Conceptual Physics

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Lesson IX
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Table of Contents

- Stars appear unchanging
- Night after night heavens reveal no significant variations
- On human time scales ☞ majority of stars change very little
- We cannot follow any but tiniest part of star life cycle

Star formation

- Stars are born when gaseous clouds (mostly hydrogen) contract due to pull of gravity
- Huge gas cloud fragments into numerous contracting masses
- Each mass is centered in area where density is only slightly greater than @ nearby points
- Once such "globules" formed gravity would cause each to contract in towards its center
- As particles of such protostar accelerate inward their kinetic energy increases
- When kinetic energy is sufficiently high
  Coulomb repulsion ☞ not strong enough to keep ^{1}H nuclei appart and nuclear fussion can take place
- In star like our Sun
  "burning" of ^{1}H occurs when $4p$ fuse to form ^{2}He nucleus with release of: γ, e^{+}, ν_e

M16 a.k.a. Eagle Nebula located $\approx 7,000$ ly away

HST's pillars of creation

Sun's energy output

- pp cycle due to following sequence of fusion reactions:

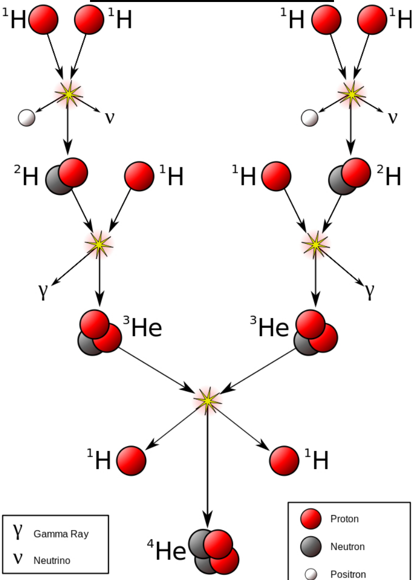
$$ {}^1_1\mathrm{H} + {}^1_1\mathrm{H} \to {}^2_1\mathrm{H} + 2\,e^+ + 2\,\nu_e $$

$$ {}^1_1\mathrm{H} + {}^2_1\mathrm{H} \to {}^3_2\mathrm{He} + \gamma $$

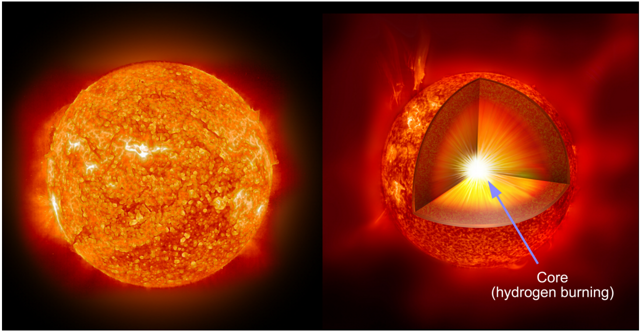
$$ {}^3_2\mathrm{He} + {}^3_2\mathrm{He} \to {}^4_2\mathrm{He} + {}^1_1\mathrm{H} + {}^1_1\mathrm{H} $$

- Released energy ➢ mass difference between initial & final states
  ➢ carried off by outgoing particles
- Net effect $4\,{}^1_1\mathrm{H} \to {}^4_2\mathrm{He} + 2e^+ + 2\nu_e + 2\gamma$
- Takes 2 of each of first 2 reactions to produce two ${}^3_2$He
- Deuterium formation has very low probability
  infrequency of reaction limits rate at which Sun produces energy

Nuclear Burning



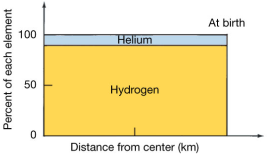
- Star turns on and becomes a *main sequence star* powered by hydrogen fusion
- Fusion produces outward pressure that balances inward pressure caused by gravity ☞ stabilizing star
- Fusion reactions take place in star core ☞ $T \sim 10^7$ K
- Surface temperature is much lower ☞ about few thousand K

