How Nature Makes Elements

- All elements heavier than Helium are made inside stars
  - Carbon and Oxygen in medium mass stars which end up as white dwarfs
  - up to Iron - fusion in massive stars
  - above Iron – supernovas and neutron star-neutron star collisions

- Stars lose matter at end of their life-cycle
  becoming Red Giants (can detect as Planetary Nebula)
  Supernova debris (can detect)

releasing all the elements into interstellar material and this matter forms new stars (and planets and us). “we are stardust” Joni Mitchell, song Woodstock
Nuclear Synthesis above Iron

- supernova core collapse gives 200 billion degrees → energetic photons

- In Type II supernova photons break up many nuclei
  \[ \text{Fe} \rightarrow 26p + 30n \quad \text{O} \rightarrow 8p + 8n \]

- neutrons attach themselves to nuclei say Iron: \( \text{Fe}(26p + 30n) \rightarrow \text{Iron: Fe}(26p + 58n) \)

- new nuclei have say 10 or 20 or 50 “too many” neutrons

- they Beta decay \( n \rightarrow p \) giving nuclei with more protons than Iron \( \text{Fe}(26p+58n) \rightarrow \text{Krypton: Kr}(36p+48n) \)

- Cycle repeats itself – happens very fast “rapid”
Nuclear Synthesis above Iron

- Before 2010 it was thought that all heavy elements, like Gold, Lead, and Uranium, were made during Type II supernovas
- But computer programs which used better knowledge of nuclei obtained at labs on Earth were not able to simulate the production of very heavy elements
- Neutron star-neutron star collisions would make heavy elements as has more “available” neutrons, already some heavy elements, and more energy
- While story is not complete the best assumption is that these heavy elements are mostly made in NS-NS collisions – the gold in a ring probably originated there
Neutron Star collisions

- Have about 1 neutron star-neutron star collision every 10,000 years in the Milky Way galaxy
  sometimes called kilonova and will be 1/10 times brighter than a Type Ia supernova
- Had about 10 NS-NS collisions within 1000 LY of us in the 1 billion years before the Sun and the other stars in our local cluster were formed
Cosmic Abundance of Elements

H = 92% of elements = mass-fraction 74%
He = 8% = mass-fraction 25%
All others < 1% mass-fraction about 1%
Discovered by Cecilia Payne about 1921, but she didn’t become Harvard faculty until 1956 as “no female faculty rule”
From Matthew Gardner 2018 FB post
Cecilia Payne’s mother refused to spend money on her college education, so she won a scholarship to Cambridge.

Cecilia Payne completed her studies, but Cambridge wouldn’t give her a degree because she was a woman, so she said to heck with that and moved to the United States to work at Harvard.

Cecilia Payne was the first person ever to earn a Ph.D. in astronomy from Radcliffe College, with what Otto Strauve called “the most brilliant Ph.D. thesis ever written in astronomy.”

Not only did Cecilia Payne discover what the universe is made of, she also discovered what the sun is made of (Henry Norris Russell, a fellow astronomer, is usually given credit for discovering that the sun’s composition is different from the Earth’s, but he came to his conclusions four years later than Payne—after telling her not to publish).

Cecilia Payne is the reason we know basically anything about variable stars (stars whose brightness as seen from earth fluctuates). Literally every other study on variable stars is based on her work.

Cecilia Payne was the first woman to be promoted to full professor from within Harvard, and is often credited with breaking the glass ceiling for women in the Harvard science department and in astronomy, as well as inspiring entire generations of women to take up science.

“Since her death in 1979, the woman who discovered what the universe is made of has not so much as received a memorial plaque. Her newspaper obituaries do not mention her greatest discovery. […] Every high school student knows that Isaac Newton discovered gravity, that Charles Darwin discovered evolution, and that Albert Einstein discovered the relativity of time. But when it comes to the composition of our universe, the textbooks simply say that the most abundant atom in the universe is hydrogen. And no one ever wonders how we know.”

