Astronomy 330

<u>This class (Lecture 6):</u>

Star Formation

<u>Next Class:</u>

Origin of planets

Music: *We are all made of Stars* – Moby

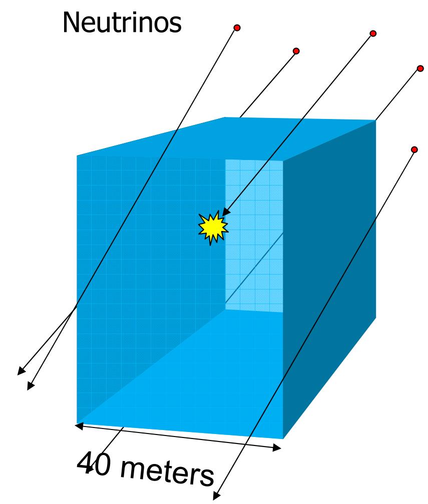
Outline

- From molecular clouds to baby stars– protostars.
- Star formation requires a circumstellar disk that is often seen around young stars.
- The origin of the Solar system also requires a disk of material in which dust clumped, forming planetesimals, then planets.
- Planets are different due to distance away from Sun..

Sneaky Little Neutrinos

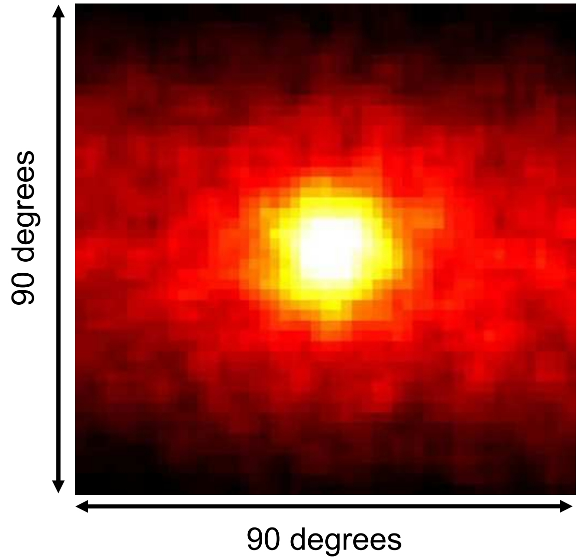
- The Sun's nuclear fusion produces a particle called a *neutrino*
- Matter is almost transparent to neutrinos
- On average, it would take a block of lead over a quarter of a light-year long to stop one
- Roughly 1 billion pass through every square centimeter of you every second!

Detecting Neutrinos



The Sun in Neutrinos

- **Confirmation** that nuclear fusion is happening in the Sun's core
- 500 days of data
- As they can only be produced by nuclear processes, our energy source concept must be fundamental



Cosmic Gall

very little
hardly

NEUTRINOS, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And scorning barriers of class,
Infiltrate you and me! Like tall
and painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
and pierce the lover and his lass
From underneath the bed-you call
It wonderful; I call it crass.

- *Telephone Poles and Other Poems*, John Updike, Knopf, 1960

How much Gas do we have left?

- Total energy available is easily calculated by mass of hydrogen in Sun and energy released by each hydrogen conversion.
- We only have about 5 billion years left!

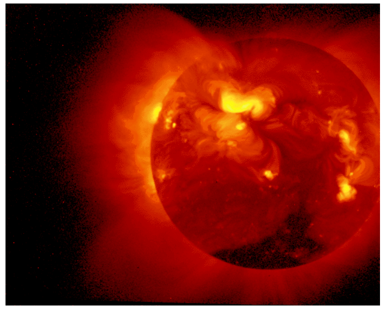
http://skeptically.org/sitebuildercontent/sitebuilderpictures/.pond/suv-econ-gas-pump.jpg.w300h294.jpg

Think-Pair-Share

If we could sustain fusion in the lab we could meet humankind's energy needs forever! Why is it so difficult to achieve this, when stars do it every day?

Nuclear Fusion in the First Stars

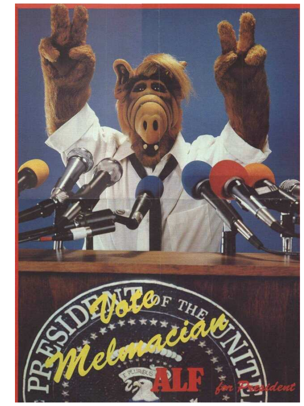
- Core $T > 10$ million K
  - Violent collisions
  - e^- stripped from atoms (ionized)
  - Nuclei collide, react
    - They get close enough that the nuclear strong force takes over.



- Thru series (chain) of reactions
- 4 protons → helium (2p,2n) nucleus + energy
- **Fusion:** light nuclei combine → heavier nuclei

Alf Doesn't Care?

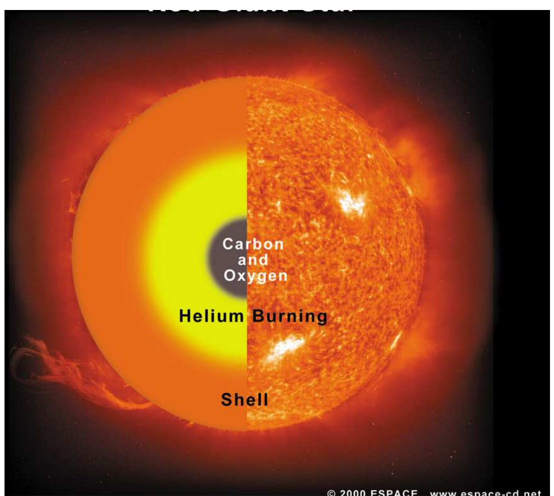
- A star in hydrostatic equilibrium will not shrink or swell.
- It will maintain constant size, density, and temperature for more than a million years!
- At this point, the star is called a main sequence star.
- If stars were not constant, what effect would that have on life on orbiting planets. Ultraviolet light variations?



http://alf.disim.com/photos/photoposter.htm

The First Stars

- In the cores of the first stars, it gets hot enough for nuclear fusion.
- In the internal furnace of these first stars is where carbon and oxygen are created for the first time in the Universe.
- Higher density and temperature of the red giant phase allows for the creation of sulfur, phosphorous, silicon, and finally iron.

