# Astronomy 230

## TR 1300-1420

134 Astronomy Building

This class (Lecture 8):

Nature of Solar Systems

Next Class:

Habitable Planets

**HW 3 is due next Thursday.**

**Allison Hanna &**
**Nick Mucia**

Music: *Sonne* – Rammstein



# Outline

- What is $f_p$?
- Maybe some reasons the Earth is good for life.
- The importance of water.
- Requirements for life on Earth.
- The effects of the star on life.



# What Are We Looking For?

## General Predictions of Solar Nebula Theory

☺ Are interstellar dust clouds common? ***Yes!***

☺ Do young stars have disks? ***Yes!***

? Are the smaller planets near the star?

***Not the ones found so far! Haven't found smaller planets yet!***

? Are massive planets farther away?

***Not most of the ones found so far!***



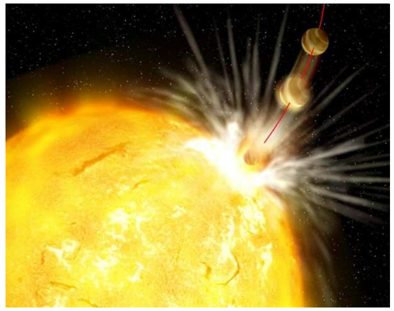
# Important Caveat

- Our current observations of extrasolar planets do **not** exclude planetary systems like our solar system
- Current instruments are most sensitive to large planets close to their stars
  - Big planet - big wobble
  - Close planet - fast wobble
- We only have a little over 10 years of data – 1 orbit's worth for Jupiter
- To find solar-type systems, we need more sensitive equipment

# Exoplanets: Implications

Solar Nebula **Theory**:
- Giant planets born far from star

Exoplanet Data:
- Giant planets found very close



**Theory is *incomplete/wrong*!**

New questions:

? Who is normal: Them or us?

? Are giant planets born close in?

? Are some giant planets born far out, move in?
"planet swallowing"!?!

Anyway: Planets are common!

✓ Good news in search for life elsewhere...maybe



# Future Projects

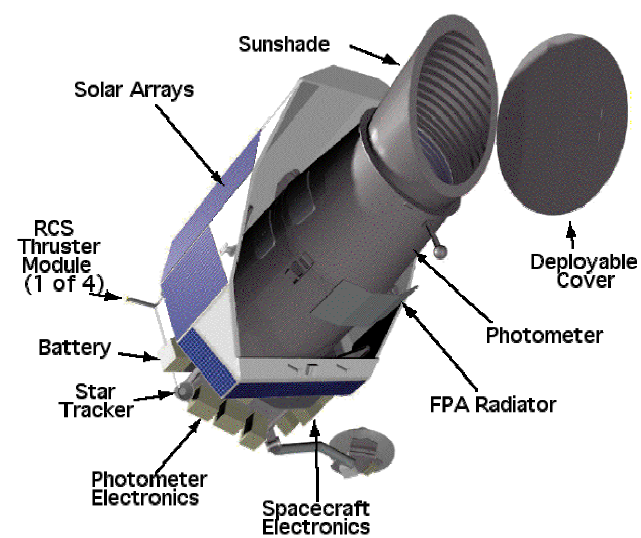
- Atacama Large Millimeter Array (ALMA): 2010
  - mm interferometer: direct detection of young gas giants
- Kepler: Feb 2009
  - Planet Transits
- Next Generation Space Telescope
  James Webb Space Telescope (JWST): 2013
  - Direct imaging of forming gas giants?
- Space Interferometry Mission (SIM): 2016?
  - Astrometry
- Terrestrial Planet Finder (TPF): Mission 1: deferred
  - Coronagraph
  - IR interferometer
- Terrestrial Planet Finder (TPF): Mission 2: deferred
  - A large-baseline infrared interferometer. Imaging extrasolar Earths!!!!




# Kepler

1.4 meter mirror, measuring accurate brightness of stars.

A terrestrial-sized Earth-like planet would dim the star's light by 1/10,000th – comparable to watching a gnat fly across the beam of a searchlight.

