming where the asteroids are.**

From Melinda Hutson




We've also discovered a lot of planets/solar systems around other stars that don't look at all like ours – data to left 2006. WHY?

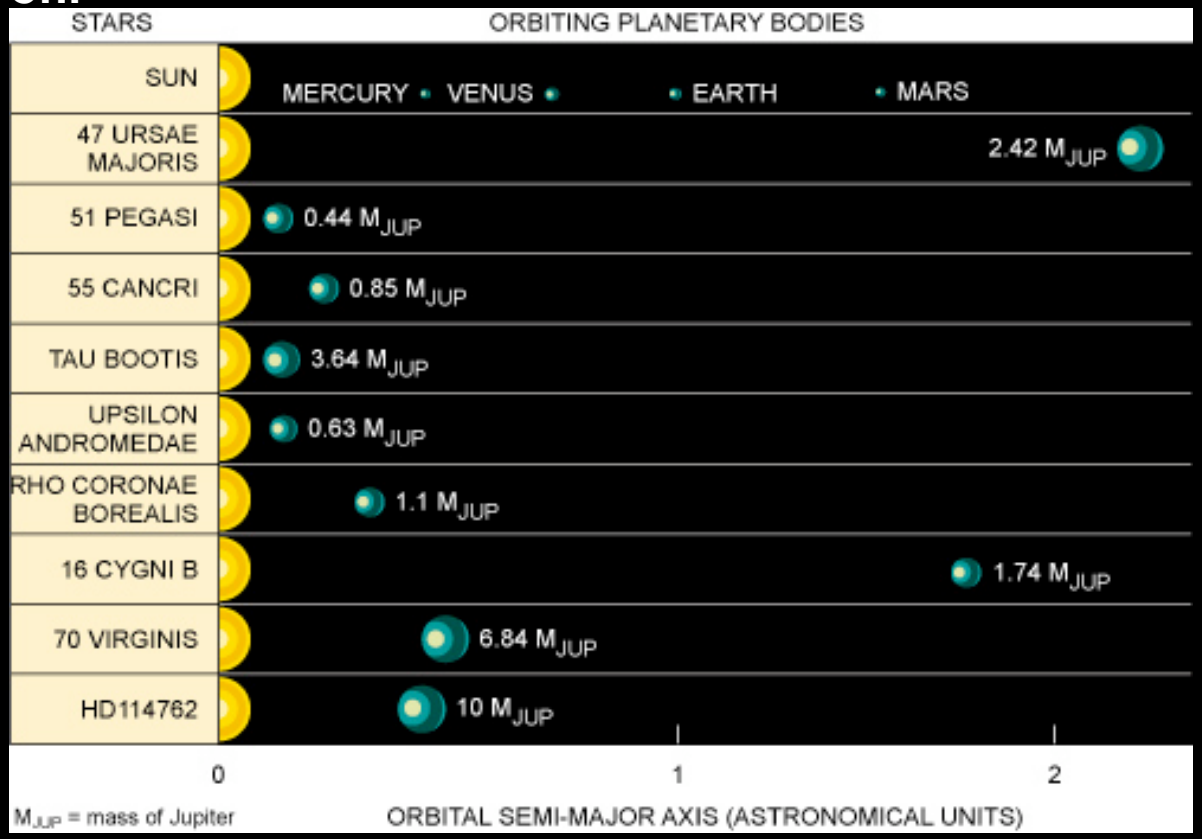



http://www.oklo.org/wp-content/images/sofarin2008.gif

From Melinda Hutson

**Well, the methods we have (until very recently) for detecting extrasolar planets can only find large planets close to their stars. There may be millions of solar systems like our own "out there", but we can't see them (yet!).**

**Additionally, models now suggest that during star formation, planetary material spirals in to the growing star. In all of the systems with "hot Jupiters", any small rocky Earth-like planets were swallowed by their stars early on.**




**MVEM all have $M \leq 1/1000\ M_J$**

http://www.thenakedscientists.com/index.htm?Exoplanets/index.htm~mainFrame

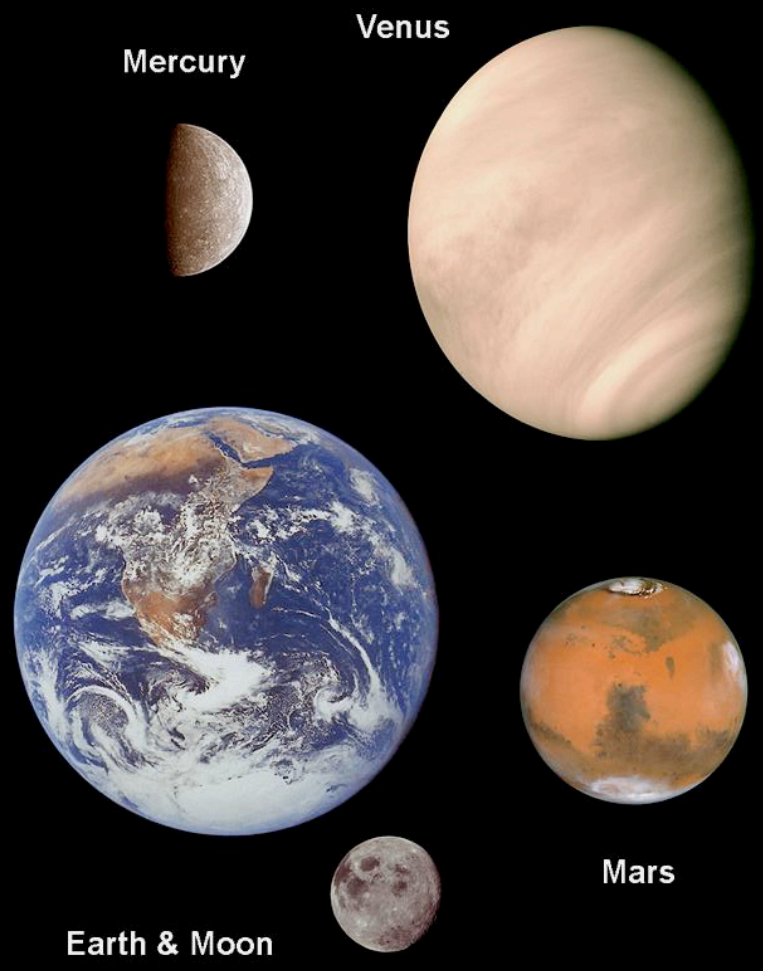
From Melinda Hutson

**In the case of our solar system, the process of star formation stopped early enough that the Earth and other terrestrial planets survived.**

**Image from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra Satellite**

From Melinda Hutson

## Inner Solar System family portrait




From Melinda Hutson

So we have some idea about how and when the solar system formed.

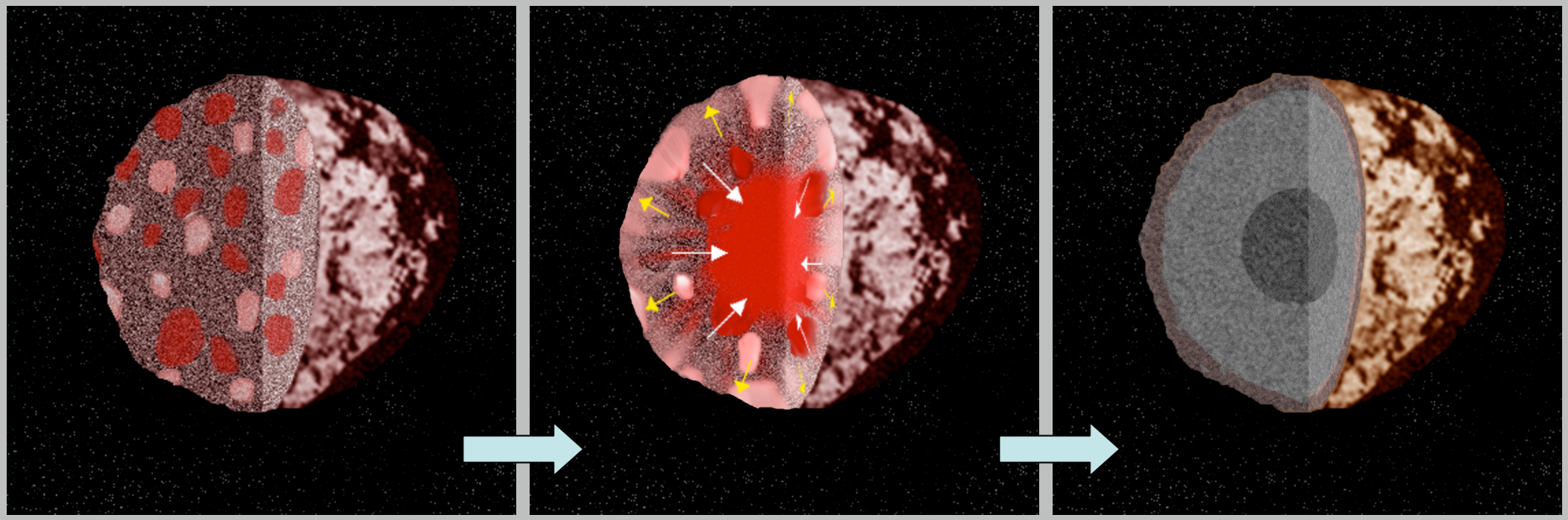
**Question:** How has the solar system evolved with time?