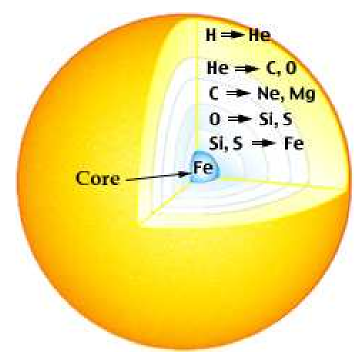


Iron – The End of the Road

- "Burning" heavier and heavier atoms in the fusion process
- Each stage faster than the last
- After iron - no fuel left!
  - It requires energy to produce heavier atoms

Stage	Temperature	Duration
H fusion	40 million K	7 million yr
He fusion	200 million K	500,000 yr
C fusion	600 million K	600 yr
Ne fusion	1.2 billion K	1 yr
O fusion	1.5 billion K	6 mo
Si fusion	2.7 billion K	1 day

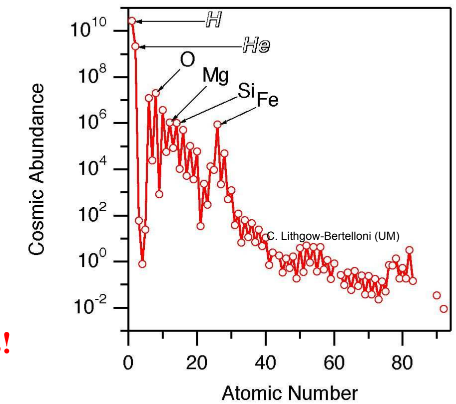
Values for a $25 M_{Sun}$ star



Supernova!

Making Heavy Elements

- The star goes **supernova** and explodes. Some of C, O, P, S, Si, and Fe get carried away. At this point, even heavier elements can be made.
- During the explosion, energy-consuming fusion reactions are possible
- These by-products are *blasted* into space (>90% of star)
- Supernovae provide much of the building blocks for planets… and us!
- **We are recycled supernova debris!**
- **We are Star stuff.**

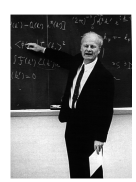


Delenn, B5

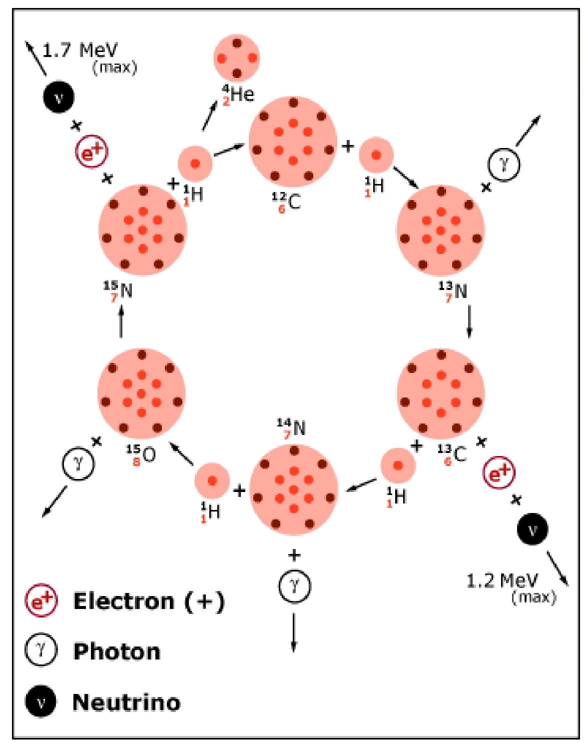
CNO-ing

- Now the Universe has some C and O laying around, it can use it.
- In the next generation of stars, the CNO cycle can be used in the fusion process.
- It is more efficient in stars slightly more massive than the Sun.
- Remember the Sun mostly uses proton-proton fusion.

The CNO Cycle



Hans Bethe



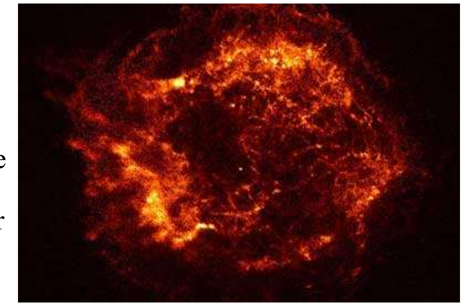
The Second Generation

- The first stars blew up their new elements into the proto-galaxy.
- Now, the second stars form in the ashes of the first.
- With C and N, the 2^{nd} generation can form helium through the CNO cycle, in which most of the Universe's nitrogen is created.
- The 2^{nd} generation also eventually explodes blowing nitrogen and the other elements into the galaxy.

A supernova in a nearby galaxy. A single star exploding can be brighter than millions of stars in the nucleus.