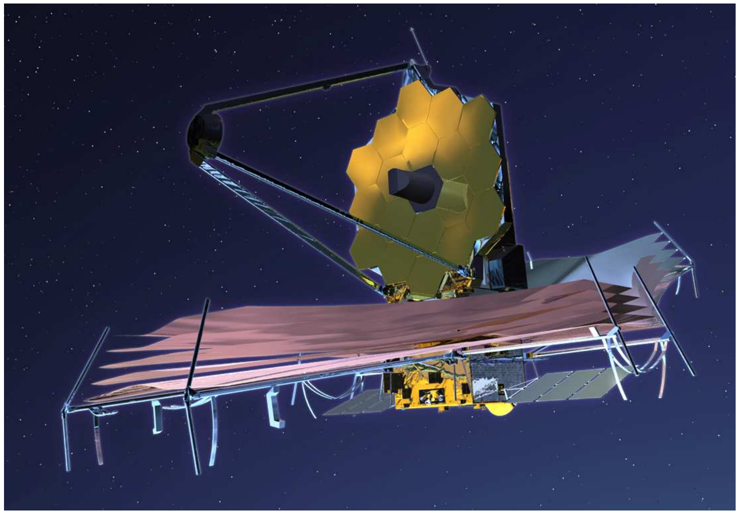


# JWST

James Webb Space Telescope: Successor to HST

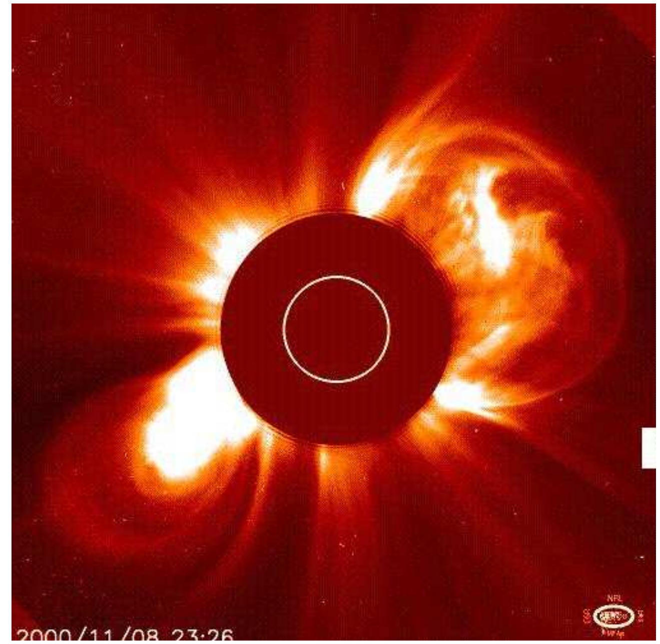
6.5 meter observatory

Working in the infrared with a coronagraph.





# The Coronagraph Advantage






# Space Interferometry Mission

Accurately measure location of stars to micro-arcseconds.

Need to know relative location of components to 50 pm.

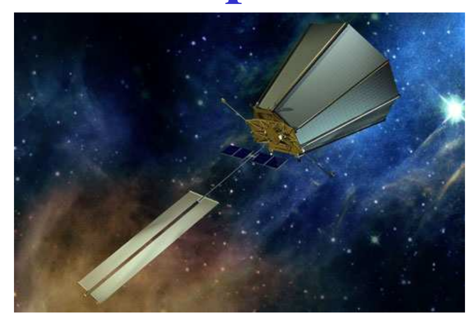
Funding in question.

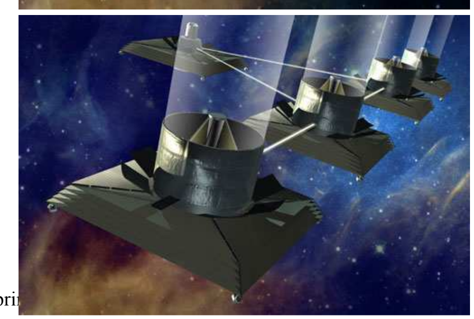

http://planetquest.jpl.nasa.gov/SIM/sim_index.html



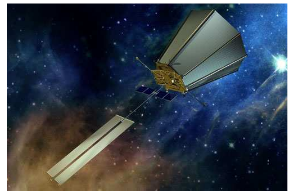
# Terrestrial Planet Finder Mission: Two Telescopes

- Survey nearby stars looking for terrestrial-size planets in the "habitable zone”
- Follow up brightest candidates looking for atmospheric signatures, habitability, or life itself
- Then, the ultimate: image the little blue dots

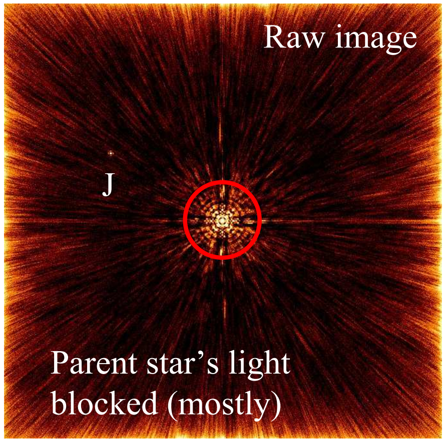


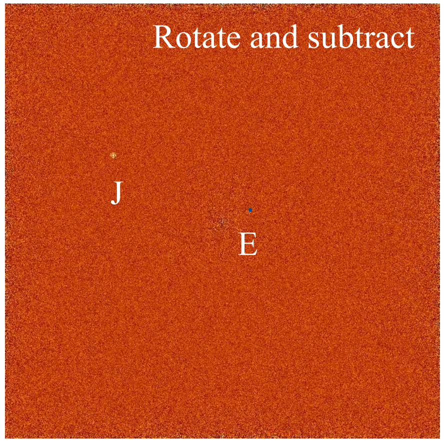


# TPF



Visual wavelength `coronagraph'
- Find Earth-like planets
- Characterize their atmospheres, surfaces
- Search for bio-signatures of life ($O_2$, $H_2O$, etc)



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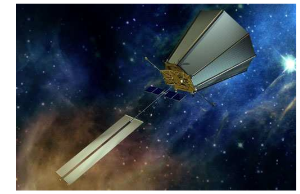

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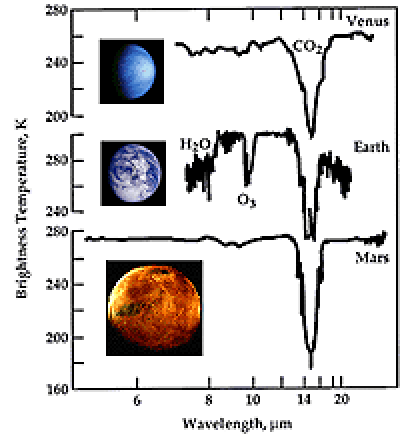
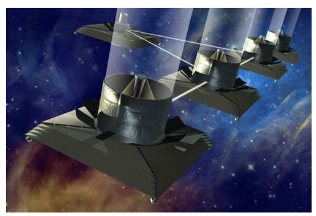





