The Birth, Life, and Death of Stars

The Osher Lifelong Learning Institute
Florida State University

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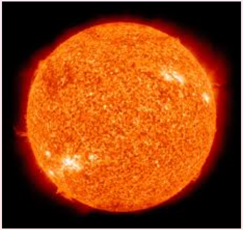
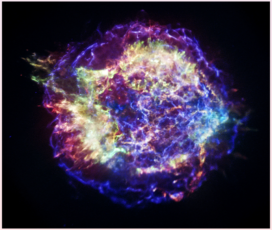
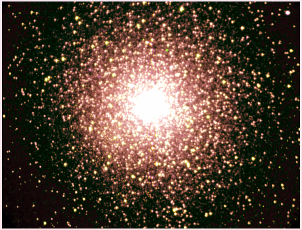
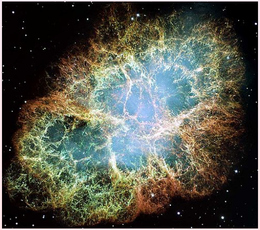
Schedule:	September 29 – November 3
Time:	11:30am – 1:30pm
Location:	Pepper Center, Broad Auditorium





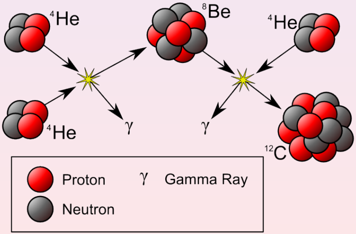
Ten Compelling Questions

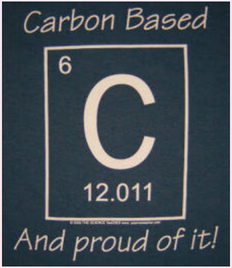
- What is the raw material for making stars and where did it come from?
- What forces of nature contribute to energy generation in stars?
- How and where did the chemical elements form? ⋆
- How long do stars live?
- How will our Sun die?
- How do massive stars explode? ⋆
- What are the remnants of such 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?

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 ${}^{8}\mathrm{Be}\ \ (n_8/n_4\approx 10^{-8})$
  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!

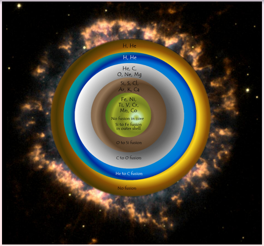


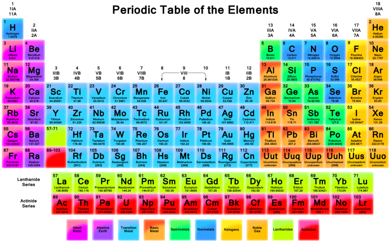


Stellar Nucleosynthesis: From Carbon to Iron

- 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

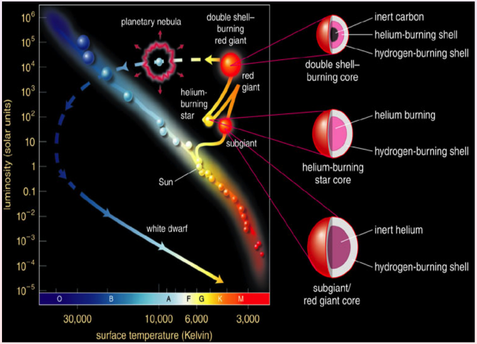
▸ Movie on Stellar Nucleosynthesis





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



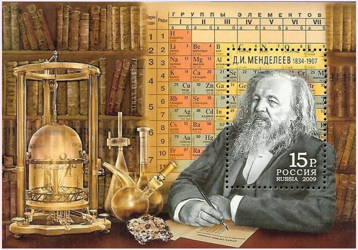
- Core contracts but C does not ignite
  Core becomes "*degenerate*"
  Core T does nor reach 600 MK
- H and He burning in outer shells
  Expanding shell decouples from core
  Beautiful "*planetary nebula*"
  Sun dies as a "*white dwarf star*"

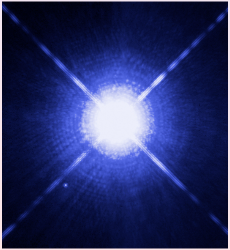
▸ Life Cycle of Stars Video

White Dwarf Stars: The Ultimate Fate of our Sun

- Most of Chemistry is based on one simple fact: the existence of electron shells
  Mendeleev provided a powerful organizational scheme: Periodic Table of the Elements
- The underlying physical concept behind electron shells: The Pauli Exclusion Principle
  No two electrons in an atom can have the same quantum numbers
  First one to predict the existence on the neutrino based on the decay of the neutron
  Famous for coining the phrase: “Das ist nicht nur nicht richtig, es ist nicht einmal falsch”
- The same Pauli principle makes electrons highly resistance to compression
  Electron degeneracy pressure prevents the Sun from dying as a black hole
  Electron degeneracy pressure will support the Sun in death as a white dwarf star
  Tiny electrons and quantum mechanics support a massive star in death