The Next Stars

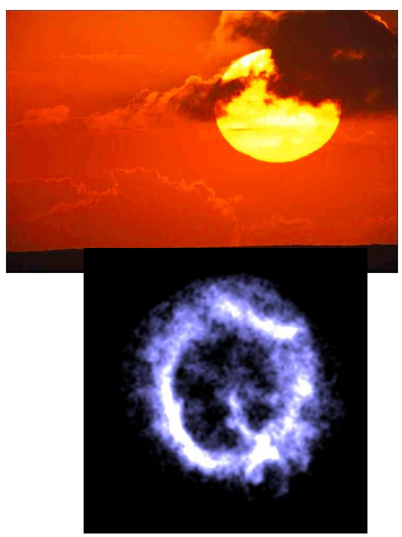
- The new atomic elements from the 1^{st} and 2^{nd} stars are spread out into the galaxy.
- The Sun must be at least a 3^{rd} generation star as we have **nitrogen** in abundance.
- Indeed, the percentage of heavier elements is larger toward the center of the galaxy, where the first generation of stars probably formed. (Seen in ours and other galaxies.)
- **Again, we are star stuff.**
- Keep in mind that this is all from the nuclear strong force– fusion.



The Chandra x-ray observatory has shown that the CasA supernova has flung calcium, iron, and silicon into space.

Star Stuff

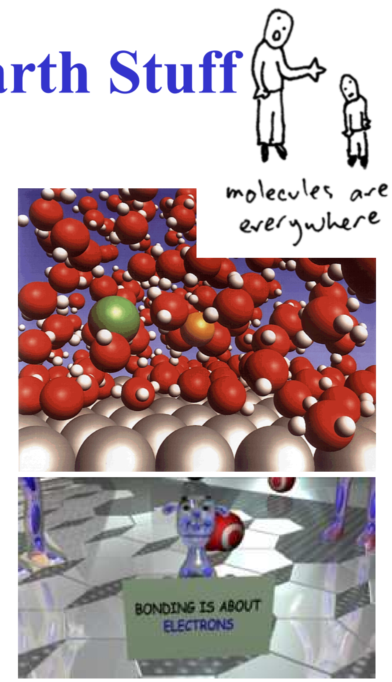
- Now, we have the elements crucial to life in the Galaxy-- **HONC**.
- There are about 92 elements found in the Universe and about 20 more elements that have been created in laboratories (but decay quickly).
- The 92 elements were almost all made in the interiors of massive stars or during a supernova explosion.



http://www.astronomyinfo.pwp.blueyonder.co.uk/starstuff.htm
http://antwrp.gsfc.nasa.gov/apod/ap991209.html

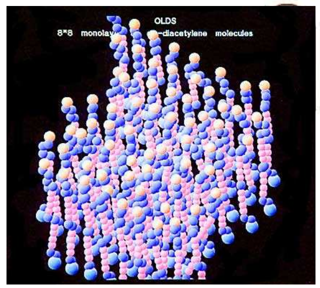
Star Stuff and Earth Stuff

- Deep inside stars the electrons are stripped away, and only the nucleus (and the strong nuclear force) play roles.
- But, most of the important aspects of life depend on molecules. That involves electrons and the electromagnetic force that keeps the electron(s) with the nucleus.

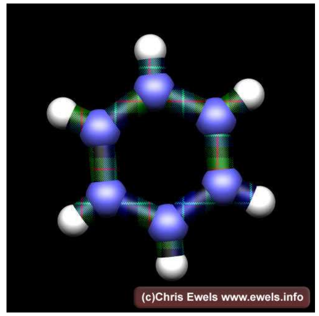


http://nanokids.rice.edu/explore.cfm
http://www.toothpastefordinner.com/archives-sum02.php
http://www.psc.edu/science/Voth/Voth.html

Molecules



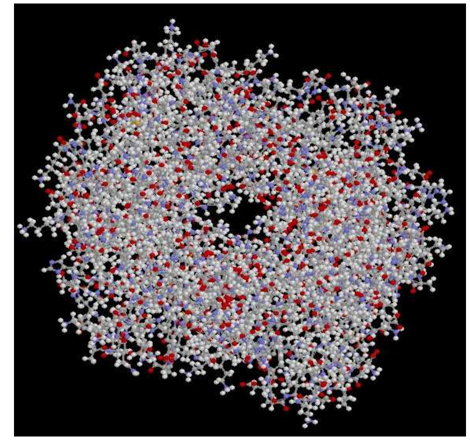
- Combination of 2 or more atoms such that they are bound together without their nuclei merging.
- Just like an atom is the smallest piece of an element, a molecule is the smallest piece of an compound.
- When dividing water, smallest division, before separation of hydrogen and oxygen.



http://www.ph.qmw.ac.uk/research_bk/theory.htm

Molecules

- Wow! An enormous jump in complexity. There are only about 115 elements, but there are millions of known molecules and nearly infinite number of possibilities.
- Some of the key life molecules contain billions of atoms.