Let's ignore the outer solar system and concentrate on the Earth and the other terrestrial planets.

It is important to understand that the act of planet formation causes a planet to be **HOT** and to **DIFFERENTIATE** (have material separate into a metallic core and a rocky exterior)

# Differentiation

The simple view…



Hot silicate & metal mixed throughout body

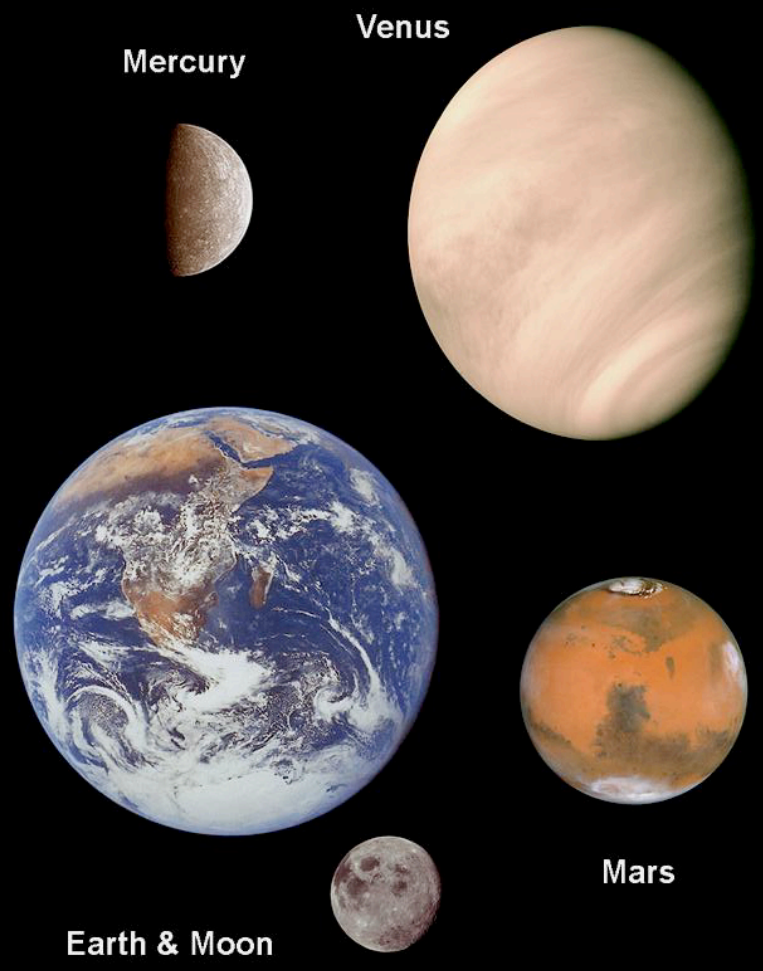
Silicate magma rises, metallic magma sinks

Core-mantle-crust Structure forms

**Size matters:** Larger planets form hotter than smaller planets. Larger planets continue to generate more heat (from decay of radioactive elements) than smaller planets. Larger planets cool more slowly than smaller planets.

From Melinda Hutson

## Inner Solar System family portrait




From Melinda Hutson

**Question:** Why are the various terrestrial planets different from each other?

**Answer:** For the most part – size (mass) and location!

Some of the major differences between the terrestrial planets:

1) Amount and type of geologic activity
2) Presence of a magnetic field
3) Atmosphere (whether planet has one and what composition)
4) Presence of liquid water on surface
5) Presence of life

**Much of the major geologic activity we see on the surfaces of planets (mountain building, volcanism, faulting/earthquakes) is the result of the way a planet cools.**

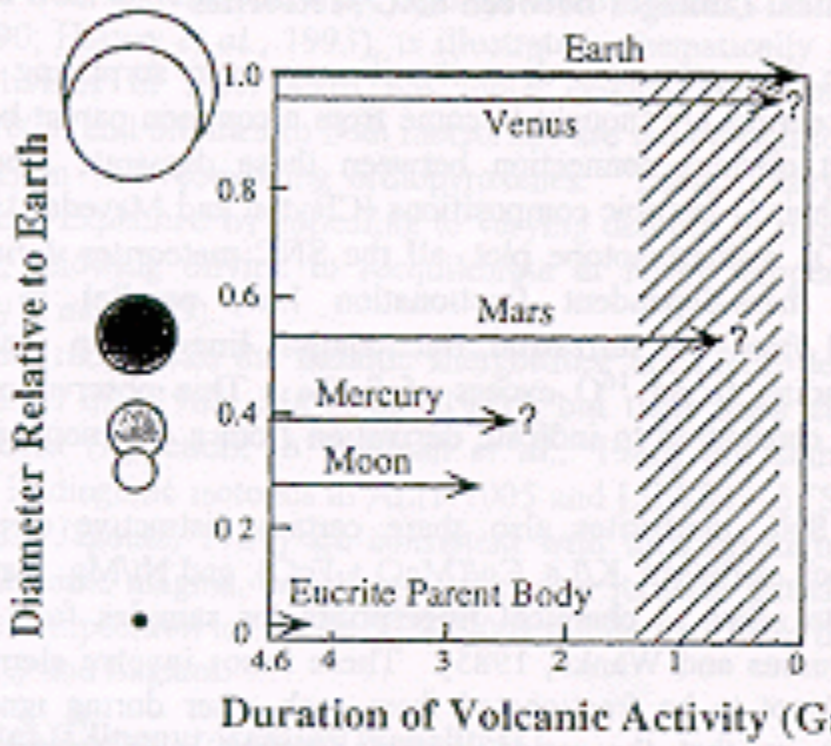



FIG. 4. Relationship between planet size and duration of igneous activity, after McSween (1985). Arrows indicate volcanism histories inferred from crater counting of volcanic plains or from radiometrically dated samples. The eucrite parent body is inferred to be asteroid 4 Vesta. The cross-hatched bar indicates SNC crystallization ages of 1.3 Ga to 180 Ma.

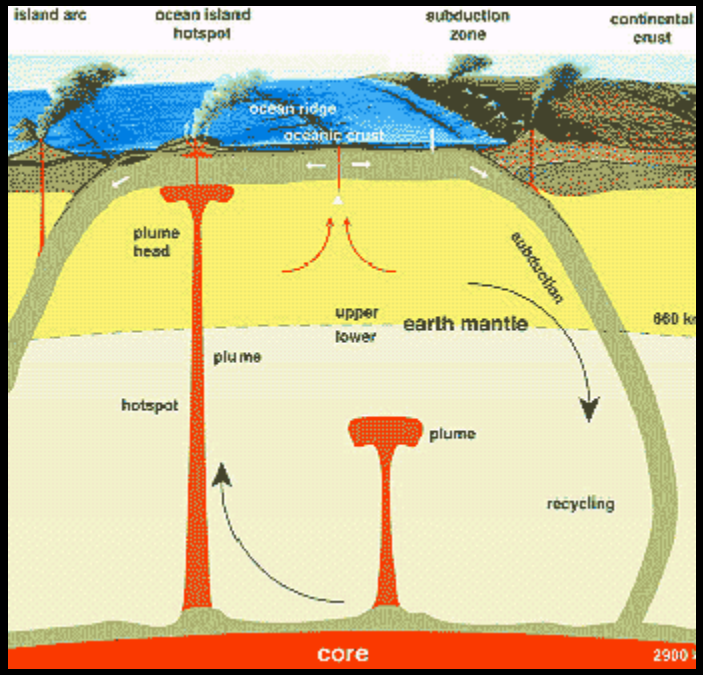
From Melinda Hutson

**Question:** How do planets cool?

**Answer:** For the rocky portion of the planet, hot material from the interior rises towards the surface.

We know of at least two ways to do this: convection currents and plumes.

Convection currents will create compression and tension on the surface, creating complex surface geology, whereas a plume will just rise straight up and create what is known as a "**hot spot**" volcano or flood basalts.



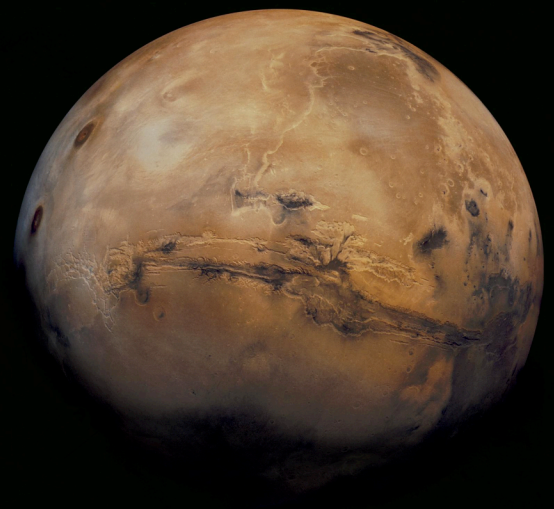

http://www.humboldt-foundation.de/kosmos/titel/img/sobolev_2_gross.gif

From Melinda Hutson

**Mercury and the Moon are both small. Both are now geologically dead. Both appear to have cooled by plumes (we don't see the kinds of widespread compressional and tensional features expected of convection).**



From Melinda Hutson



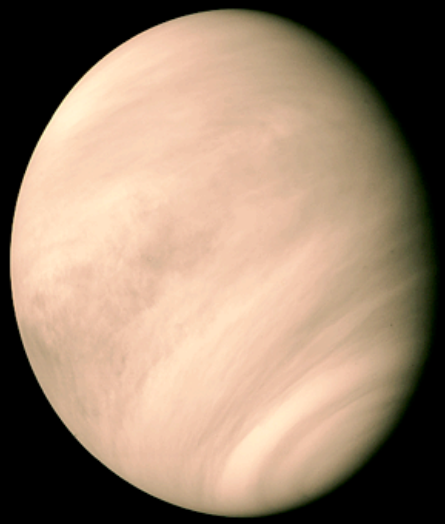
Is Mars still volcanically active?