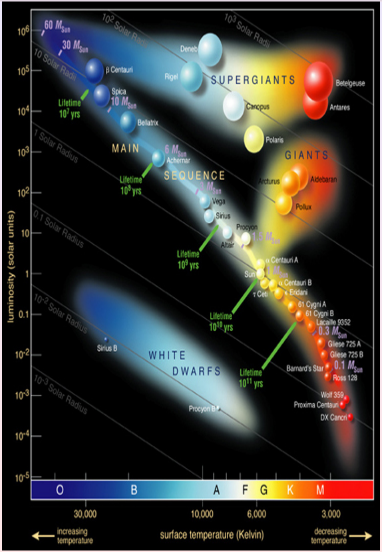
▸ The Ultimate Fate of our Sun and the Solar System





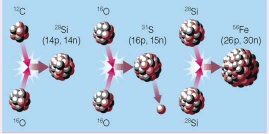
How do massive stars die?

- Early life much the same as our Sun: $4p \to {}^{4}\mathrm{He}$
  Much faster burning since large M implies large T

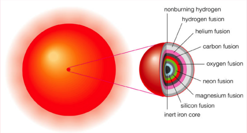


- A Massive Star: Spica (α-Virgo)
  $M_\star = 10.25 M_\odot$ $\quad$ $R_\star = 7.4 R_\odot$
  $T_\star = 22\,400\,\mathrm{K}$ $\quad$ $L_\star = 12,100 L_\odot$
  $t_\star \approx 30$ million years

- Advanced nuclear fusion needs immense T
  Need to fuse nuclei with increasing Z

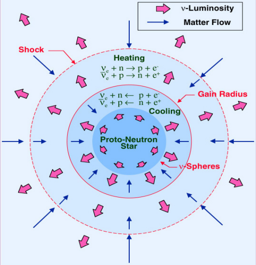


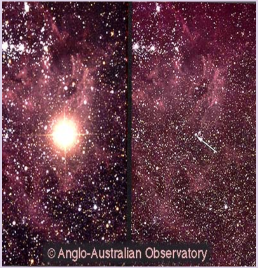
- Onion-like structure of advanced burning



- **Advance burning stops with inert Fe-core!**

Death of a Massive Star: Core-Collapse Supernova





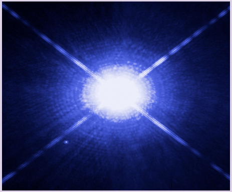
- Core-Collapse Supernovae
  Once ^{56}Fe is produced, the stellar core collapses
  Fe-core reaches enormous densities $10^{14}\mathrm{g/cm^3}$
  Stellar core overshoots and rebounds: SN shock
  Shock wave dissociates Fe and ... $p + e^- \rightarrow n + \nu_e$
  99% of the gravitational energy radiated in neutrinos
  Incredible dense object left behind: neutron star or black hole

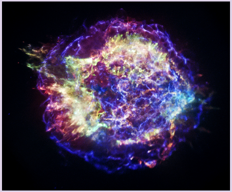
- Supernovae mechanism
  Extraordinarily energetic event $10^{44}\mathrm{J}$
  Equals Sun's lifetime energy output!
  May outshine the whole host galaxy (SN1987a)
  Can the ν_{s} stop the infalling material and revive the shock?
  Precise core-collapse mechanism is yet to be understood
  Core-collapse SN unlikely to produce r-process elements

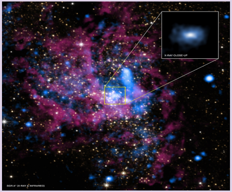
▸ Core Collapse Suprernova: The Challenges

"Numerical simulations suggest that neutrino-powered explosions might not explain the most energetic supernovae" (H.T. Janka; 2012)