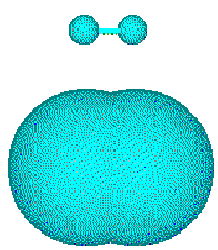


http://www.bris.ac.uk/Depts/Chemistry/MOTM/silly/sillymols.htm

http://www.steve.gb.com/science/molecules.html

Example H_2

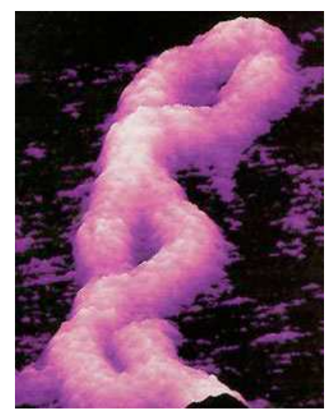
- H_2 is the simplest molecule– two hydrogen atoms.
- What does that mean?
  - There are 4 particles.
    - 2 protons of the 2 nuclei, which repel each other
    - 2 electrons of the 2 atoms, which repel each other
  - But
    - The electron of each atom will attract the other nucleus
- Although not obvious, the 2 attractive forces and 2 repulsion forces equal out.
- The electromagnetic force works for hydrogen, but there is no He_2.



http://www.historyoftheuniverse.com/h2.html

Molecule Benefits for Life

- Molecules can easily be broken apart, but are also stable.
- Flexibility in arrangement.
- Plethora of molecules.
- Electromagnetic force is much weaker than strong nuclear force, lower energies– lower temperatures.
- Perfect for life.



http://www.time.com/time/daily/special/genetics/

How to Write Molecules

- We'll talk about H_2 or CO_2
- Or

Molecular Hydrogen

H-H

Single bond

Sharing 1 electron pair

Carbon Dioxide

O=C=O

Double bond

Sharing 2 electron pairs

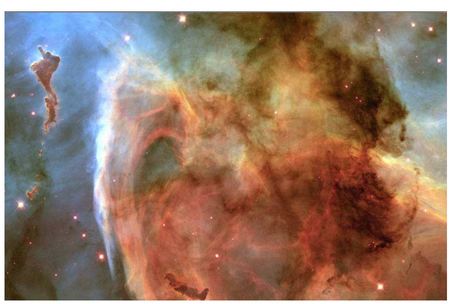
http://www.gristmagazine.com/dogood/connections.asp

Talkin' About a Revolution

- Molecules first showed up in space after enough heavy elements accumulated.
- There is **a lot** of interstellar molecular gas clouds in space.
- First complicated molecules found in space in 1968, and we have found even more over the last 20 years.
- They often emit light in the millimeter regime.

The Interstellar Medium (ISM)

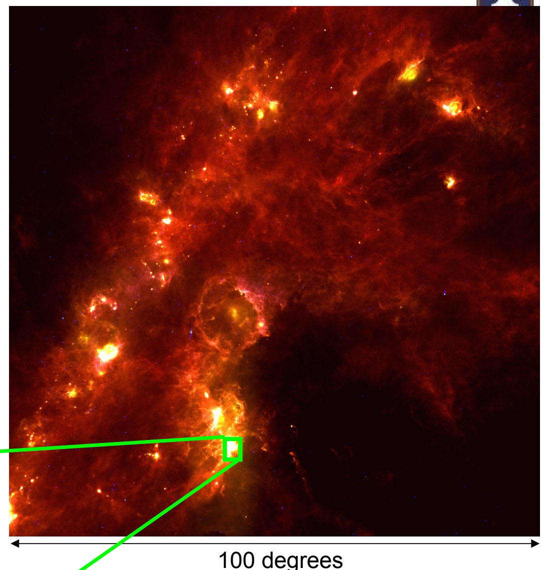
- Stuff between the stars in a galaxy.
- Sounds sort of boring, but
  - Actually very important
  - Features complex physical processes hidden in safe dust clouds
- Every star and planet, and maybe the molecules that led to life, were formed in the dust and gas of clouds.
- Exists as either
  - Diffuse Interstellar Clouds
  - Molecular Clouds

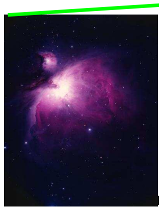


Keyhole Nebula

Giant Molecular Clouds

- Cool: < 100 K
- Dense: $10^2 - 10^5$ H_2 molecules/cm^3
  (still less dense than our best vacuum)
- Huge: 30 – 300 lyrs across, $10^5 - 10^6$ solar masses
- CO molecular emission & dust emission trace structure