# TPF: Step 2



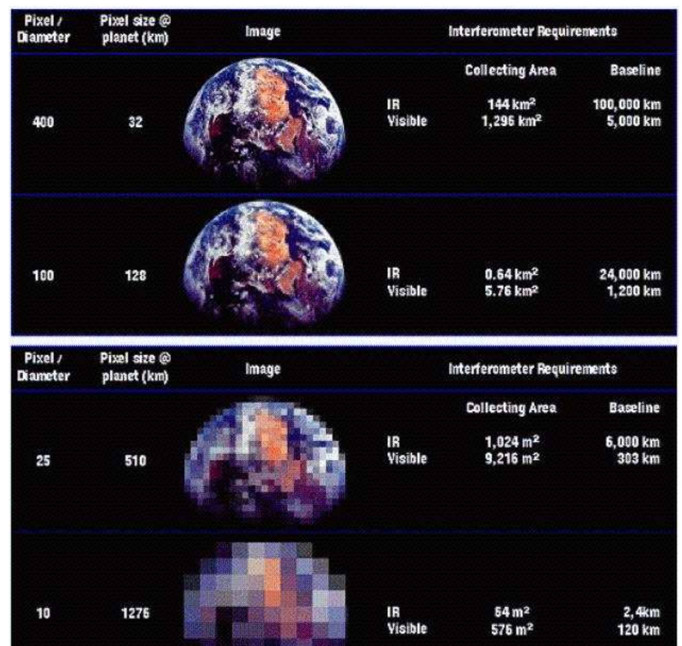
The goal of imaging an Earth-like planet.

5 platforms of 4 eight meter interferometer in space.

spider.ipac.caltech.edu/staff/jarrett /talks/LiU/origins/openhouse30.html



# TPI -- Scales



| Pixel / Diameter | Pixel size @ planet (km) | Image | | Interferometer Requirements: Collecting Area | Baseline |
|---|---|---|---|---|---|
| 400 | 32 | | IR<br>Visible | 144 km²<br>1,296 km² | 100,000 km<br>5,000 km |
| 100 | 128 | | IR<br>Visible | 0.64 km²<br>5.76 km² | 24,000 km<br>1,200 km |
| 25 | 510 | | IR<br>Visible | 1,024 m²<br>9,216 m² | 6,000 km<br>303 km |
| 10 | 1276 | | IR<br>Visible | 64 m²<br>576 m² | 2,4km<br>120 km |

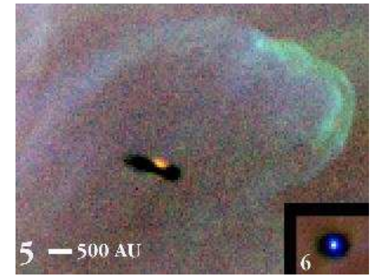
# Disks in Binary Systems

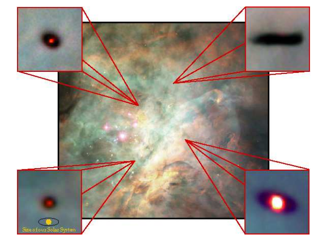
- >60% of all stars are in binary or multiple systems.
- We do see circumstellar disks in binary systems
- We do see exoplanets in binary systems.
- But we also see effects of the binary on the disk.
  - Still unclear how large of an effect.



# Now, for $f_p$

- About 2/3 of all stars are in multiple systems.
  - Is this good or bad?
- Disks around stars are very common, even most binary systems have them.
- Hard to think of a formation scenario without a disk at some point– single or binary system.
- Disk formation matches our solar system parameters.
- We know of many brown dwarves, so maybe some planets do not form around stars.
  - There might be free-floating planets, but…

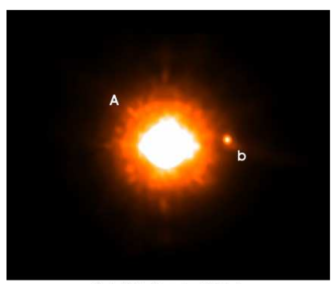


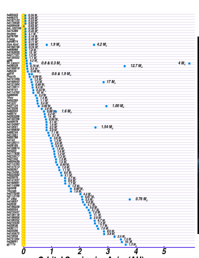


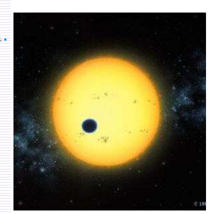
# Now, for $f_p$

- Extrasolar planet searches so far give about $f_p \sim 0.03$, but not sensitive to lower mass systems.
- Maximum is 1 and lower limit is probably around 0.01.
- A high fraction assumes that the disks often form a planet or planets of some kind.
- A low fraction assumes that even if there are disks, planets do not form.
- <u>This is not Earth-like planets, just a planet or many planets.</u>



The Sub-Stellar Companion to GQ Lupi (NACO/VLT)





# Drake Equation


Frank Drake

*Earth Chauvinism?*

$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

| $N$ | $R_*$ | $f_p$ | $n_e$ | $f_l$ | $f_i$ | $f_c$ | $L$ |
|---|---|---|---|---|---|---|---|
| # of advanced civilizations we can contact in our Galaxy today | Star formation rate | Fraction of stars with planets | # of Earthlike planets per system | Fraction on which life arises | Fraction that evolve intelligence | Fraction that commun-icate | Lifetime of advanced civilizations |
| | 19 stars/ yr | ? systems/ star | planets/ system | life/ planet | intel./ life | comm./ intel. | yrs/ comm. |