The Stellar Graveyard



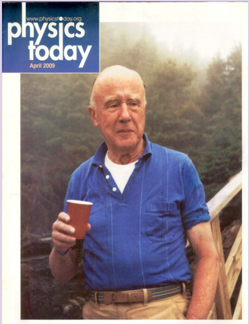




- White Dwarf Stars
  $M_{\rm WD} \lesssim 1.4\,{\rm M}_{\odot}$ – $R_{\rm WD} \approx 10,000\,{\rm km}$
  Composition: Carbon and Oxygen
  Pressure Support: e- degeneracy pressure
  Escape Velocity: $v \approx c/100$
- Neutron Stars
  $M_{\rm NS} \lesssim 3\,{\rm M}_{\odot}$ – $R_{\rm NS} \approx 10\,{\rm km}$
  Composition: Mostly neutrons
  Pressure Support: n degeneracy pressure
  Escape Velocity: $v \approx c/2$
- Black Holes
  $M_{\rm BH} \gtrsim 3\,{\rm M}_{\odot}$ – $R_{\rm BH} \approx 0(?)$
  Composition: ??
  Pressure Support: ??
  Escape Velocity: $v \approx c$

Black Holes ... "an object from which not even light can escape"

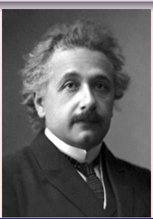
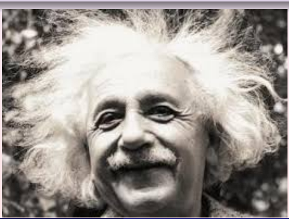
- Gravity is a geometric property of spacetime
  Photons, although massless, feel the effect of gravity
- Event horizon of a black hole
  Unrelated to the physical dimensions of the BH
  A "boundary" from which not even light can escape
- Schwarzschild radius of a non-rotating black hole
  $r_s(M) = 2GM/c^2 \rightarrow r_s(M_\odot) \approx 3$ km

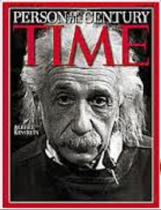


- John Archibald Wheeler (1911-2008; born in Jacksonville, FL)
  Responsible for reviving interest in GR after WWII
  Responsible for coining the term "black hole"
- J.A. Wheeler's "*No Hair Theorem*"
  BH are completely characterized by 3 observable properties
  - Mass: by its influence on "satellites" orbiting the BH
  - Charge: by its influence on far-away charges
  - Angular Momentum: through complicated GR effects
- J.A. Wheeler ... some quotes
  – *Time is what prevents everything from happening at once*
  – *In any field, find the strangest thing and then explore it*
  – *If you haven't found something strange during the day, it hasn't been much of a day ...*

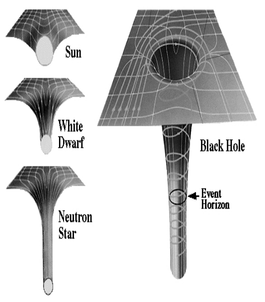
Albert Einstein: The Paradigm of a Scientist

- Born in Ulm, Germany in 1879 and died in Princeton in 1955
- Questions the basic tenets of Quantum Mechanics:
  God does not play dice with the Universe ...
- Yet, is awarded the 1921 Nobel Prize in Physics:
  ... for his discovery of the law of the photoelectric effect
- 1905 Einstein's Miracle Year while working as a patent clerk in Bern
  Culmination of the "Special Theory of Relativity" ($E = mc^2$)
  Revises fundamental Newtonian concepts of space and time
- 1915: Einstein's General Theory of Relativity
  Revises Newton's Law of Universal Gravitation
  Principle of equivalence between inertial and gravitational mass (Galileo)
  Gravity is a property of space-time; even massless objects feel its effects
  Confirmation of the theory by Arthur Eddington in 1919 during a Solar eclipse
- Offered the Presidency of Israel in 1952 ... did not accept ...
- Einstein named Time magazine "Person of the Century"



Black Holes and some of its strange properties



- How do they form?
  Neutron star limit of: $\lesssim 3M_{\odot}$
- Black Hole formation: Gravity's ultimate victory
  No known force can prevent the collapse (singularity?)
- Gravitational redshift: "near a BH time stands still"

$$(\Delta t)_{\text{receiver}} = \frac{(\Delta t)_{\text{emitter}}}{\sqrt{1 - r_s/r}}$$

  photon has to climb out of a very deep gravitational well!
- What would happen to Earth's orbit if Sun becomes a BH?
  Nothing; GR effects only noticeable near the event horizon!

- Cygnus X-1: The first Black Hole candidate
  Discovered in 1964 as a very strong X-ray source
  X-ray emission from massive supergiant blue companion
  $M_{BH} \approx 15\, M_{\odot} \;\rightarrow\; r_s = 45\, km$
  Subject of a famous bet between Hawking and Thorne!
- Evidence of a super-massive BH near center of Milky Way
  Sagittarius A*: $M_{BH} \approx 4\,\text{million}\, M_{\odot}$
- ▸ A Journey into a Black Hole ▸ The Hunt for a Supermassive Black Hole