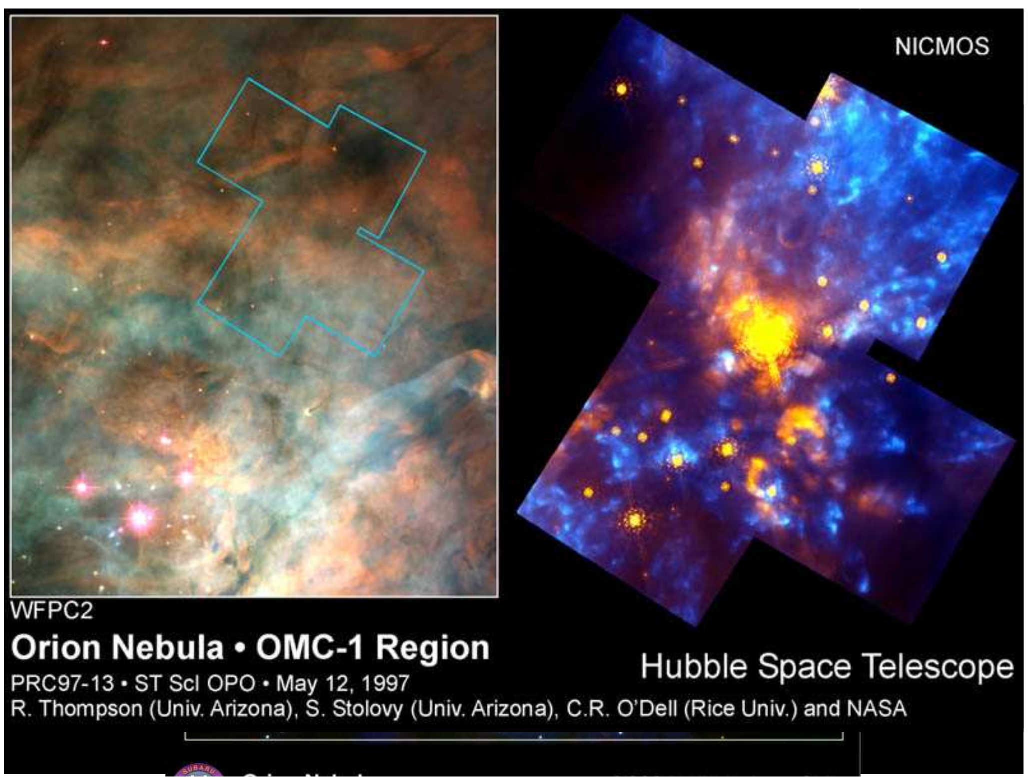


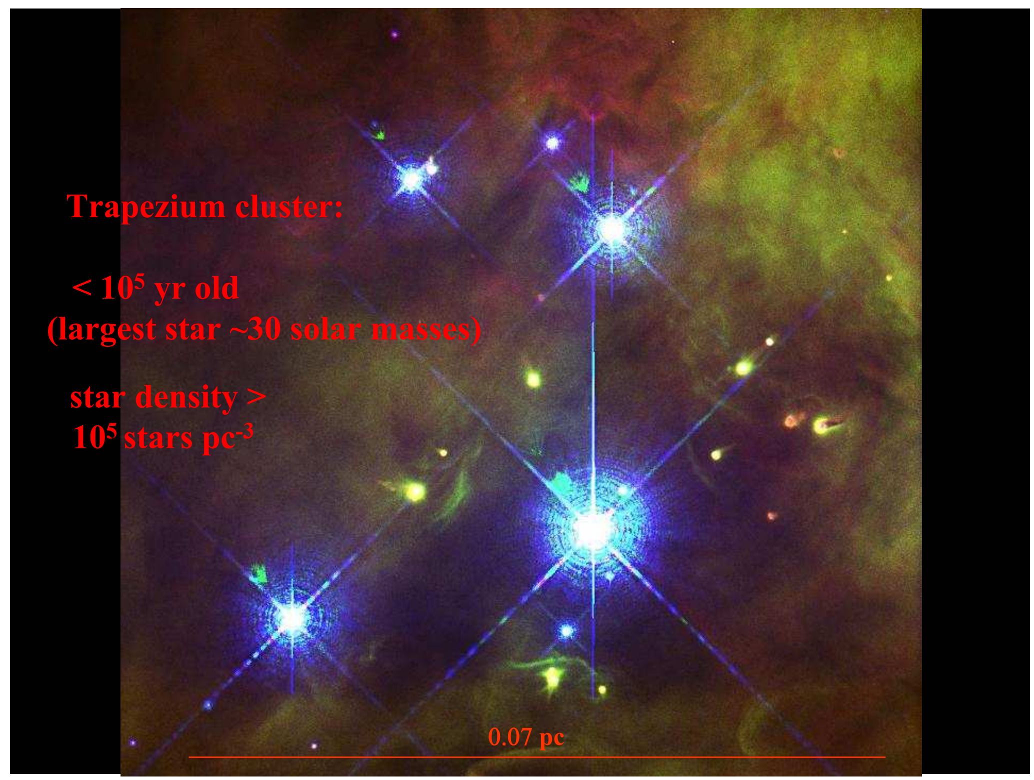
Infrared image from *IRAS*

Orion Nebula

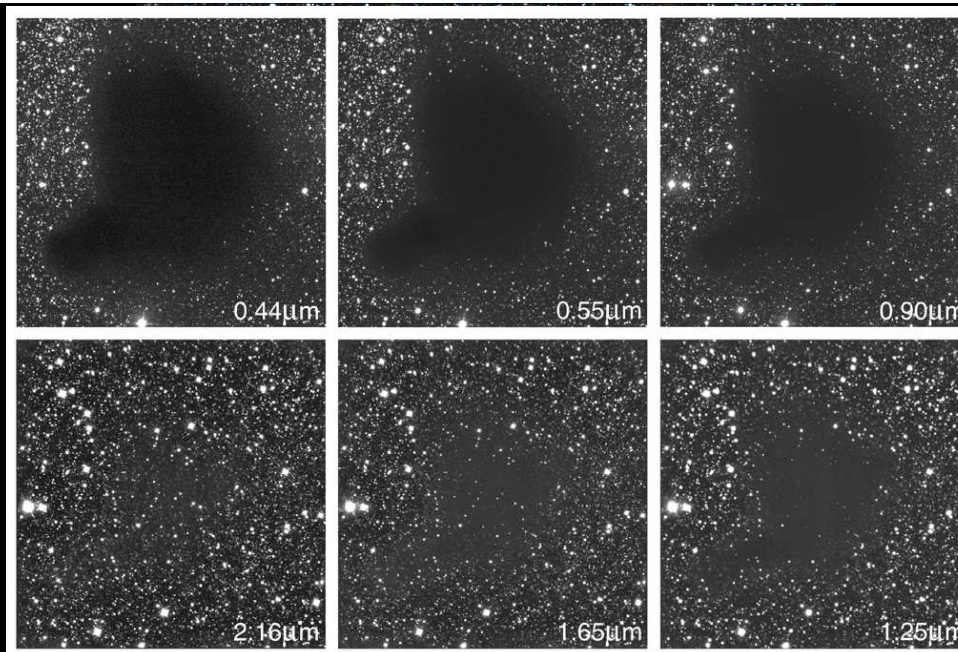
(near infrared)