# $n_e$

Complex term, so let's break it into two terms:

- $n_p$: number of planets suitable for life per planetary system
- $f_s$: fraction of stars whose properties are suitable for life to develop on one of its planets

$$n_e = n_p \times f_s$$

http://nike.cecs.csulb.edu/~kjlivio/Wallpapers/Planets%2001.jpg



# $n_e = n_p \times f_s$

$n_p$: number of planets suitable for life per planetary system (an average per planetary system)

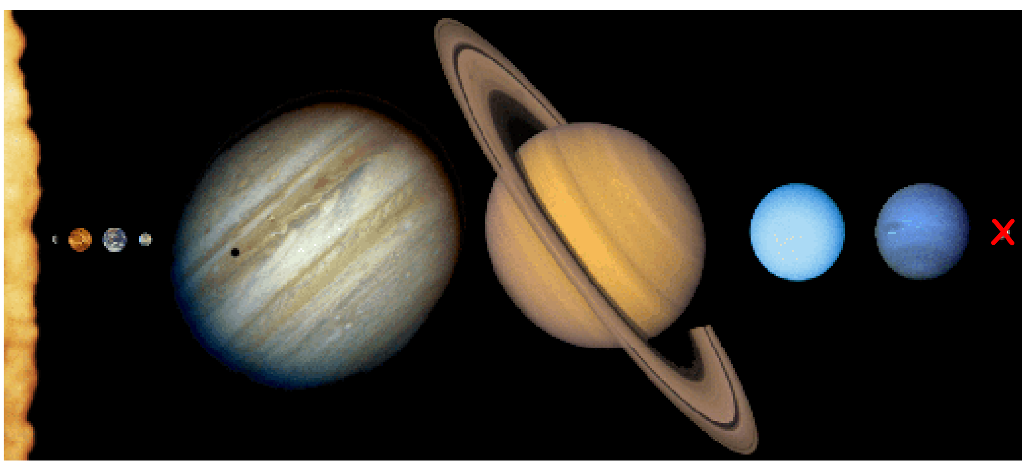
$f_s$: fraction of stars whose properties are suitable for life to develop on one of its planets

http://nike.cecs.csulb.edu/~kjlivio/Wallpapers/Planets%2001.jpg



# Our Solar System

Terrestrial planets and Gas Giants… but how many are valid planets/moons for $n_p$?





# Earth-Moon Comparison

| | | | |
|---|---|---|---|
| Radius | 6378 km | Radius | 0.272 Earth |
| Surface gravity | 9.8 m/s$^2$ | Surface gravity | 0.17 Earth |
| Mass | $6.0 \times 10^{24}$ kg | Mass | 0.012 Earth |
| Distance to Sun | $1.5 \times 10^{8}$ km | Distance to Earth | 384,000 km |
| Year | 365.2422 days | Orbital Period | 27.3 days |
| Solar day | 1 day | Solar day | 27.3 days |

# Formation of the Earth

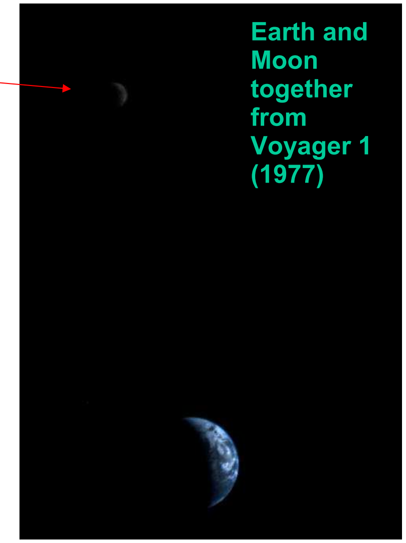
- Focus on the formation of the Earth, including its atmosphere and oceans.
- Earth formed from planetesimals from the circumstellar disk.
- Was hot and melted together.
- The biggest peculiarity, compared to the other planets, is the large moon.



# A Double World

Why a "double world"?

- Most moons are tiny compared to the planet
  - The Moon is over 25% the diameter of Earth
  - Jupiter's biggest moons are about 3% the size of the planet
- The Moon is comparable to the terrestrial planets
  - About 70% the size of Mercury
  - Nearly the same density as Mars





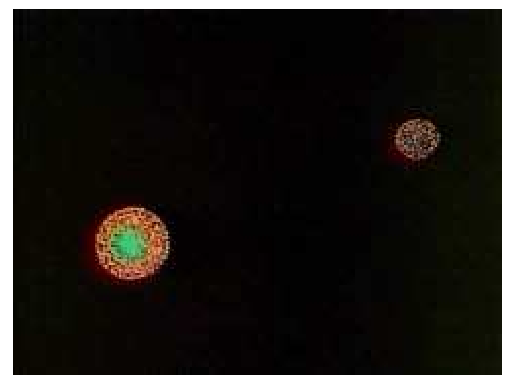

# The Moon

The Moon's surface is barren and dead

- No water, no air
- No life!