**Mars shows no signs of convection-related compression or tension. It has huge hot spot volcanoes, suggesting it cooled by plumes.**

From Melinda Hutson

Earth

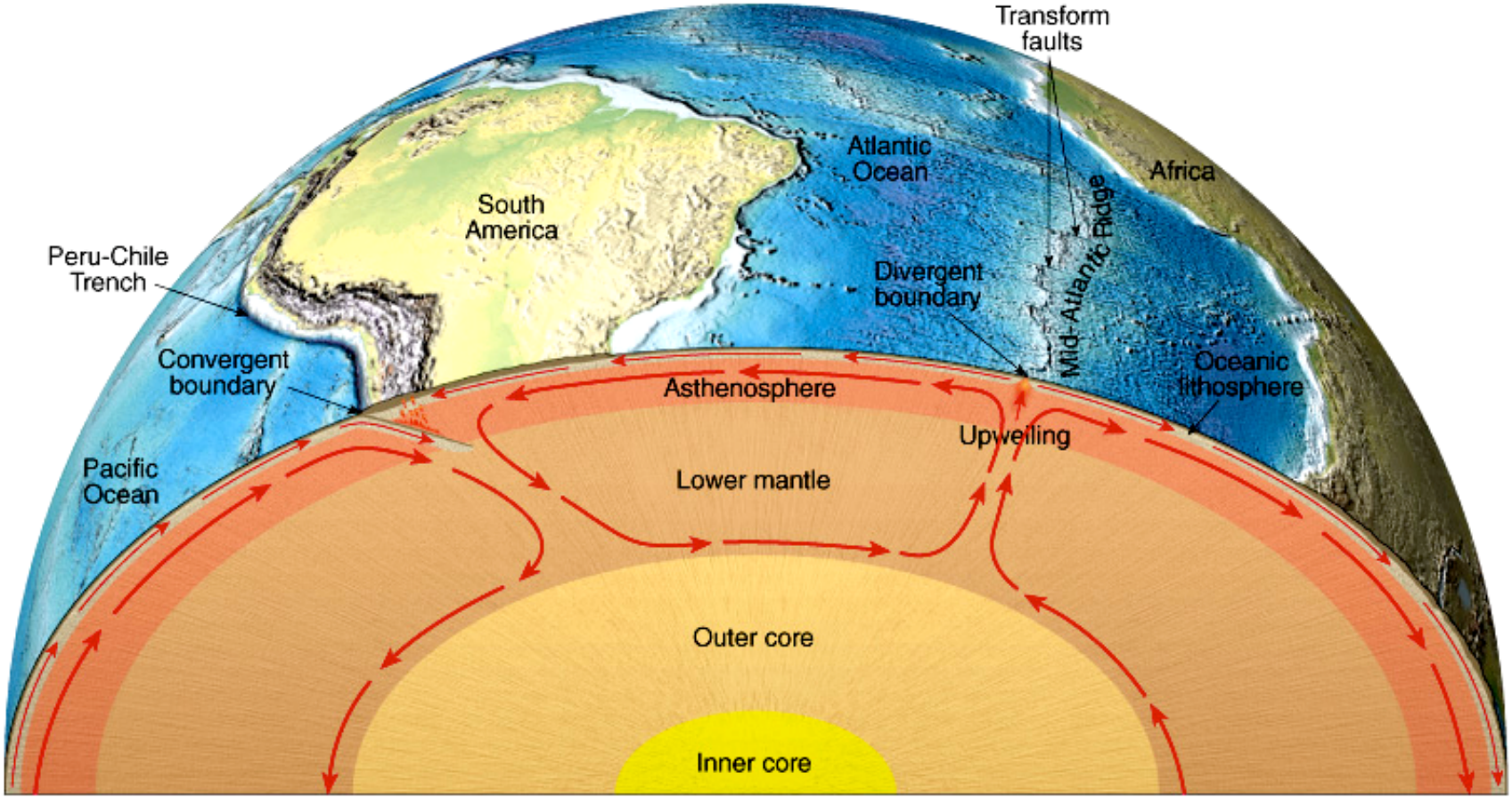
Venus



**Both the Earth and Venus show surface features indicating that they are cooling by both convection and plumes. In the case of the Earth, the surface has broken into pieces that move around relative to each other in a process called plate tectonics.**

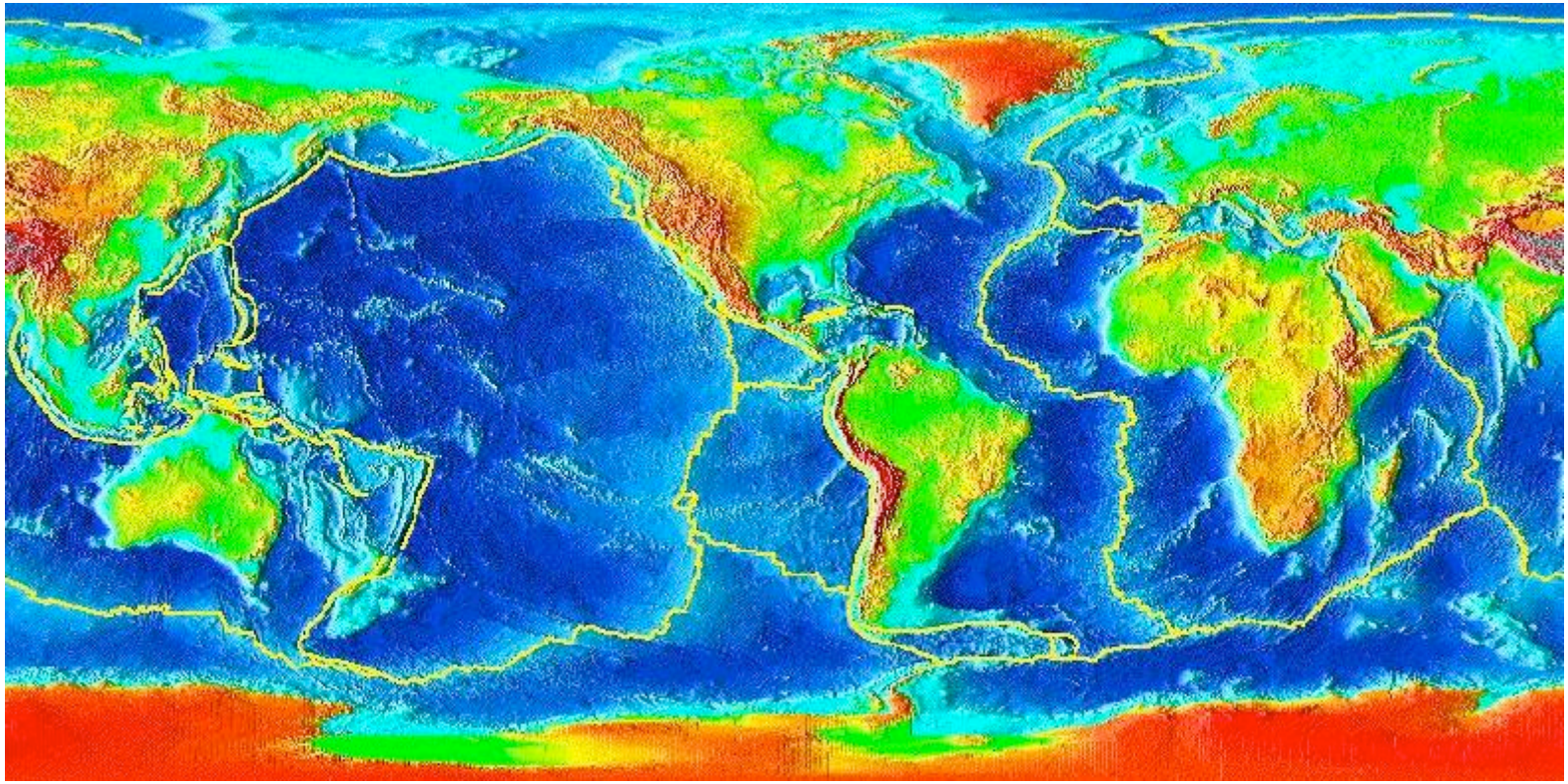
From Melinda Hutson

**Plate Tectonics – this theory became widely accepted about 30-40 years ago – its basic premise: the brittle surface of the Earth (the lithosphere) is broken into pieces (plates) that ride atop a convecting mantle – most earthquakes, volcanism and mountain building occur at plate boundaries**