Nearest massive star forming region with a large molecular cloud associated (distance of 1500 lys)





Interstellar Clouds

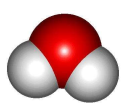


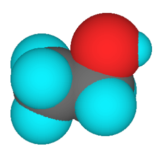
The Dark Cloud B68 at Different Wavelengths (NTT + SOFI)

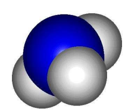
ESO PR Photo 29b/99 (2 July 1999)

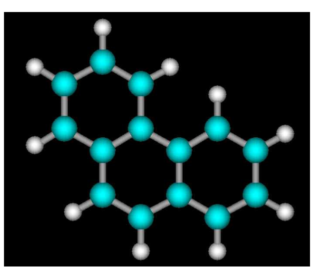
Other Things Besides Hydrogen in Molecular Clouds

- Molecules (e.g.)
  - Carbon monoxide (CO)
  - Water (H_2O)
  - Ammonia (NH_3)
  - Formaldehyde (H_2CO)
  - Glycine (NH_2CH_2COOH)?
  - Ethyl alcohol (CH_3CH_2OH)
  - Acetic Acid (CH_3COOH)
  - Urea [$(NH_2)_2CO$]
- Dust particles
  - Silicates, sometimes ice-coated
  - Soot molecules

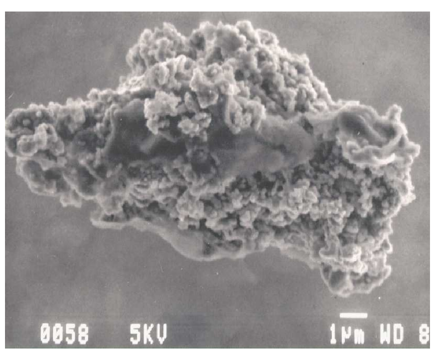








Polycyclic aromatic hydrocarbons (PAH)

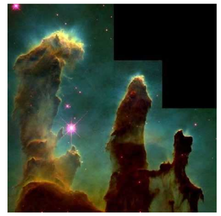


Dust particle (interplanetary)

So?

- Complex molecules (>13 atoms) have evolved in places other than the Earth.
- Maybe there are more? The more complex molecules are harder to detect.
- Seen in other galaxies too.

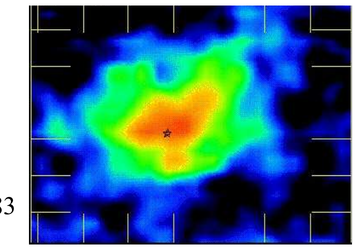
Molecular Clouds



- Interstellar clouds are important molecular factories.
- Analogous to clouds in our atmosphere
- Primarily molecular hydrogen (~93%) and atomic helium (~6%) with (~1%) heavy molecules– molecules or dust.
- H_2 is not good at emitting photons, so easier to see larger molecules emitting– especially CO (which tells the temperature of these clouds).
- Other molecules (mostly H_2CO, HCN, or CS) are used to derive estimates of density.

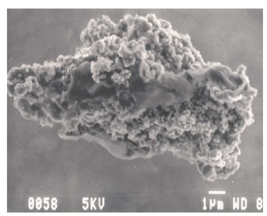
The Importance of being a Molecular Cloud

- Different than the clouds that formed the First Stars
- Stars form in cold, dense molecular clouds (normally starless)
  - Colder: molecules and dust easily emit in the radio and infrared, which cools the cloud.
  - Clumpy: clumps more easily, as the material is cold, forming regions of high density.
- Formation of more complex molecules
  - Density allows for more collisions, interactions, formation of molecules
  - *Maybe formed biological compounds?*



$C^{18}O$ emission from L483

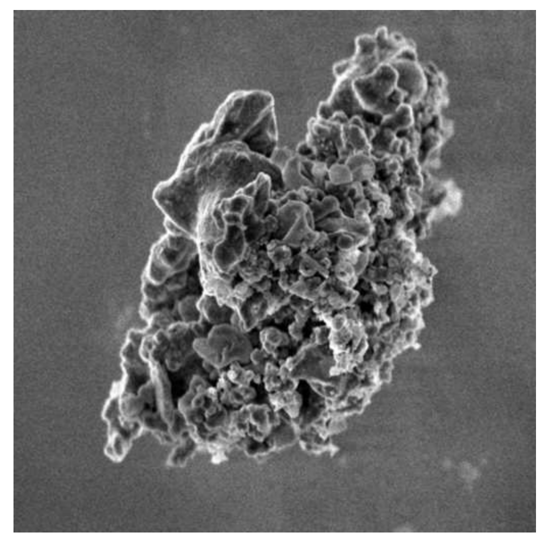
In Dust We Trust



- Small (< 1 micron), solid particles in space
- Two types:
  - Primarily carbon (sort of like what we call soot)
  - Silicates, minerals of silicon and oxygen (sort of like what we call dust)
- Produced in material flowing from old stars, but mixed in space.
- When concentrated can protect molecules from ultraviolet light, which destroy molecules.
- Dust plays a role in formation of molecules.