—Jeremy Knowles, discussing the complete lack of recognition Cecilia Payne gets, even today, for her revolutionary discovery. (via alliterate)
Cosmic Abundance of Elements

Nature prefers elements with an even number of protons and an even number of neutrons as those nuclei have larger binding energy. Carbon, Oxygen, Silicon, Iron are abundant. All elements heavier than lead are unstable, radioactive, decay to lead.
Cosmic Abundance of Elements

Most of what makes up “us” are C, O, and H.
Supernova Debris  SN1987a

Can detect heavy elements by spectrum and so study supernova debris over time to observe the elements at different layers of the star before it blew up.
Planetary Nebula + Supernova Debris

Dumbbell Nebula M27

Planetary nebula. Shows H, He, C, O from Red Giant moving to white dwarf

Cassiopeia A supernova from 1680. Has iron, silicon, other heavy elements. Probable neutron star
Uranium – not on tests

Uranium has 92 protons and mostly comes in 2 isotopes: U(235) with 143 neutrons and U(238) with 146 neutrons. 99.27% of Uranium is U(238). But it is U(235) which chain reacts and so used in nuclear reactors and atomic bombs. “enriching” uranium increases the amount of U(235). The US has a stockpile of about 550 tons of enriched uranium for reactors on navy ships and the arsenal of nuclear weapons.

The relative fraction of U(235) to U(238) and their lifetimes of 1 billion and 6.5 billion years can be used to estimate when the Uranium was produced. This is similar to Carbon 14 dating. The calculation gives a production date of about 5.8 billion years ago, which is maybe when a neutron star-neutron star collision occurred near where the Sun formed about 1 billion years later.

Detailed studies of the abundance of other radioactive elements heavier than lead can be used to determine the age of the Earth.
Uranium – not on tests - arithmetic

Feel free to skip if you dislike logarithms

Fraction U(238) = 99.27%
Fraction U(235) = 0.72%
Lifetime U(235) = 6.52 billion years
Lifetime U(238) = 1.02 billion years

ASSUME at production equal amounts of U(235) and U(238)

Amount(today) = exponential(-time/lifetime)
Ln(.0072) = -4.9 = -time(1/1.02 -1/6.52)
Time = 5.76 billion years ago - when uranium was produced
Test 2 Study Guide

- How to measure distances to stars (1) helio-centric parallax and (2) spectroscopic parallax
- Hertzsprung-Russell diagram identifiers (main sequence, red giant, white dwarf)
- Luminosity vs radius vs surface temperature for stars
- Star clusters and how they are used to study star aging
- Steps leading from gas cloud to main sequence star
- Steps leading from Red giant to supernova (or white dwarf to SN) and what happens during supernova
- Difference between white dwarf, neutron star, black hole
- Production of elements
Star Life Cycles

- Interstellar clouds
- Stellar winds
- Star formation
- Stellar evolution
- Planetary nebulae, supernovae
# Fate of Stars

<table>
<thead>
<tr>
<th>INITIAL MASS relative to Sun’s mass</th>
<th>Final State</th>
</tr>
</thead>
<tbody>
<tr>
<td>M &lt; 0.01</td>
<td>planet</td>
</tr>
<tr>
<td>0.01 &lt; M &lt; 0.08</td>
<td>Brown dwarf (not true star)</td>
</tr>
<tr>
<td>0.08 &lt; M &lt; 0.25</td>
<td>not Red Giant $\rightarrow$ White Dwarf</td>
</tr>
<tr>
<td>0.25 &lt; M &lt; 12</td>
<td>Red Giant $\rightarrow$ White Dwarf</td>
</tr>
<tr>
<td>12 &lt; M &lt; 40</td>
<td>Supernova: neutron star</td>
</tr>
<tr>
<td>M &gt; 40</td>
<td>Supernova: black hole</td>
</tr>
</tbody>
</table>
Star Life Cycles - Summary

- **Protostar**
  - Less than 0.08M\(_\odot\) brown dwarf
  - Between 0.08 and 0.4M\(_\odot\) main-sequence (red dwarf) star
  - 0.4 to 8M\(_\odot\) main-sequence star
  - 8 to 25M\(_\odot\) main-sequence star
  - More than 25M\(_\odot\) main-sequence star

- **Supergiant**
- **Giant star**
- **Red supergiant**
- **Supernova**
- **Black hole**
- **Neutron star**
- **Planetary nebula**
- **White dwarf**

**TIME**
REMINDER
Hertzprung-Russell Diagram

Plot Luminosity versus surface temperature
Part of test will be identifying stars on an HR diagram.
Check example test 2 on course web page for possible questions
Lecture Feedback

E-mail me a few sentences describing one topic you learned from this set of presentations. Please include the phrase “All elements heavier than Helium are formed inside of stars; we are made from stardust” in your mini-report but do not use that as your “one topic”.