From Melinda Hutson

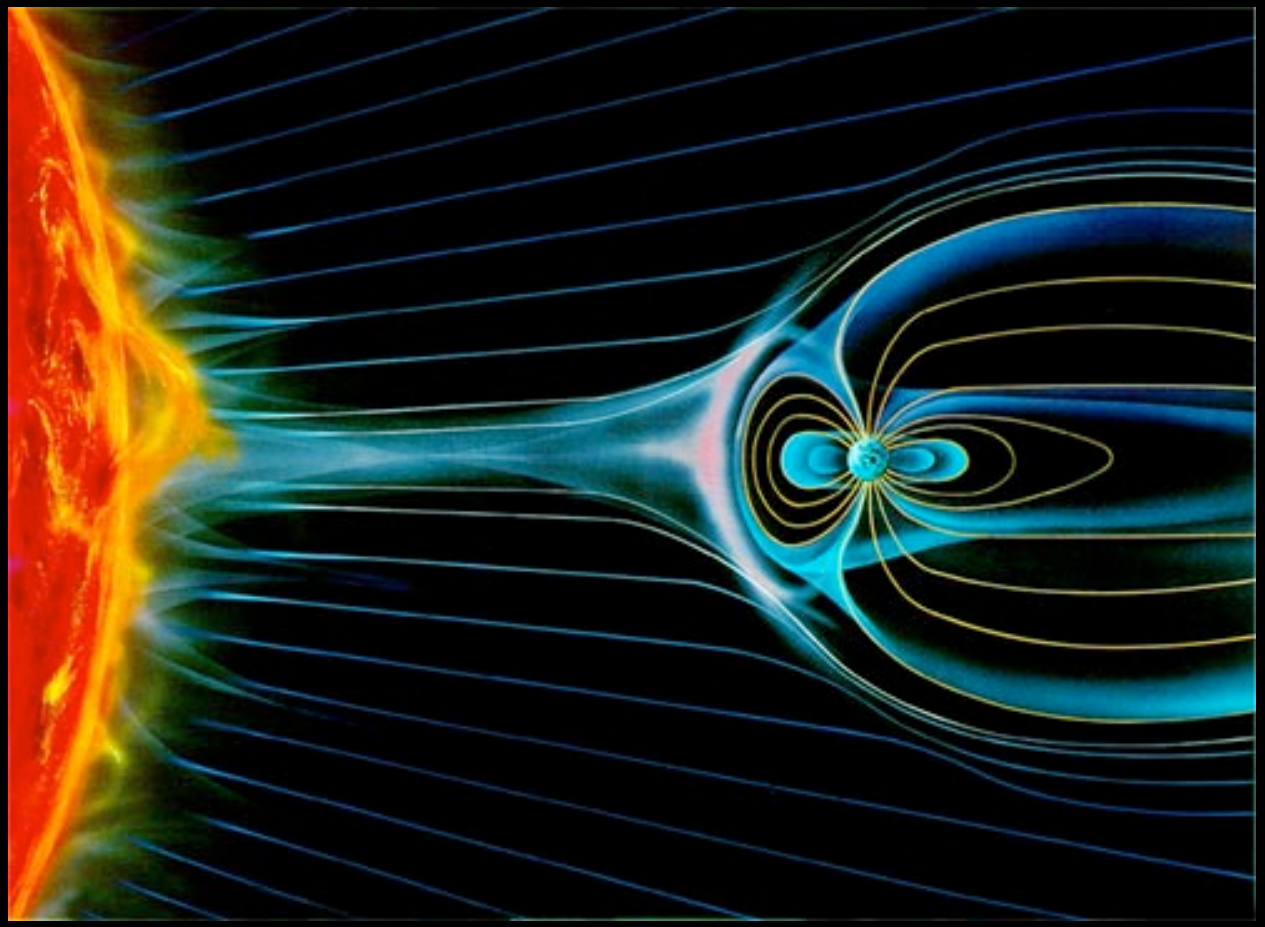
Plate Tectonics is obvious from the topography of the Earth



linear ridges in oceans, linear mountain belts on land,
two distinctly different types of crust (“granitic” continental and “basaltic” oceanic) at very different elevations

From Melinda Hutson

Magnetic fields protect a planet from charged particles streaming off the sun. These particles are deadly to living organisms. In addition, a magnetic field helps prevent erosion of a planet's atmosphere.



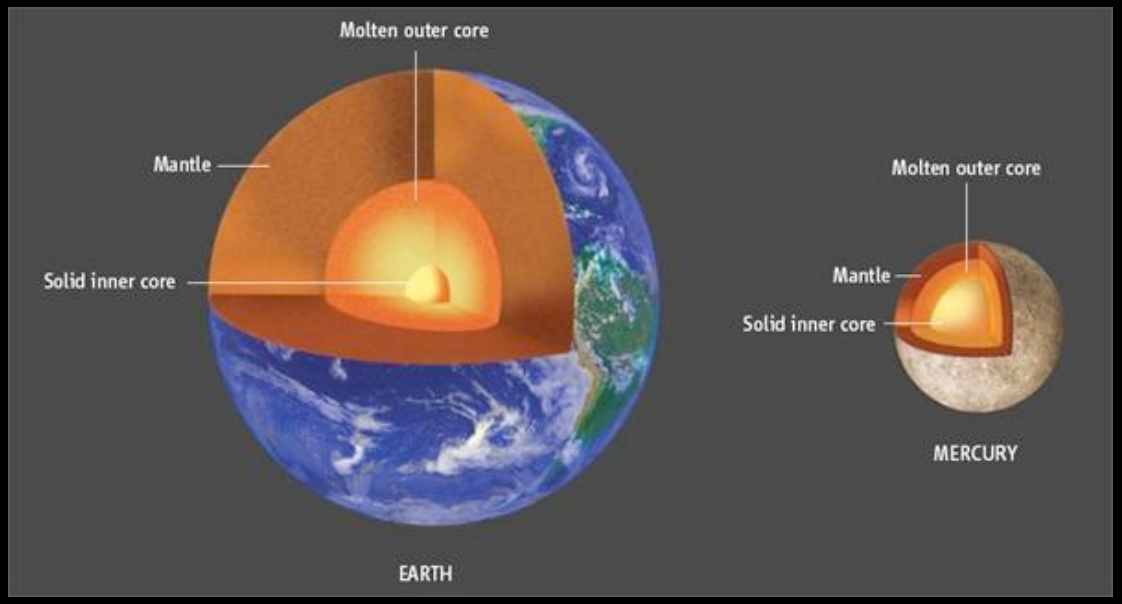
http://www.dailygalaxy.com/photos/uncategorized/2007/03/21/earths_magnetic_field.jpg

To have a magnetic field, a planet needs two things:

1) a conducting fluid in its interior

2) "rapid" rotation

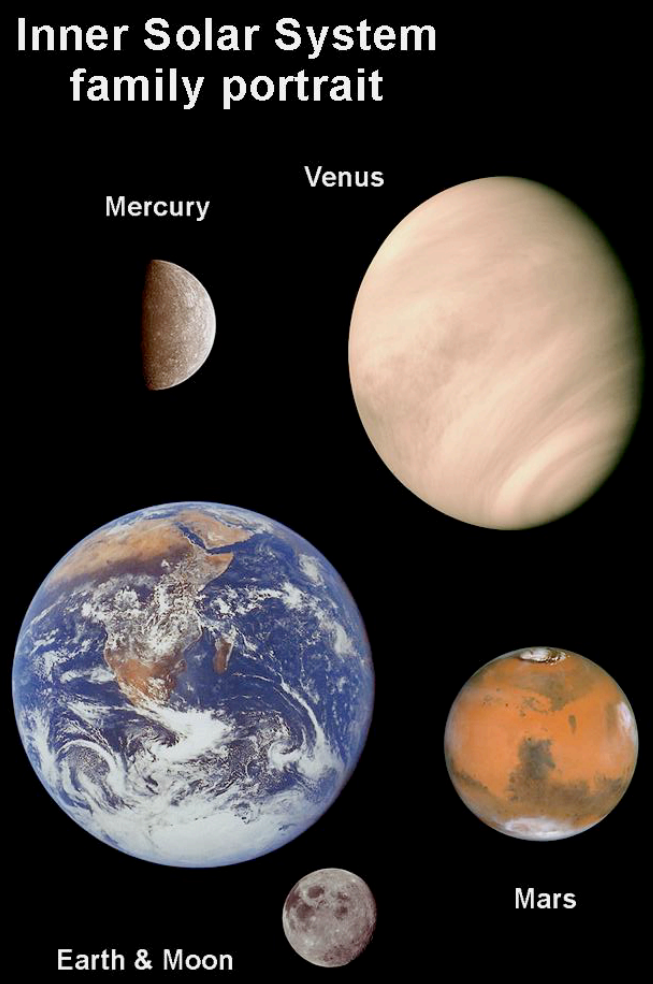
From Melinda Hutson



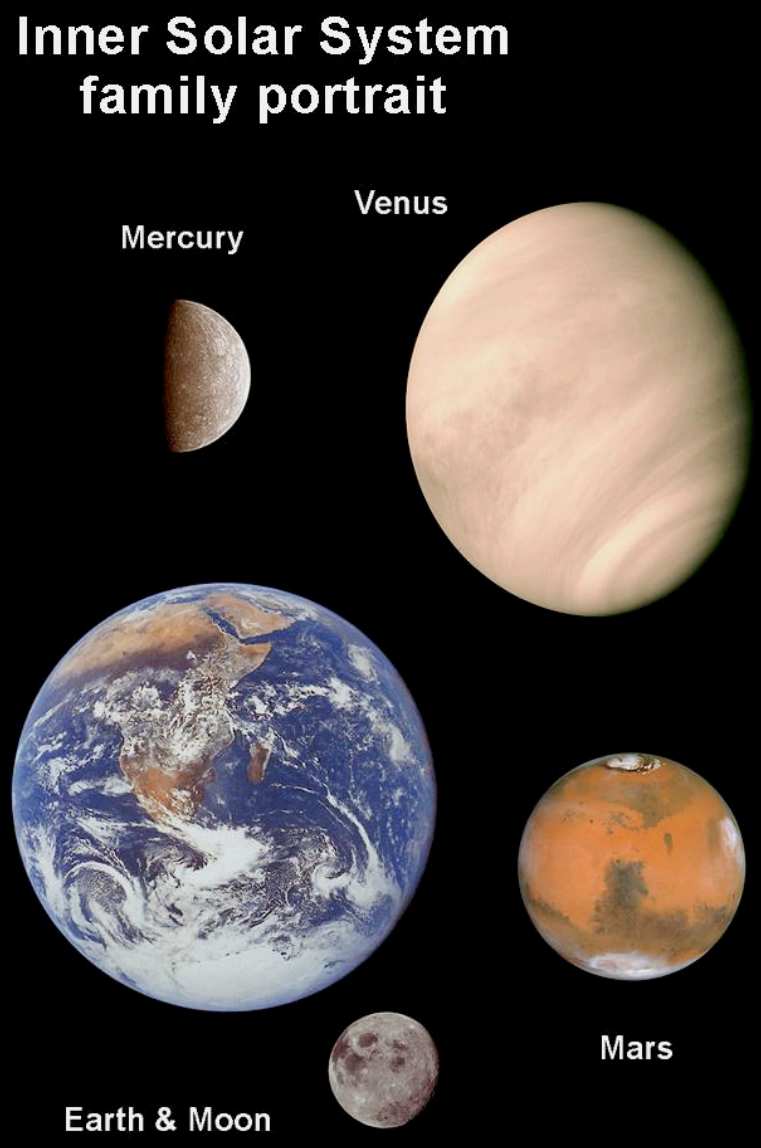

http://www.daviddarling.info/images/Mercury_interior.jpg

Only Earth and Mercury currently have magnetic fields (and Mercury's is 1% or less than Earth's). Why?

- The Moon has a tiny solid core
- Mars' core is smaller than Mercury's and has apparently solidified over time
- Venus rotates too slowly (243 days vs. 24 hours)




From Melinda Hutson

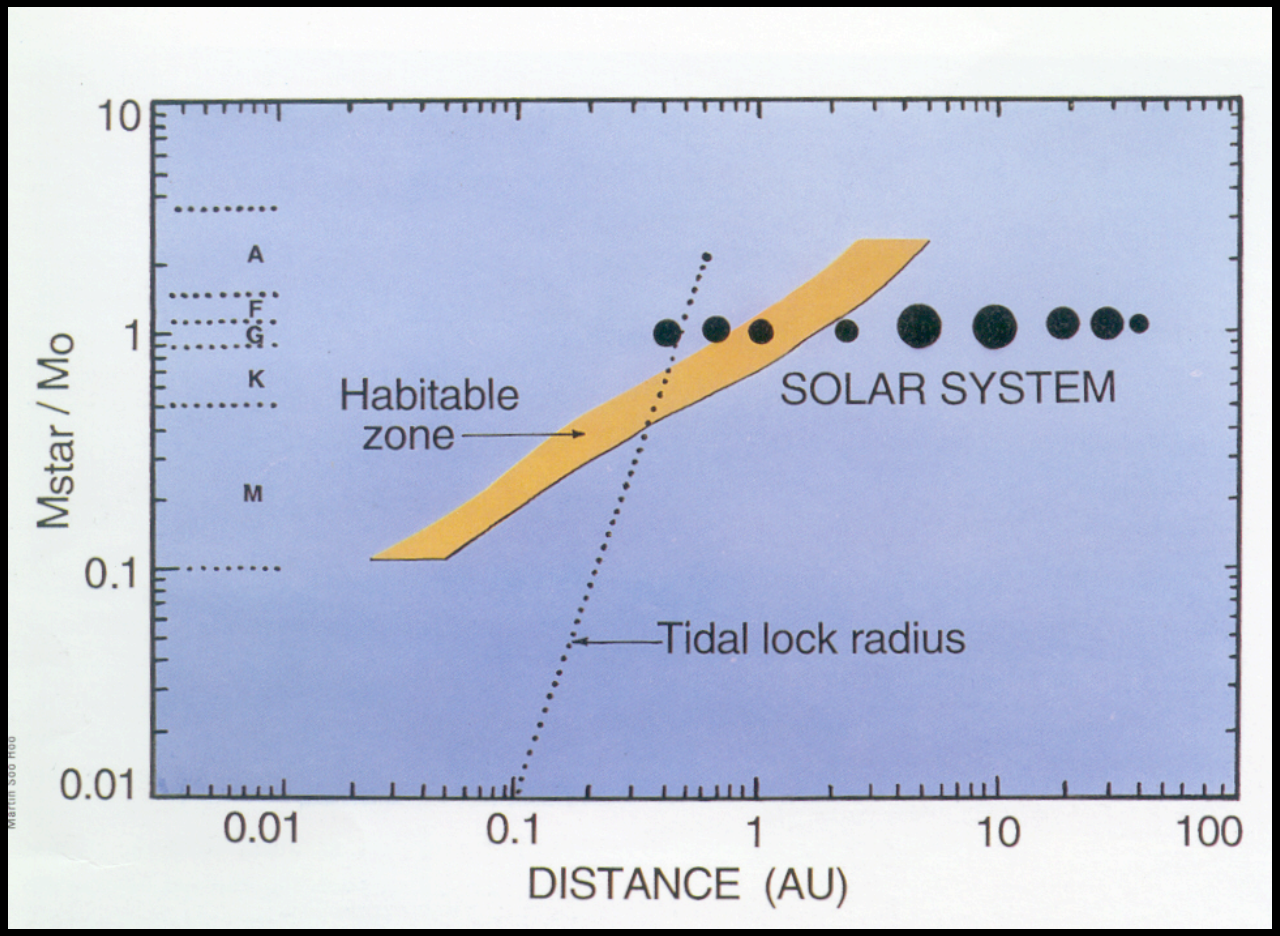



Question: What sort of volatiles (atmosphere or liquids) should a terrestrial planet have when it forms?

Answer: Mostly carbon dioxide and water, with nitrogen in distant third place. The amount of volatiles available during assembly of a planet should be less nearer the sun and more farther from the sun.

From Melinda Hutson

While carbon dioxide and nitrogen will remain in gaseous form in the inner solar system, water will be solid, liquid, or gas depending on distance from the sun and a planet's atmospheric pressure.

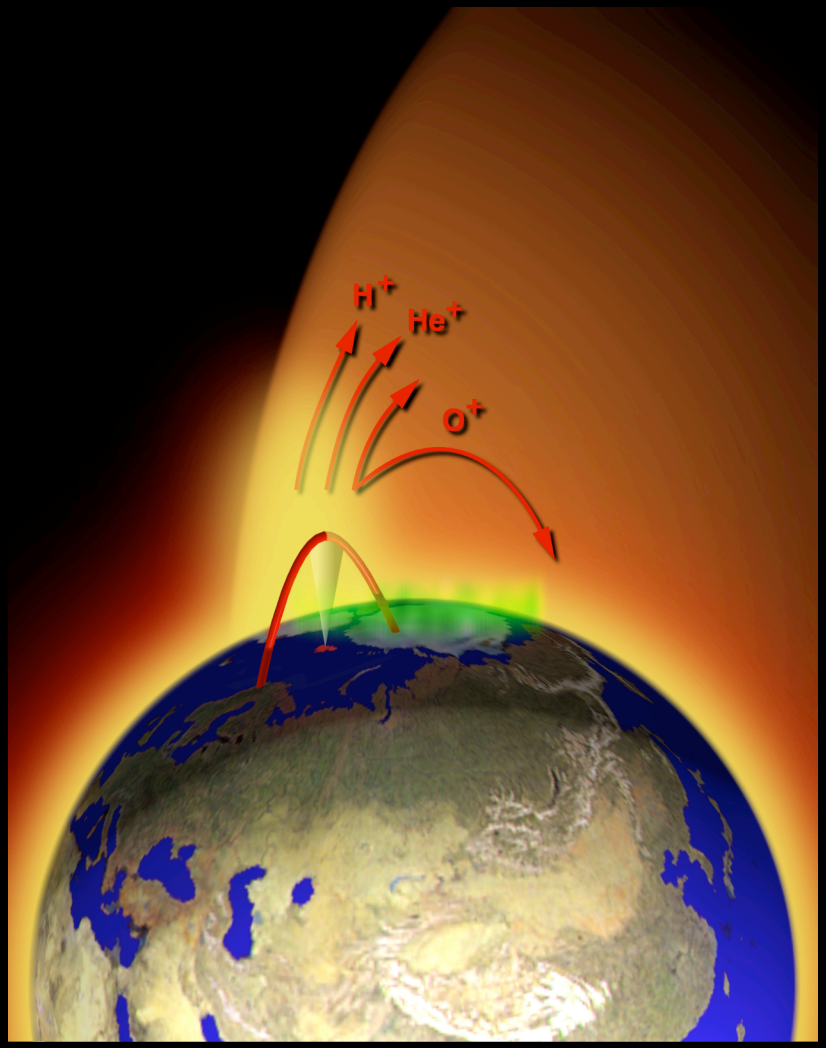



http://www.geosc.psu.edu/~kasting/PersonalPage/Jpgs/HabitableZone.jpg

Water initially:

Venus = gas
Earth = liquid
Mars = liquid/ice

From Melinda Hutson




http://www.sflorg.com/missionnews/cluster/images/imclsmn082808_01_02.jpg

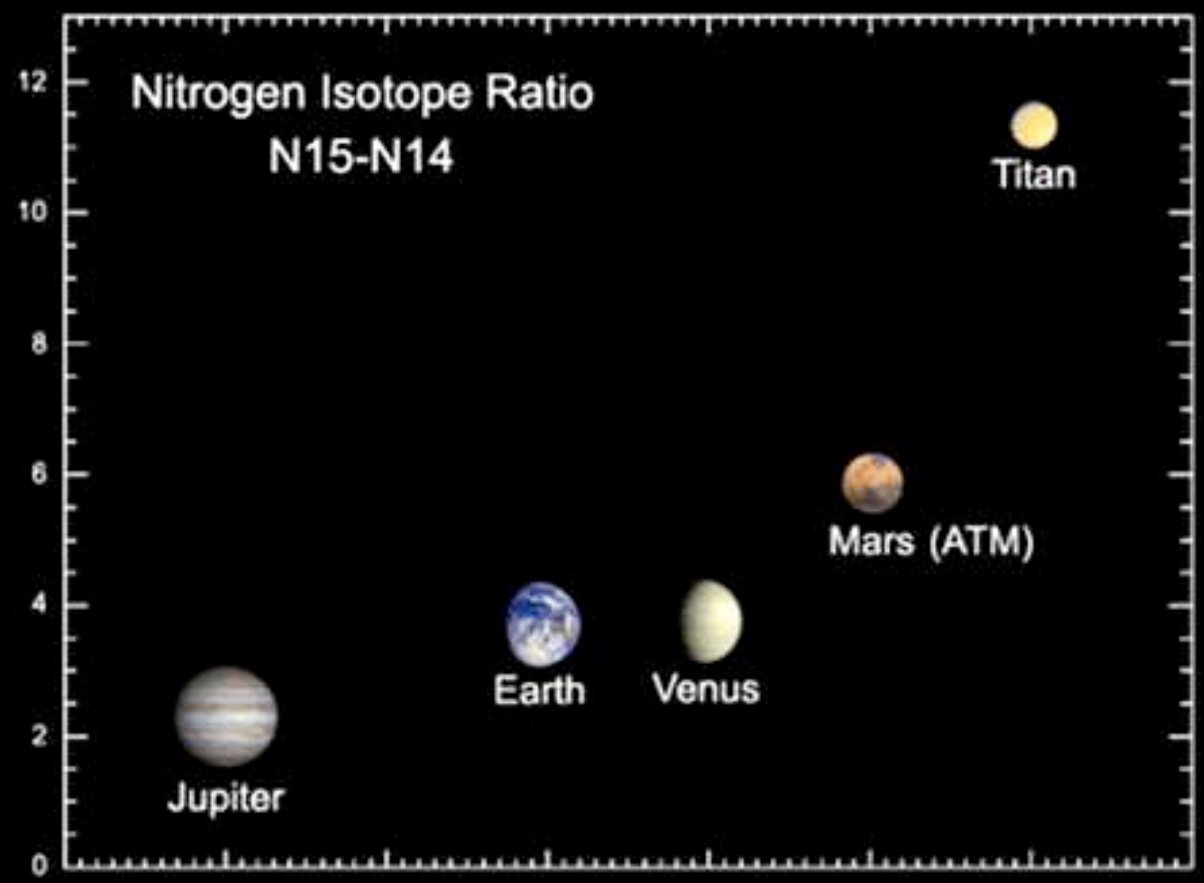
Molecules in the atmosphere break apart and reassemble constantly. If the atoms have enough velocity, they can “leak off” the top of the atmosphere.

Atoms move faster if they are hotter, and they can “leak” easier if gravity is lower (so once again size/mass and location are important).

We see more atoms leaking from Earth’s poles than from other places. ESA's Cluster mission discovered that this accelerated escape is driven by changes in direction of the Earth’s own magnetic field.

From Melinda Hutson

We can estimate how much atmosphere has been lost to space by looking at the difference between light and heavy isotopes of nitrogen (the light isotope is more easily lost). Mars has lost quite a bit more atmosphere to space than has Earth or Venus, even though Mars is farther from the sun (an therefore cooler). This is because Mars is a smaller planet with much lower surface gravity than Earth or Venus.




http://www.holoscience.com/news/img/Nitrogen_isotopes.jpg

From Melinda Hutson

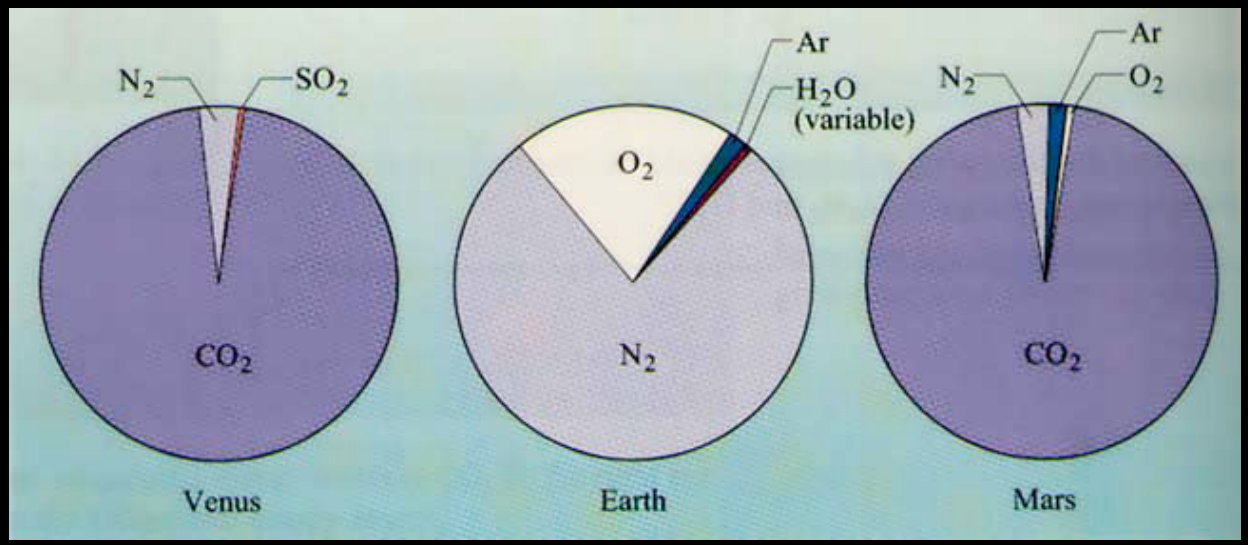
For their respective sizes/masses/surface gravities, both Mercury and the Moon are too hot to hold onto an atmosphere.