Molecule Formation

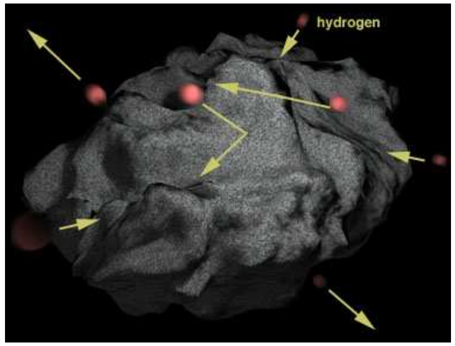
- When molecules form, they must release energy by emitting light or colliding
- Difficult to do in the gas phases, need dust grains as a catalysis.



http://spiff.rit.edu/classes/phys230/lectures/ism_dust/ism_dust.html

Molecule Formation

- H on dust grain, gets hit by another H, then extra energy ejects the newly formed molecule H_2 from the dust grain.
- For more complicated molecules, they need to be ionized to get easy reaction in space.
- What ionizes the molecules? Ultraviolet light would work, but then the molecules would get destroyed.

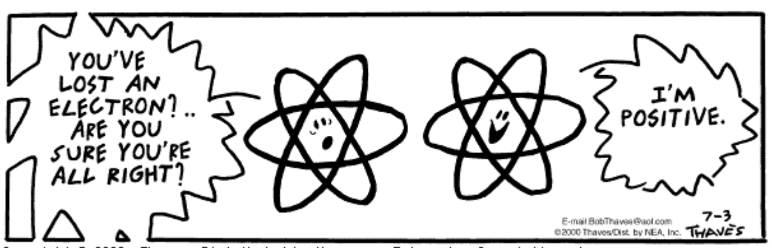


How to Get Complex Molecules

- Best answer is that the rare cosmic rays ionizes molecules inside of a molecular cloud.
- For example:

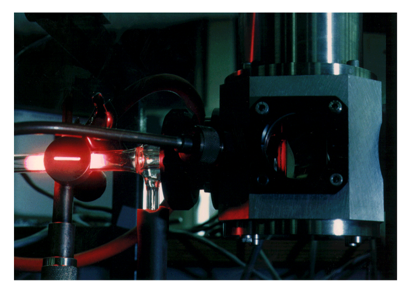
$$H_2^+ + H_2 \rightarrow H_3^+ + H$$
$$H_3^+ + CO \rightarrow HCO^+ + H_2$$

- HCO^+ can then be involved in other reactions, building bigger and bigger molecules.
- These ion molecules can form more complex molecules.



More to the Story: HONC

- But if H_2 can stick to the dust grains, shouldn't larger molecules stick too? In fact, we see water (H_2O), ammonia (NH_3), methane (CH_4), and methanol (CH_3OH) frozen to the dust grains.
- **Hey, that's the most important bioelements (H, O, N, and C) on dust grains!**
- Mayo Greenberg and co-workers studied these ices in the lab and by adding a little of ultraviolet light, would get what he called "Yellow Stuff" on the dust grains. This stuff is similar to products from experiments designed to study the origin of life.
- Others have taken this a step farther, postulating that life originated on these dust grains, and even today new life is raining down on the earth.



http://www.strw.leidenuniv.nl/~greenber/

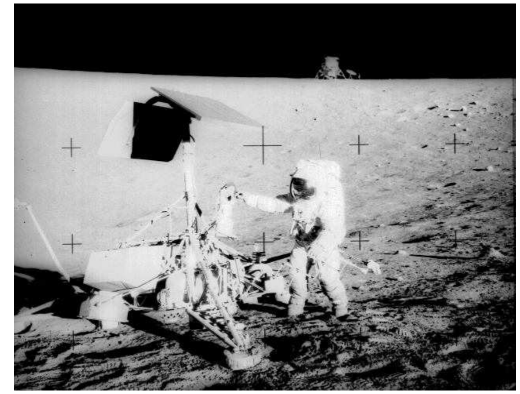
Panspermia

- Some have stated that perhaps life-important molecules formed in these clouds and spread to planets. **Infection!**
- Comets could have carried molecules to Earth's surface. Or ordinary meteors.
- Maybe epidemic outbreaks on Earth related to comet landings?
  - Incidentally, it has been observed that peaks in the influenza cycle matches the 11 year solar cycle (see William Corliss' work)
- http://www.panspermia.org/

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

Panspermia: Case in Point

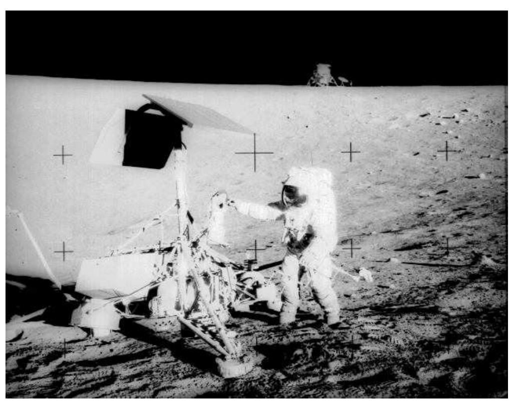
- Surveyor 3: unmanned lunar probe which landed in 1967.
- 2.5 years later, a camera was retrieved by Apollo astronauts.
- The camera had 50 to 100 viable specimens of *Streptococcus mitis*, a harmless bacterium commonly found in the human nose, mouth, and throat.



http://nssdc.gsfc.nasa.gov/planetary/news/image/conrad_19990709_c.jpg

Panspermia: Case in Point

- The camera was returned under strict sterile conditions.
- The bacteria had survived 31 months in the absence of air or water!
- In SPACE!
- Was subjected to large monthly temperature variations and hard ultraviolet radiation from the Sun.



