The Birth, Life, and Death of Stars

The Osher Lifelong Learning Institute
Florida State University

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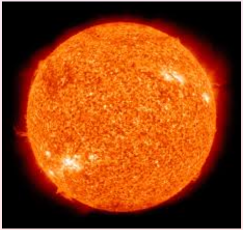
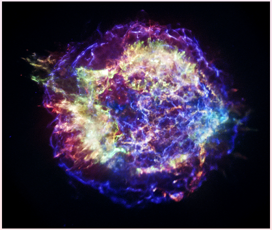
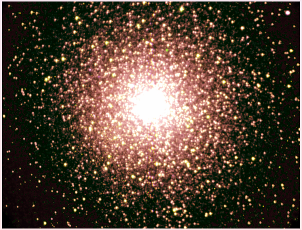
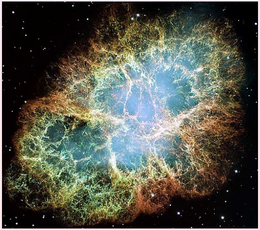
Schedule: September 29 – November 3
Time: 11:30am – 1:30pm
Location: Pepper Center, Broad Auditorium


Ten Compelling Questions

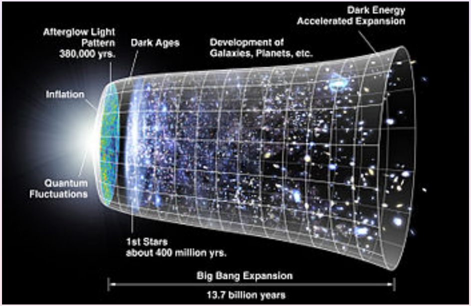
- What is the raw material for making stars and where did it come from?
- What forces of nature contribute to energy generation in stars?
- How and where did the chemical elements form? ⋆
- How long do stars live?
- How will our Sun die?
- How do massive stars explode? ⋆
- What are the remnants of such stellar explosions?
- What prevents all stars from dying as black holes?
- What is the minimum mass of a black hole? ⋆
- What is role of FSU researchers in answering these questions?

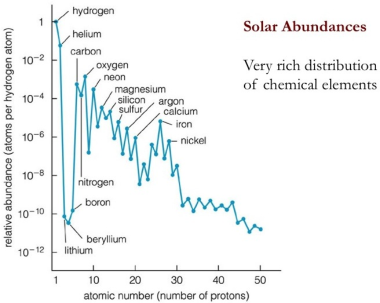




Nucleosynthesis

- Big Bang: The Universe was created about 13.7 billion years ago
- BBN: Hydrogen, Helium, and traces of light nuclei formed after 3 minutes
- Sun displays a rich and diverse composition of chemical elements

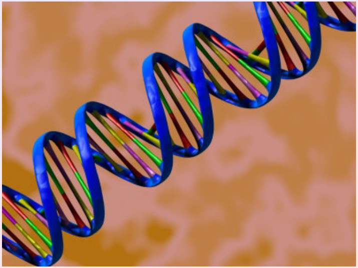


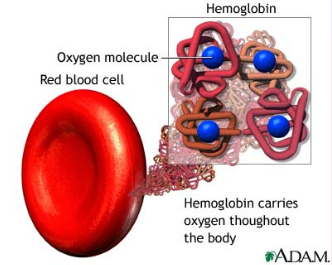


If the Solar System is rich in chemical elements other than H and He; where did they come from?

The Human Blueprint

- Human beings are C-based lifeforms
- Human beings have Ca in our bones
- Human beings have Fe in our blood
- Human beings breath air rich in N and O

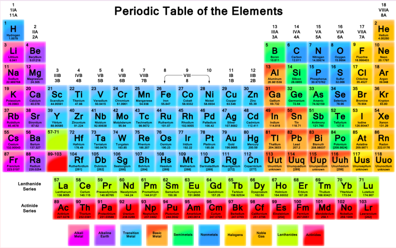




If only Hydrogen and Helium were made in the Big Bang, how and where did the rest of the chemical elements form?