# Formation of the Moon: Smack



- Collision of Earth with a Mars-sized body early in the solar system's history
- Iron-rich core of the impactor sank within Earth
- Earth's rotation sped up
- Remaining ejecta thrown into orbit, coalesced into the Moon

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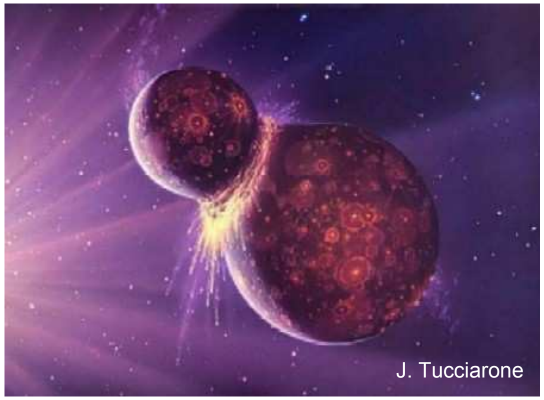


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# *Why is this a good hypothesis?*

- The Earth has a large iron core (differentiation), but the moon does not.
  - The debris blown out of collision came from the rocky mantles
  - The iron core of the impactor merged with the iron core of Earth
- Compare density of 5.5 g/cm$^3$ to 3.3 g/cm$^3$— the moon lacks iron.

http://www.flatrock.org.nz/topics/odds_and_oddities/assets/extreme_iron.jpg



# Moon Life?

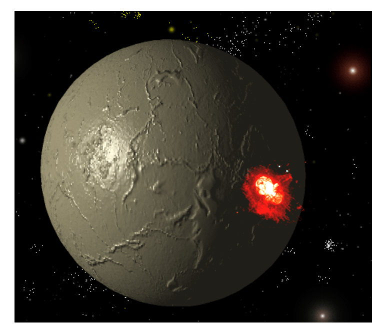
- Some think that our large Moon is very important for life on Earth.
  - Tides! Important to move water in and out of pools.
  - Stable Axial Tilt: 23.5 deg offset from the collision
  - Metals! Heavy elements at Earth's surface may be from core of impactor.

http://www.michaelbach.de/ot/sze_moon/index.html



# Implications

- **Hot, Hot, Hot!** Even if the moon theory is incorrect, other smaller bodies were playing havoc on the surface.
- When they impact, they release kinetic energy and gravitational potential.
- In addition, some of the decaying radioactive elements heated up the Earth– stored supernova energy!
- The planetesimals melt, and the Earth went through a period of differentiation.





http://www.udel.edu/Biology/Wags/wagart/worldspage/impact.gif

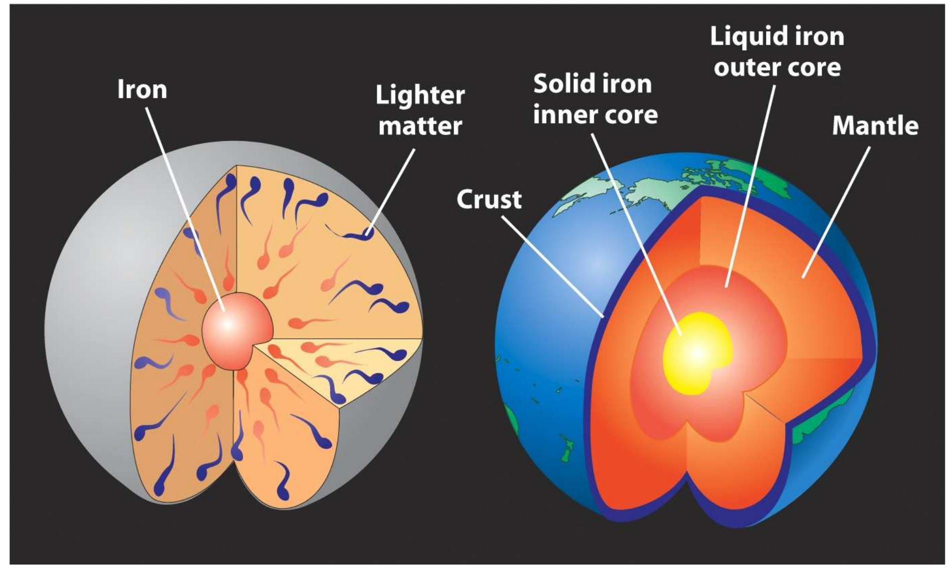
# Early Earth

- No atmosphere
- No water
- High temp
- No life…….
- Big rocks keep falling on my head…



http://www.black-cat-studios.com/catalog/earth.html

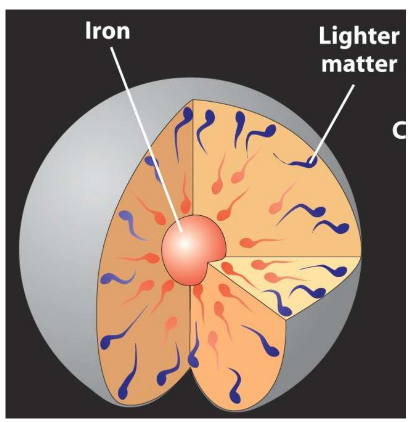
# *Planetary Differentiation*






# Differentiation: Iron Catastrophe

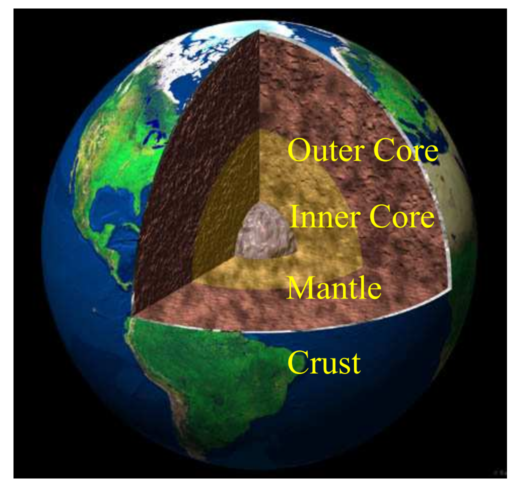
- Average density of Earth is 5.5 g/cm$^3$
- Average density on the surface is 3 g/cm$^3$
- So, something heavy must be inside
- When the Earth formed it was molten
  - Heavy materials (e.g. iron, nickel, gold) sank
  - Lighter materials (e.g. silicon, oxygen) floated to the top