From Melinda Hutson

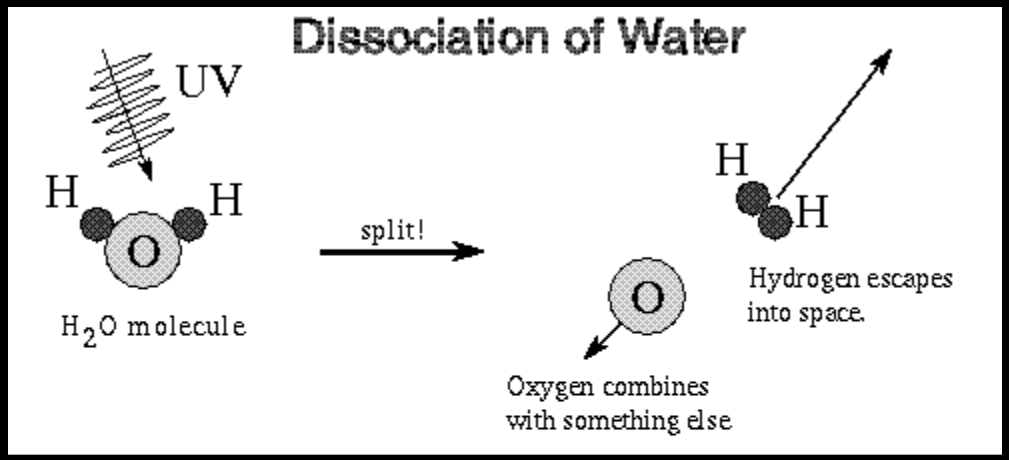
90 bars 1 bar ~.01 bars


**Venus and Mars have the atmospheric composition we expect for a terrestrial planet (ignoring water)**



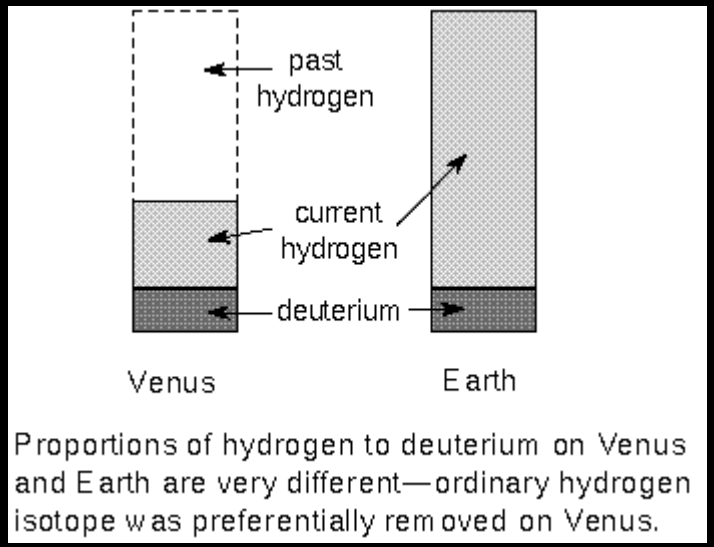

**Questions: Where is the water? Why is Earth's atmospheric composition different?**

From Melinda Hutson




http://www.jb.man.ac.uk/distance/strobel/solarsys/solsysb_files/uvdissoc.gif

Venus was too close to the sun. Water stayed in the atmosphere, broke apart. Hydrogen lost to space, Oxygen "rusted" rocks.

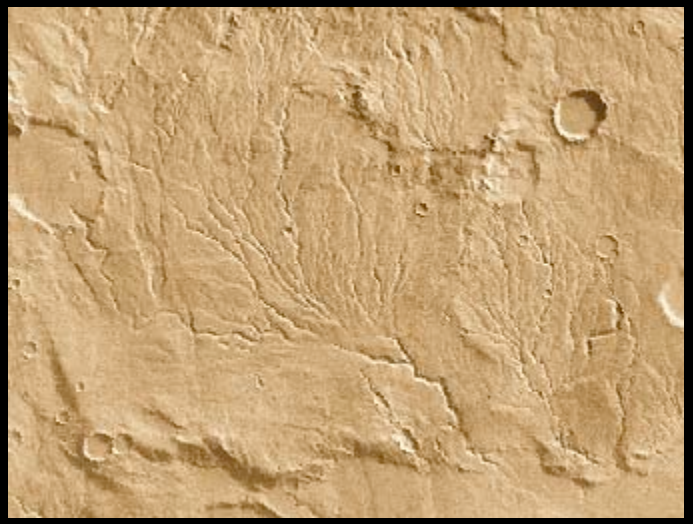



http://www.jb.man.ac.uk/distance/strobel/solarsys/solsysb_files/htdratio.gif

**Venera 9 image of rocks on Venus' surface – chemical analysis shows the rocks are heavily oxidized**

http://www.fas.org/irp/imint/docs/rst/Sect19/Sect19_7.html

From Melinda Hutson

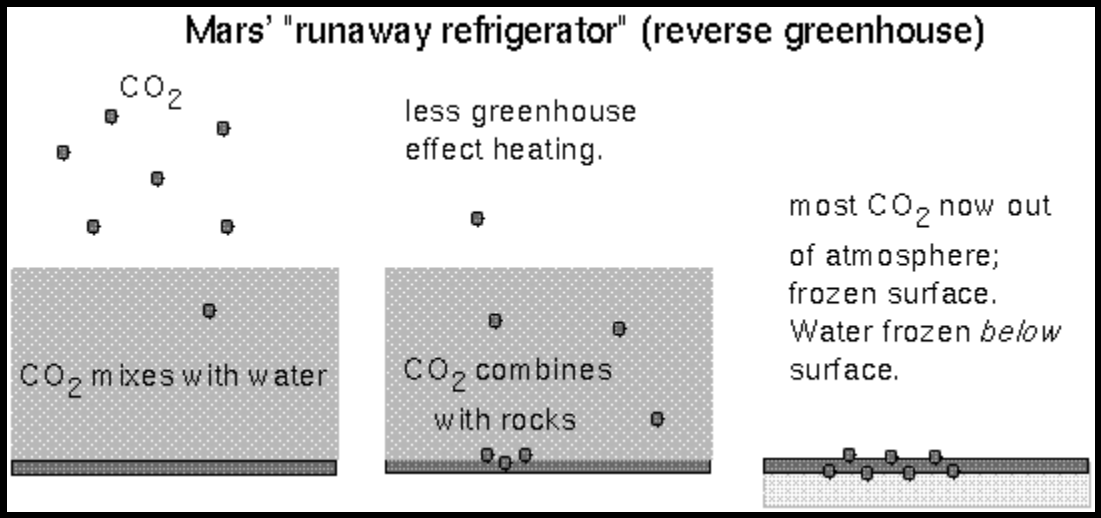


Both images from:
http://www.jb.man.ac.uk/distance/strobel/solarsys/solsysb.htm

Mars initially had liquid water on its surface, but had two problems:

1) size/mass – has lost too much atmosphere to space – surface atmospheric pressure now too low for liquid water to be stable

2) location – farther from sun – could have lead to a “runaway refrigerator”.




From Melinda Hutson

http://coe.sdsu.edu/people/jmora/Ocean.JPG

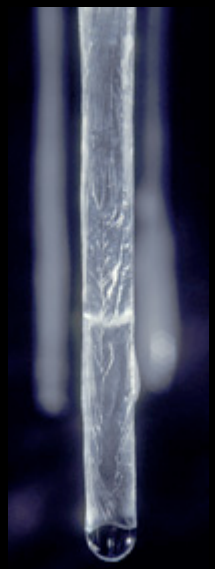
http://www.devsys.co.uk/Album/Places%20of%20Interest/limestone%20caves.jpg

Earth was massive enough to hold onto a substantial atmosphere, and far enough from the sun that water was mainly in liquid form.

Carbon dioxide dissolves in water and then precipitates out as carbonate rock.

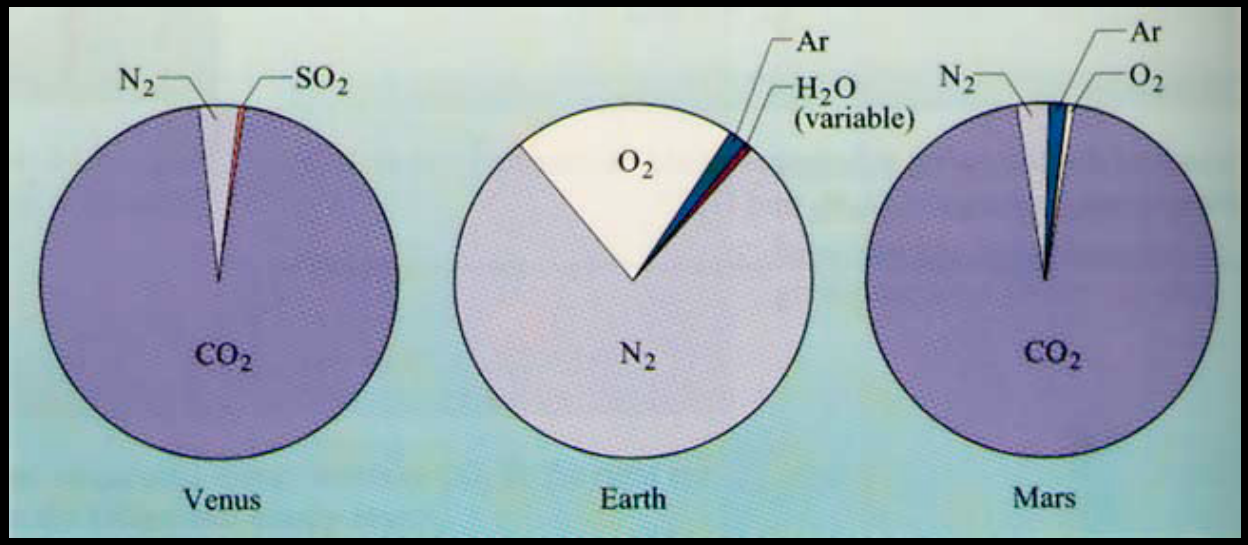
It is currently estimated that roughly 70-75 bars of carbon dioxide is locked up in rocks on the surface of the Earth.