Stellar Nucleosynthesis

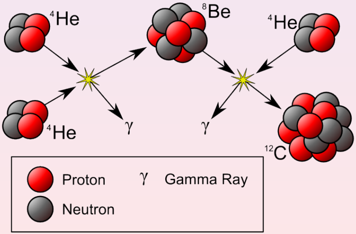
- A protostar achieves stardom at 10 million K
  - Gravitational energy converted into thermal/kinetic energy
  - Protons overcome their Coulomb repulsion and fuse
  - Thermonuclear energy is generated by converting 4 protons into ^{4}He
- What happens after H fuel is exhausted in the stellar core?
  - Stars are remarkably efficient thermonuclear furnaces
  - Loss of pressure support results in gravitational contraction
  - Gravitational energy is transformed into thermal/kinetic energy
  - Core contracts until temperature increases to about 100 million K
  - The heavier He-ashes (with a larger $Z=2$) can now fuse
  - Energy generation via thermonuclear fusion is restored!

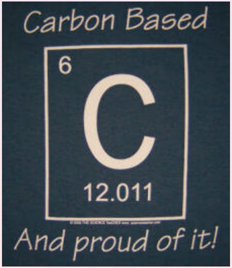


There are 112 known chemical elements listed in the periodic table. We have a long way to go ...

The Birth of Carbon: The Triple-Alpha Reaction

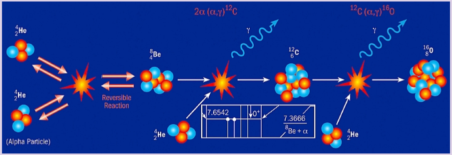
- The $A=5$ and $A=8$ *Bottle-Neck*
  $p + \alpha \rightarrow {}^{5}\mathrm{Li} \rightarrow p + \alpha \quad (t_{1/2} \approx 10^{-22}\,\mathrm{s})$
  $\alpha + \alpha \rightarrow {}^{8}\mathrm{Be} \rightarrow \alpha + \alpha \quad (t_{1/2} \approx 10^{-16}\,\mathrm{s})$
  BBN does not generate any heavy elements!
- He-ashes fuse in the hot $(T \approx 10^{8}\,\mathrm{K})$ and dense $(n \approx 10^{28}\,\mathrm{cm}^{-3})$ core
  Physics demands a tiny concentration of ${}^{8}\mathrm{Be} \quad (n_8/n_4 \approx 10^{-8})$
  Carbon is formed: $\alpha + \alpha \rightarrow {}^{8}\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C} + \gamma \quad (7.367\,\mathrm{MeV})$
  Every atom in our body has been formed in stellar cores!

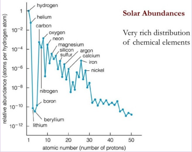




The Hoyle State and the Synthesis of Life

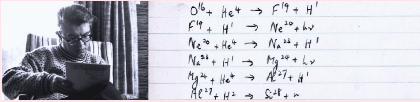
- The formation of ^{12}C via the 3-α reaction is truly remarkable!
  In spite of this "fine tuning", ^{12}C is fairly abundant in the Universe
  To reproduce known abundances, Fred Hoyle predicted in a "resonant" state in ^{12}C
  Willy Fowler (Nobel Prize in Physics in 1983) found the "Hoyle" state (7.65 MeV)
- The Hoyle state is critical for the formation of C,O, and most elements essential to life!





- The quest to unravel the nature of the Hoyle state continues to this day
  The Hoyle State: A Primordial Nucleus behind the Elements of Life (Sci. Am. 2012)

- Burbidge, Burbidge, Fowler, and Hoyle (B^2FH)
  Landmark paper on stellar physics (1957):
  "Synthesis of the Elements in Stars"
- Fred Hoyle never awarded the Nobel Prize!



Fred Hoyle and the Anthropic Principle

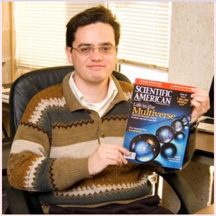
Was the Universe made for us? Are we unique?

- Nicolaus Copernicus (1473-1543)
  Formulated the heliocentric model of the solar system
- Galileo Galilei (1564-1642)
  Father of observational astronomy
  Discovered the four largest (Galilean) moons of Jupiter
  Became a strong advocate of Copernicus' heliocentric model
  Tried by the Holy office for heresy and sentenced to house arrest

The Anthropic Principle:

"Our existence requires the nature's physical constants to be such that beings like us can exist"

- Fred Hoyle (1915-2001)
  Did Hoyle invoked the anthropic principle in predicting the Hoyle state?