# Structure

- Luckily, not all of the iron sank to the center, else we would be still in the Stone Age.
- Temperature increases as you go deeper underground. From around 290 K on surface to nearly 5000 K at center.
  - Heated by radioactive decay
  - Supernovae remnants
- Earth's magnetic field is established early on.. after the iron catastrophe… good for life.



# The Crust

- Outside layer of the Earth (includes oceans) floats on top of still hot interior
  - About 50 km thick
  - Coldest layer – rocks are rigid
- Mostly silicate rocks
  - Made of lighter elements like silicon, oxygen, and aluminum
- Oxygen and water are abundant
- Excellent insulator
  - Keeps the Earth’s geothermal heat inside!



# Today’s Earth Surface

- 70% of the Earth's surface is covered with water
  - Ocean basins
  - Sea floors are young, none more than 200 million years old
- 30% is dry land – Continents
  - Mixture of young rocks and old rocks
  - Up to 4.2 billion years old



# Geologically Active Surface

- The young rocks on the Earth's surface indicate it is geologically active
- Where do these rocks come from?
  - Volcanoes
  - Rift valleys
  - Oceanic ridges
- Air, water erode rocks
- **The surface is constantly changing**



# *In Hawaii*

# Recycling Bio-elements

- From gravity and radioactivity, the core stays hot.
- This allows a persisting circulation of bioelements through continental drift— melting of the crust and re-release through volcanoes.
- Otherwise, certain elements might get locked into sediment layers– e.g. early sea life.
- Maybe planets being formed now, with less supernovae, would not have enough radioactivity to support continental drifts and volcanoes. (Idea of Peter Ward and Donald Brownlee.)

http://www.pahala-hawaii.com/j-page/image/activevolcanoe.jpg



# The Earth's 1st Atmosphere

- The interior heat of the Earth helped with the Earth's early atmosphere.
- The inner disk had most gases blown away and the proto-Earth was not massive enough to capture these gases. And any impacts (e.g. the moon), would have blown the atmosphere away.
- One scenario is that impacted comets released – water ($H_2O$), carbon dioxide ($CO_2$), and Nitrogen ($N_2$) – the first atmosphere.
- The water condensed to form the oceans and much of the $CO_2$ was dissolved in the oceans and incorporated into sediments– such as calcium carbonate ($CaCO_3$).



http://www.fli-cam.com/images/comet-liner.jpg

# Our Atmosphere

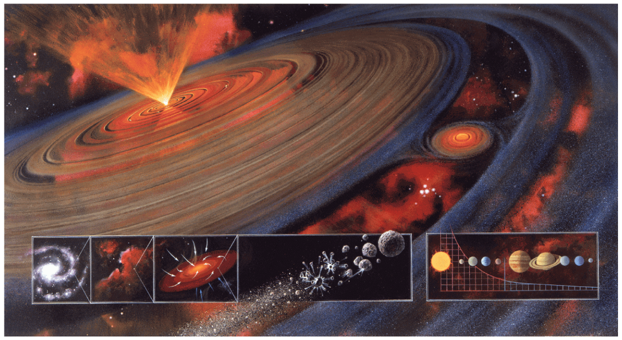
- Rocks with ages greater than **2 billion** years show that there was little or no oxygen in the Earth's atmosphere.
- The current composition: 78% nitrogen, 21% oxygen, and trace amounts of water, carbon dioxide, etc.
- Where did the oxygen come from?
- Cyanobacteria made it.
  - Life on Earth modifies the Earth's atmosphere.

http://www.uweb.ucsb.edu/~rixfury/conclusion.htm



# This New Planet

- Mostly oceans and some solid land (all volcanic).
- Frequent impacts of remaining planetesimals (ending about 3.8 billion years ago).
- Impacts would have sterilized the young Earth– Mass extinctions and maybe vaporized oceans (more comets?).



http://www.agnld.uni-potsdam.de/~frank/Images/painting.gif

# This New Planet

- Impacts and volcanic activity created the continental landmasses.
- Little oxygen means no ozone layer– flooded with ultraviolet light on surface.
- Along with lightning, radioactivity, and geothermal heat, provided energy for chemical reactions.



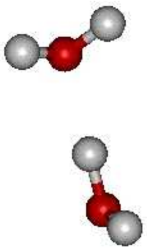
# Water

- Water is a key to life on Earth.
- Primary constituent of life– “Ugly bags of mostly water”
  - Life is about 90% water by mass.
- Primary role as a solvent
  - Dissolves molecules to bring nutrients and remove wastes. Allows molecules to “move” freely in solution.
  - Must be in liquid form, requiring adequate pressure and certain range of temperatures.
- This sets a requirement on planets, if we assume that all life requires water.