After water and carbon dioxide, the most abundant gas in a terrestrial planet is nitrogren.



http://upload.wikimedia.org/wikipedia/en/3/32/Rats-Nest-straw.jpg

From Melinda Hutson

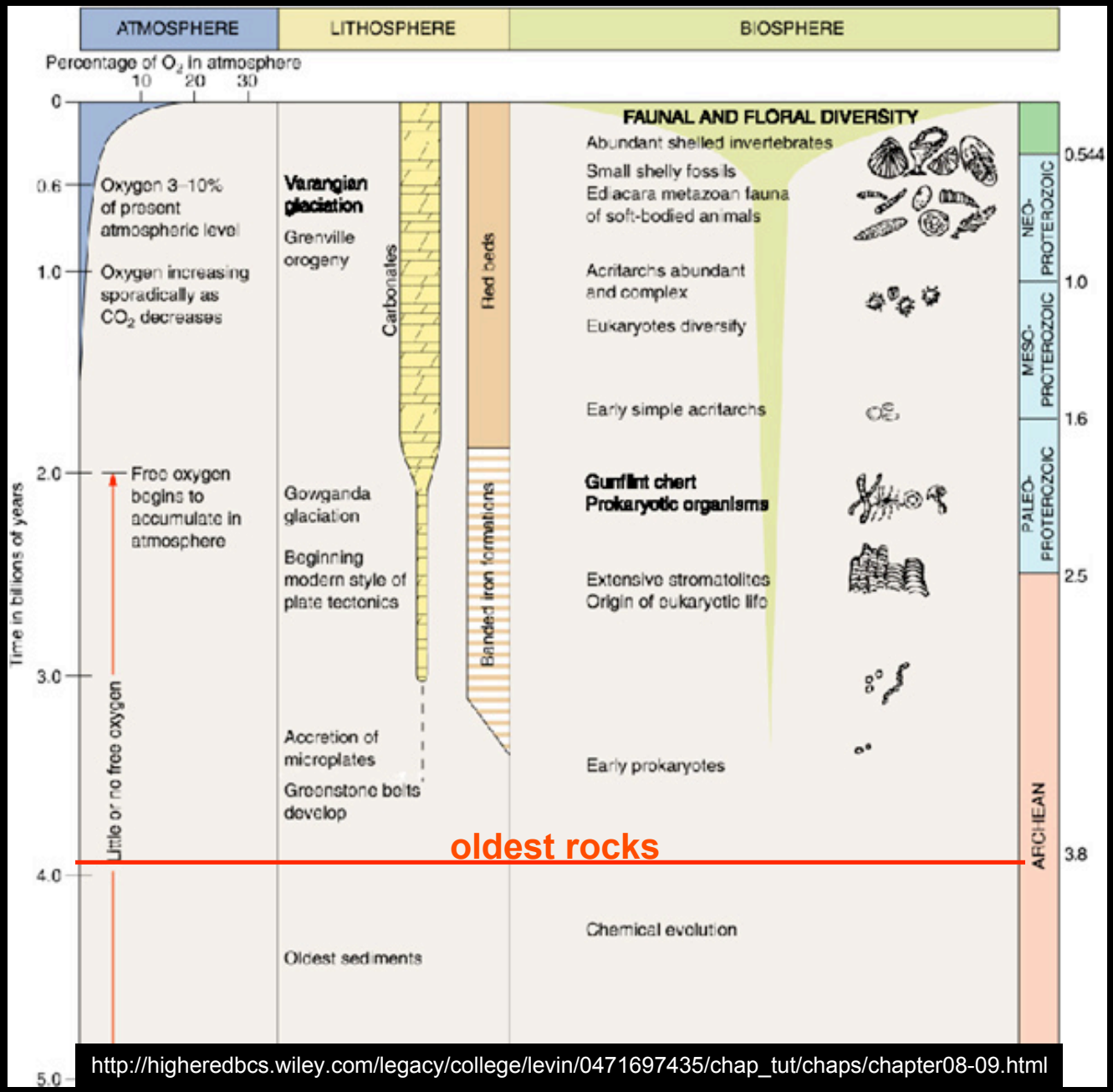



**So we understand why our atmosphere isn't mostly carbon dioxide with a little nitrogen.**

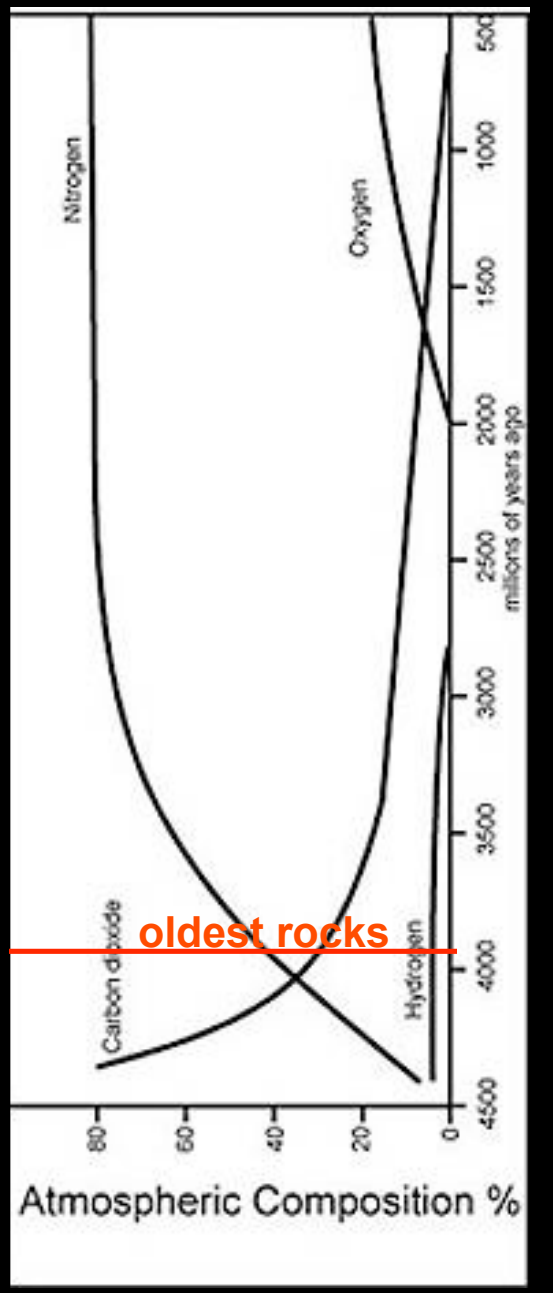
**Question: Why do we have so much oxygen?**

**Answer: LIFE**

From Melinda Hutson

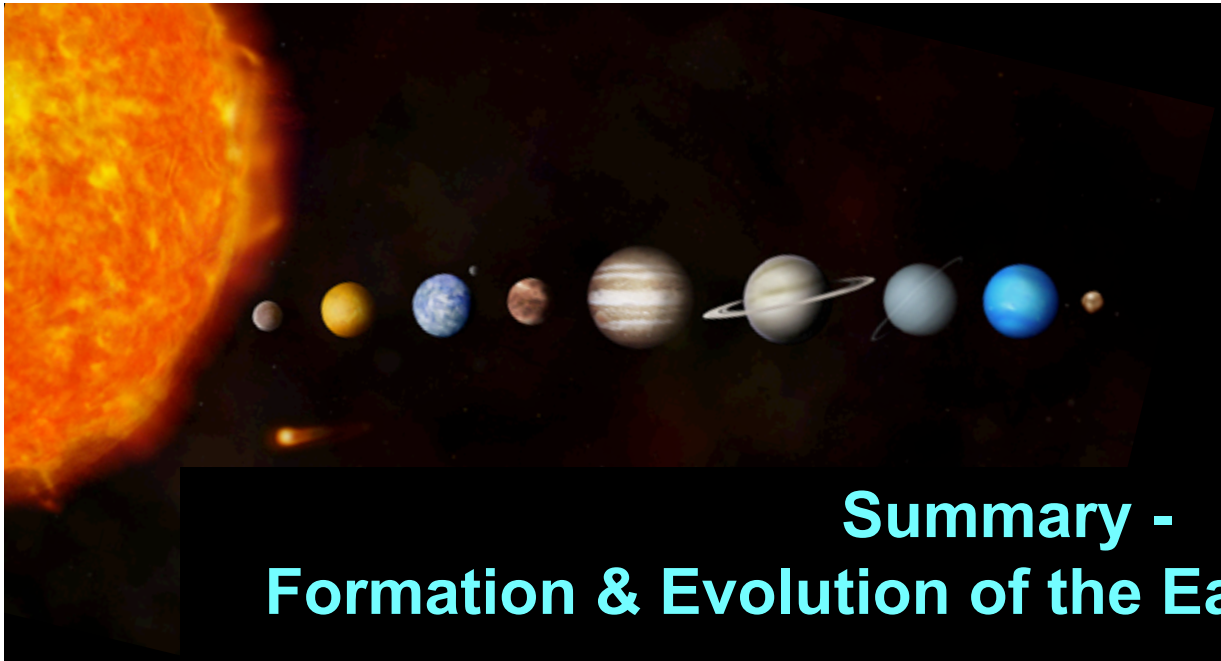



http://higheredbcs.wiley.com/legacy/college/levin/0471697435/chap_tut/chaps/chapter08-09.html




From Melinda Hutson

http://www.fas.org/irp/imint/docs/rst/Sect19/Sect19_2a.html



## Summary -
## Formation & Evolution of the Earth/Solar System

The Earth and the solar system are here as a byproduct of star formation.

Planets exist because not all of the star's building materials make it into the star before it "turns on".

The evolution of a planet depends primarily on two things: mass and location relative to its star.

The Earth is unique in our solar system in being a habitable world.

# Thanks to…

- Oregon Dept. of Education Math/Science Partners Grant (primary funding for this lecture series)
- Portland State University Center for Science Education
- Beaverton and Hillsboro School Districts
- Pacific University
- Science Integration Institute

# References/Suggested Reading


- Christian, *Maps of Time*, chs 2-3 (2004)
- Duncan & Tyler, *Your Cosmic Context*, chs 4, 5, 9, 10, 11 (2009)
- Broecker, *How to Build a Habitable Planet* (1985)
- * Collected resources: http://www.scienceintegration.org
  (click on our cosmic history series link)