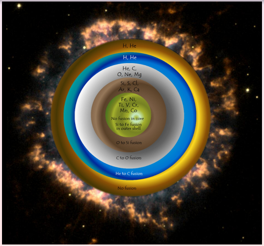


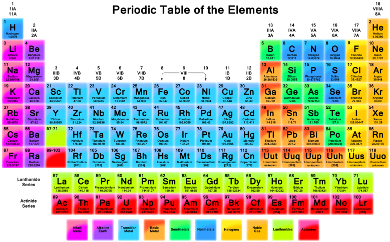
- The Super-Copernican Revolution:
  Our Universe is not unique!
  Statistical distribution of physical constants
  Ours is such that it can support intelligent life
- "Looking for Life in the Multiverse" (Sci. Am. 2010)
  Alejandro Jenkins (formerly@FSU) and Gilad Perez

Stellar Nucleosynthesis: From Carbon to Iron

- Stars are incredibly efficient thermonuclear furnaces
  Heavier He-ashes fuse to produce: *C*,*N*,*O*,*F*,*Ne*,*Na*,*Mg*,...
- Once He is exhausted the core contracts and heats to even higher T
  Carbon starts to burn to produce: *Si*,*P*,*S*,*Cl*,*Ar*,*K*,*Ca* ...
- Once C is exhausted the core contracts and heats to even higher T
  Silicon stars to burn (3 billion K) to produce: *V*,*Cr*,*Mn*,*Fe*,*Co*,*Ni* ...
  Every C in our cells, O in the air, and Fe in our blood was made in stars!
  "We are made of star stuff" ... *Carl Sagan*
- Once Si is exhausted the core contracts and heats but ...
  Iron can not burn and generate energy to stop the contraction
  Thermonuclear fusion terminates abruptly with the collapse of the core

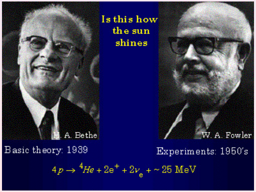
▸ Movie on Stellar Nucleosynthesis

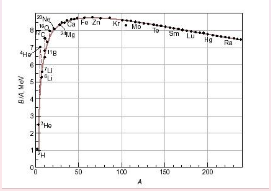


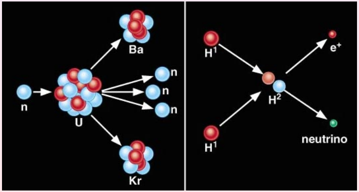


Nuclear Physics 101: Bethe-Weizsäcker Mass Formula (1935-36)

- Same Hans Bethe who was awarded the 1967 Nobel Prize
  "... his discoveries concerning the energy production in stars"
- Nuclear forces hold protons and neutrons together
  $$B(Z,N) = -a_{\rm v}A + a_{\rm s}A^{2/3} + a_{\rm c}Z^2/A^{1/3} + a_{\rm a}(N-Z)^2/A + \ldots$$
- Predictions in remarkable agreement with experiment
- Iron-Nickel region provide the most stable nuclei in nature
- Fusion of light nuclei yields enormous energy release (Stars)
- Fission of heavy nuclei yields enormous energy release (Bombs)
- Fusion and Fission both evolve in the direction of Iron peak



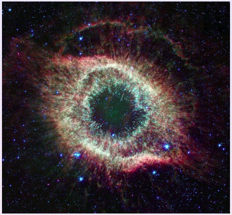


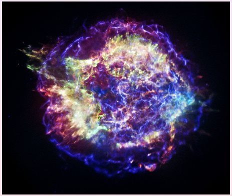


"The buck stops at Iron"

Eleven Science Questions for the New Century (2002)

3. How were the heavy elements from iron to uranium made?





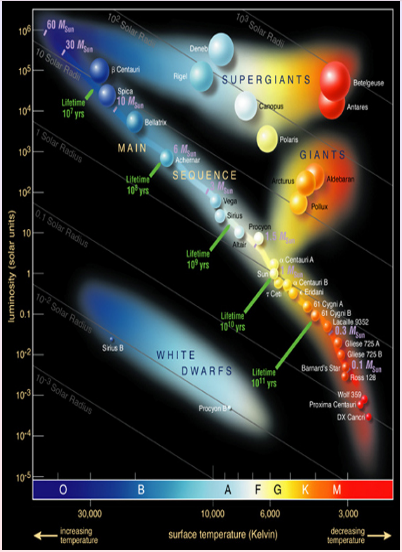
- The slow neutron capture process: "s-process"
  Add neutrons to Fe-peak elements "slowly"
  Unstable nuclei decay before capturing more neutrons
  Produces nuclei close to the "valley of stability
  Example of s-process elements: Sr, Zr, Nb, Ba, La, ...
  Astrophysical site: Asymptotic Giant Branch (AGB) stars

- The rapid neutron capture process: "r-process"
  Add neutrons to Fe-peak elements "rapidly"
  Unstable nuclei capture more neutrons before decaying
  Produces nuclei far from to the "valley of stability
  Example of r-process elements: Os, Pt, Au, Th, U, ...
  Astrophysical site: Unknown (SN, NS-mergers,?)