# Water as a Solvent

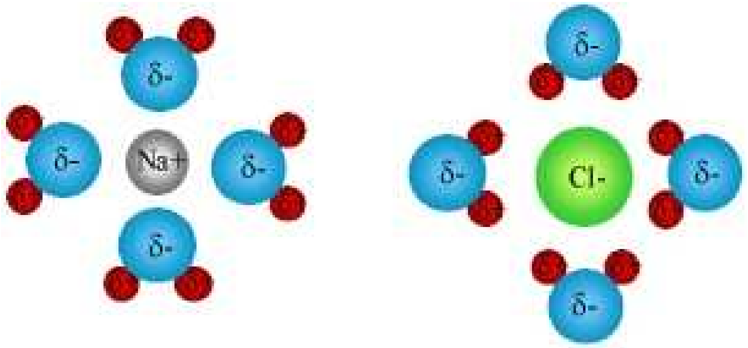
- The water molecule is “polar”. The oxygen atoms have more build-up of negative charge than the hydrogen. This allows water molecules to link up, attracted to each other.
- In this way, water attracts other molecules, surrounds them and effectively dissolves them into solution.





# Example: Dissolving Table Salt

The partial charges of the water molecule are attracted to the $Na^+$ and $Cl^-$ ions. The water molecules work their way into the crystal structure and between the individual ions, surrounding them and slowly dissolving the salt.

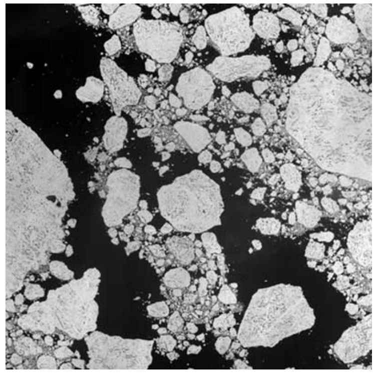



http://www.visionlearning.com/library/module_viewer.php?mid=57

# Water: Our Liquid Friend

- A very good temperature buffer
  - Absorbs significant heat before its temperature changes
  - When it vaporizes, it takes heat with it, cooling its original location

- It floats.
  - Good property for life in water.
  - Otherwise, a lake would freeze bottom up, killing life.
  - By floating to the surface, it can insulate the water somewhat.





# Keeping it Useful: Atmosphere

- Need to have enough pressure to keep water from boiling away at low temperature
  - Cooking at higher elevation requires more time. Boiling point lowered: water doesn't get as hot.
  - If pressure too low, water goes directly from ice to vapor (like dry ice $CO_2$)

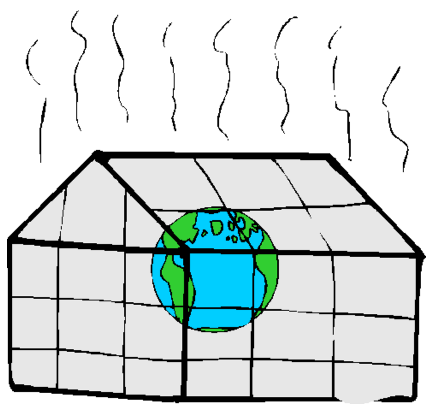
- On the other hand, high pressure may make life more difficult to form.
- In addition, the range of temperature for Earth based complex life is less than 325K.



http://www.astro.su.se/~magnusg/large/Boiling_water.jpg

# Keeping It Warm, but not too Warm

- What controls a planet's temperature?
  - The amount of light received from its star.
  - The amount of energy the planet reflects back.
  - And any Greenhouse effects of the planet.

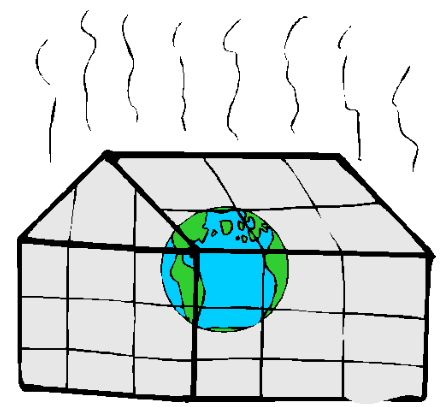




http://www.solcomhouse.com/Greenhouse_Effect.gif

# Keeping It Warm, but not too Warm

- Earth's greenhouse effect raises the temperature by about 15%.
- Given a star's luminosity, a range of acceptable temperatures translates into a range of distances to the star.
- This range is called the star's habitable zone (HZ), as planets in this range have temperatures suited for life.
- Only a rough guideline.