http://nssdc.gsfc.nasa.gov/planetary/news/image/conrad_19990709_c.jpg

3 Lessons of Interstellar Molecules

1. Molecules with as many as 13 atoms have evolved in places other than Earth.
   - In our Galaxy and beyond.
   - Hard thing is getting the lab data for searching for more complicated molecules.
   - Evidence for polycyclic aromatic hydrocarbons (PAHs) links of carbon atoms with hydrogen on the outside is found in space.
   - Also found in the exhaust of cars and may play a role in early life.
2. Dominance of carbon in interstellar chemistry. So perhaps carbon based life forms is not just Earth chauvinism.
3. Study of these in space illustrates the problems of molecules getting more and more complex and not being destroyed by UV light. That's why it wasn't expected.

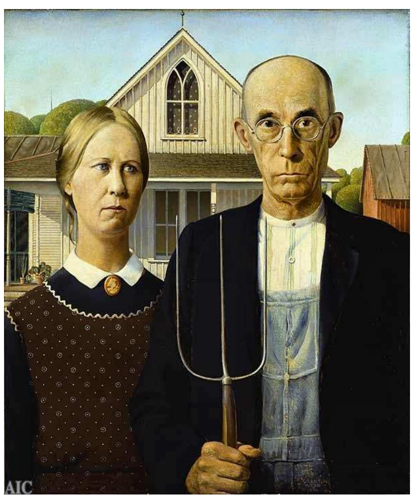
Stars

- The fundamental building blocks of the Universe.
- High mass stars are 8 to 100 solar masses
  - Short lived: 10^6 to 10^7 years
  - Luminous: 10^3 to 10^6 L_{sun}
  - Power the interstellar medium–input of energy
- Intermediate mass stars are 2 to 8 solar masses
- Low mass stars are 0.4 to 2 solar masses
  - Long Lived: $>10^9$ years
  - Good for planets, good for life.
  - Not so luminous: 0.001 to 10 L_{sun}

Lifecycle of a Star

- Star formation
  - Take a giant molecular cloud core with its associated gravity and wait for 10^4 to 10^7 years.
- Main sequence life (depends on mass!)
  - Few x 10^6 years to more than age of Universe
  - Thermonuclear burning of H to He
- Death
  - Exhaust hydrogen
  - Red giant / supergiant or supernova
  - White dwarfs, neutron stars, black holes

Stellar Lifestyles

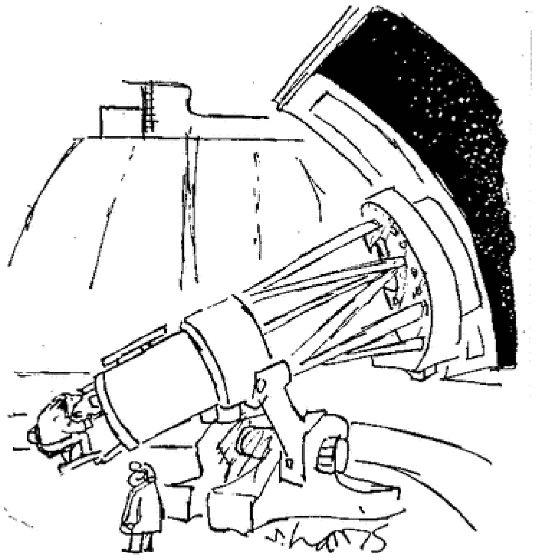


Low-mass stars

Massive stars

Estimate of R_*: The Star Formation Rate

- We are about to start the topic of star formation and planet formation, but really the field is not well enough developed to estimate R_*.
- It is more accurate to just take the total number of stars in the Galaxy and divide by the age of the Galaxy.
- Later we will correct for the stars that are too big, too small, or too variable.



'Let's see, now ... picking up where we left off ... one billion, sixty-two million, thirty thousand, four hundred and thirteen ... one billion, sixty-two million, thirty thousand, four hundred and fourteen ... "

Counting Stars

Estimate of R_*:
The Rate of star formation

Take the total number of stars in the galaxy and divide by how long it took those stars to form.

Sounds easy, but it isn't. We can't see all of the stars, interstellar dust blocks our view of most of them.

We can estimate the number of stars based on the total mass of the Galaxy and some corrections.

$$N_* = 5\times 10^{10} \text{ to } 5\times 10^{11} \text{stars}$$

Estimate of R_*:
The Rate of star formation

Age of our galaxy is around 10^{10} years (if you want to be more precise, use 13.7 billion years minus ~200 million).

$$R_* = \frac{5\times 10^{10} \textit{ to } 5\times 10^{11} \textit{stars}}{10^{10} \textit{ years}} = 5 \textit{ to } 50 \frac{\textit{stars}}{\textit{year}}$$

Probably the best estimate for the entire Drake Equation, meaning it can only be off by a factor of 10 or so.

Estimate of R_*:
Discuss

$$R_* = \frac{5\times 10^{10} \text{ to } 5\times 10^{11} \textit{ stars}}{10^{10} \textit{ years}} \approx 5 \text{ to } 50 \frac{\textit{stars}}{\textit{year}}$$

1. Discuss the calculation of this value.
2. Choose a lower/higher number if you think that the star formation rate was biased by non-uniform star formation.
   - Did the early galaxy produce more stars in the past than it does now? Was there a starburst long ago?
   - But remember that we are constantly obtaining new gas from our satellite galaxies. It might average out.