Astrophysical site for r-process elements from Fe to U remains a mystery!

How long do stars live?

The mass of a star determines its life and ultimate fate



Hertzsprung-Russell diagram

- Solar Properties:

$$M_\odot = 1.988 \times 10^{30}\ \mathrm{kg}$$
$$R_\odot = 6.995 \times 10^{8}\ \mathrm{m}$$
$$T_\odot = 5\,778\ \mathrm{K}$$
$$L_\odot = 3.846 \times 10^{26}\ \mathrm{W}$$
$$t_\odot = 10\ \text{billion years}$$

- Luminosity: $L = 4\pi\sigma R^2 T^4$
  Need to measure distance to determine L
  Spectral class ("color") determines T

- Empirical Relation: $\left(\frac{L}{L_\odot}\right) \approx \left(\frac{M}{M_\odot}\right)^{3.5}$

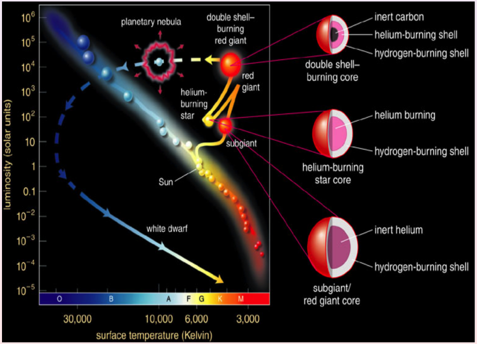
  M from orbital motion of binary companion

- Lifetime$=\frac{\text{Nuclear Fuel}}{\text{Luminosity}}$: $\left(\frac{t}{t_\odot}\right) \approx \left(\frac{M_\odot}{M}\right)^{2.5}$

  $t(10\,M_\odot) \approx 32$ million years
  $t(0.1\,M_\odot) \approx 3200$ billion years
  Universe is "only" 13.7 billion years old!

How will our Sun die?

- Most of its life, the Sun will burn H into He in its core (Main Sequence Star)
- Once H is exhausted, core contracts and heats (Gravitational → Thermal)
  Core must heat up to 100 MK to burn He; H shell to only 10 MK
  As H burns, envelope expands, cools, and leaves the main sequence ...
- Eventually core temperature reaches 100 MK and He burns for 100 million years
  Core must heat to 600 MK to burn C; He shell to only 100 MK
  As H and He burn, envelope expands, cools; Sun becomes a red giant

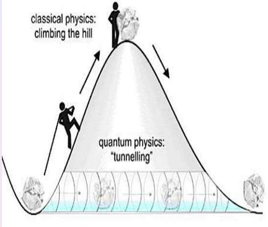


- Core contracts but C does not ignite
  Core becomes "*degenerate*"
  Core T does nor reach 600 MK
- H and He burning in outer shells
  Expanding shell decouples from core
  Beautiful "*planetary nebula*"
  Sun dies as a "*white dwarf star*"

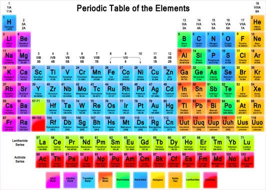
▸ Life Cycle of Stars Video

Quantum Mechanics and Stellar Astrophysics

- Classically – without QM – stars would not shine!
- Classically – without QM – our Sun would die as a black hole!



- Without QM, stars would not shine
  - pp chain: $p + p \rightarrow d + e^{+} + \nu_e$
  - Coulomb barrier 1000 higher than proton kinetic energy
  - Classically, impossible to climb the Coulomb barrier
  - **Quantum tunneling**, while unlikely, is possible!
  - **Stars shine by protons tunneling through the barrier!**



- Without QM, our Sun would die as a black hole
  - In life, our Sun is supported by thermonuclear pressure
  - No thermonuclear fusion supports C-O (white-dwarf) core
  - White-dwarf star supported by e-"degeneracy pressure"
  - Resistance to compression: e do not like to be crowded!
  - Electrons satisfy the **Pauli exclusion principle**
  - **Pauli exclusion principle behind most of Chemistry!**