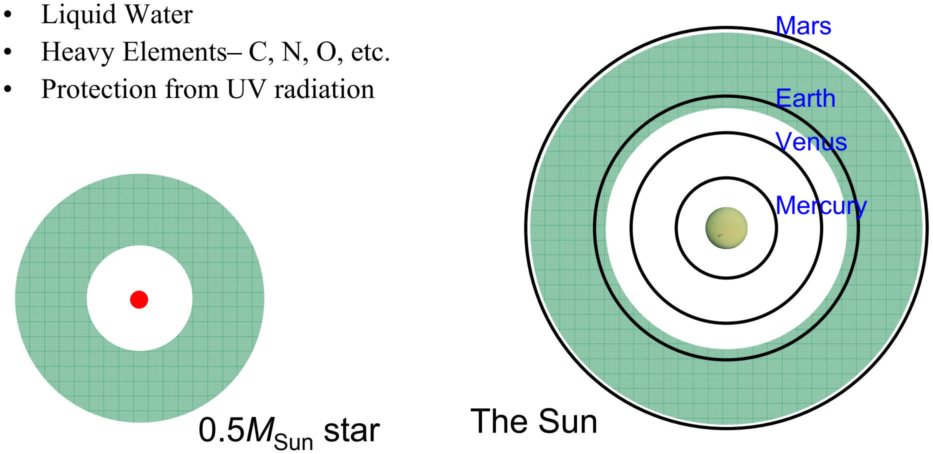




http://www.solcomhouse.com/Greenhouse_Effect.gif

# *Habitable Zones– Are you in the Zone?*

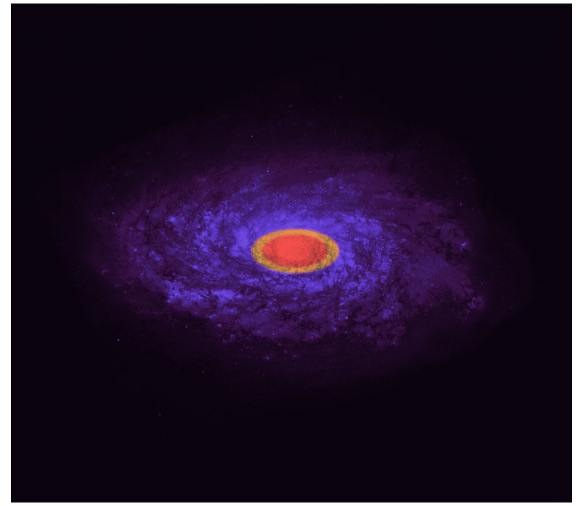
- Long living star
- Planets with stable orbits (thus stable temps)
- Liquid Water
- Heavy Elements– C, N, O, etc.
- Protection from UV radiation






# Galactic Habitable Zone

- Likewise the galaxy has regions that are better suited to life.
- In the inner regions of our galaxy, supernovae are too frequent.
- In the outer regions, there are too few metals.
- Simulation of Galaxy Zone from early stages to now.



http://astronomy.swin.edu.au/GHZ/GHZmovie.html



# The Sun's Variation

- As the Sun ages, it gets slightly brighter.
- When it was younger, its luminosity was 70% current values.
- A young Earth should have been 20K colder– iceball!
- During our ice ages, the temperature only changed by about 1%.

http://www.cherishclaire.com/iceball.htm



# The Sun's Variation

- There is evidence that the Earth did nearly freeze over– 2.8 billion years ago and 700 million years ago.
- Probably changes in the Greenhouse gases.
- This implies that the habitable zone can vary with time, thus the real habitable zone is smaller than shown before?
- Some have postulated that real zone is only 0.95 to 1.01 AU! If the Earth were 1% farther away– Iceballed. And $n_p$ would be very small ~ 0.1.

http://www.soest.hawaii.edu/gerard/GG108/images/bylot.jpg

# Earth's Atmosphere

- Most recent studies suggest an efficient planet negative-feedback mechanism (like a thermostat).
- $CO_2$ cycles from atmosphere (greenhouse gas) and oceans (buried sediment especially carbonate rock).
- $CO_2$ in atmosphere: temporarily dissolved $CO_2$ in rainfall reacts with weathered rocks, trapping it.
- Carbon is buried and can be released by volcanoes.
- Negative feedback process
  - Increase in temperature: evaporation of oceans, more rainfall, more weathering and $CO_2$ reduction, so decrease in temperature.
  - This negative feedback stabilizes the Earth's temperature.


http://www.wildtech.org/images/feedback.gif



# Life Adds to Feedback

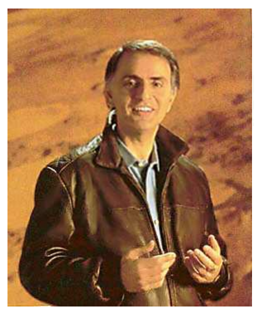
- Life increases the weathering of rock.
- J.E. Lovelock has proposed that life also stabilizes the planet temperature.
- Regardless, the negative feedback helps with the habitable zone, so we can estimate perhaps $n_p$ is more around 1– more Earth chauvinism?


While testing out his new cereal mix on his horse, Dave gets some unexpected feed-back.

http://www.cts.com/~borderln/



# Optimism?



- Carl Sagan argues for $n_p > 3$.
  - If Venus had less clouds (less greenhouse) it could have been cool enough for life.
  - If Mars had a thicker atmosphere it could have been warm enough for life.
  - If solvents other than water were used, maybe the moons of the outer planets?
  - Giant Jupiter-like planets close in?


Carl Sagan as a kid

http://www.uranos.eu.org/biogr/sagane.html
http://spider.ipac.caltech.edu/staff/jarrett/sagan/sagan.html



# Pessimism?

- We only considered temperature. What about:
  - Gravity?
  - Atmospheric pressure?
  - Size of the moon or planet?
  - Does life need a Moon-like moon? Does life need the tides? Does the Moon protect the Earth's rotation? Is a Jupiter needed?
- If we impose Earth chauvinism, we can easily reduce to $n_p \sim 0.1$

http://sagiru.tripod.com/Travel/Lost_in_the_Sahara/lost_in_the_sahara

# $n_p$: number of life planets per planetary system (average)

- Can range from 0.01 to >3.
  - Is seismic activity necessary to recycle bioelements?
  - How important is the first atmosphere? Ozone?
  - Is a moon needed? A large Jupiter-like planet?
  - Is liquid water a requirement? Other solvents okay?
    - Not too hot, not too cold; not too much pressure, not too little– Goldilocks requirement?
  - Habitable Zone around the star.
  - Galactic Habitable Zone
  - Does atmosphere need feedback mechanism?
  - But in our solar system, maybe 5 nearly possible life planets.