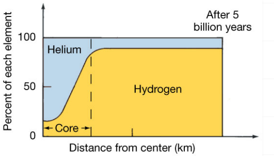


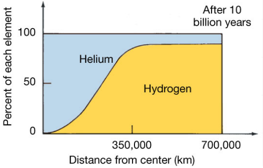
- As hydrogen fuses to form helium @ star's core
  helium formed is denser and tends to accumulate in central core
- As core of helium grows
  hydrogen continues to fuse in a shell around it
- When much of hydrogen within core has been consumed
  production of energy decreases at center and ...
  cannot prevent gravitational force to contract and heat up core
- Hydrogen in shell around core fuses more fiercely
  as T rises causing outer envelope to expand and cool
- Surface T reduces ☞ spectrum peaks at longer wavelength
  (reddish)
- By this time the star has left the main sequence:
  - It has become redder
  - It has grown in size
  - It has become more luminous
  - It enters red giant stage
- Model explains origin of red giants as step in stellar evolution

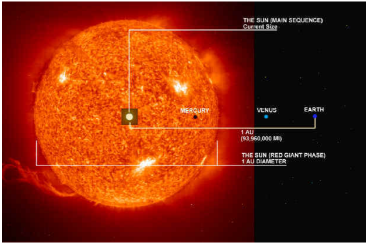
Example

- Sun has been on main sequence for $\sim$ four and a half billion years
- It will probably remain there another 4 or 5 billion years
- As becomes red giant expected to grow out to Mercury's orbit

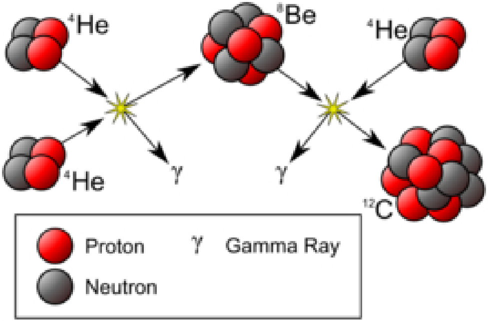








- If star is like our Sun or larger ☞ further fusion can occur
- As star's outer envelope expands ☞ core shrinks and heats up
- When the temperature reaches about 10^8 K
  helium nuclei reach each other and undergo fusion
- Reactions are



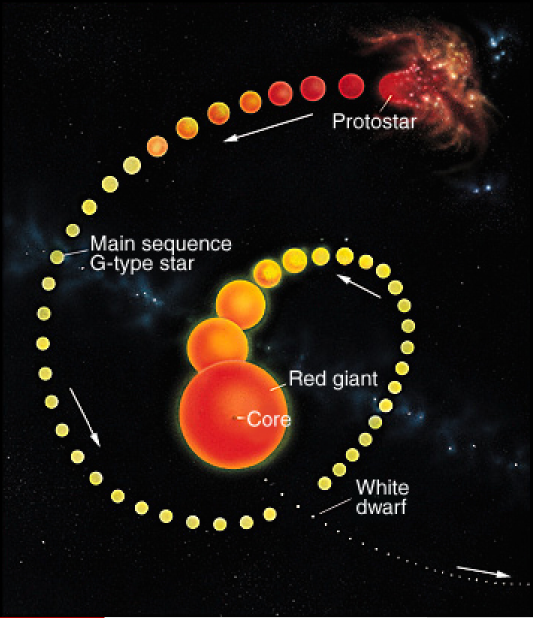
- Two reactions must occur in quick succession
  because ${}^8_4$Be is very unstable

Sirius

- Sirius @ 2.6 pc ☞ fifth closest stellar system to Sun
- Analyzing motions of Sirius Bessel concluded
  it had an unseen companion with an orbital period $T \sim 50~\mathrm{yr}$
- In 1862 ☞ Clark discovered this companion ☞ Sirius B
- Following-up observations showed that for Sirius B $M \approx M_\odot$
- Sirius B's peculiar properties were not established until 1915
- Adams noted high temperature of Sirius B ☞ $T \simeq 25,000~\mathrm{K}$
  which together with its small luminosity ☞ $L = 3.84 \times 10^{26}~\mathrm{W}$
  requires extremely small radius and thus large density of this star

- Stars like Sirius B are called white dwarfs
- They have very long cooling times
  because of their small surface luminosity
- White dwarfs are numerous ☞ mass density in solar neighborhood
  - main-sequence stars ☞ $0.04 M_\odot/\mathrm{pc}^3$
  - white dwarfs ☞ $0.015 M_\odot/\mathrm{pc}^3$
  - parsec ☞ 1 pc = 3×10^{16} m
- Typical mass in range $0.4 - 1 M_\odot$ ☞ peaking @ $0.6 M_\odot$
- For white dwarfs ☞ no further fusion energy can be obtained
- White dwarf continues to lose internal energy by radiation decreasing in T and becoming dimmer until its light goes out
- Star has then become cold dark chunk of ash

Life cycle of the Sun



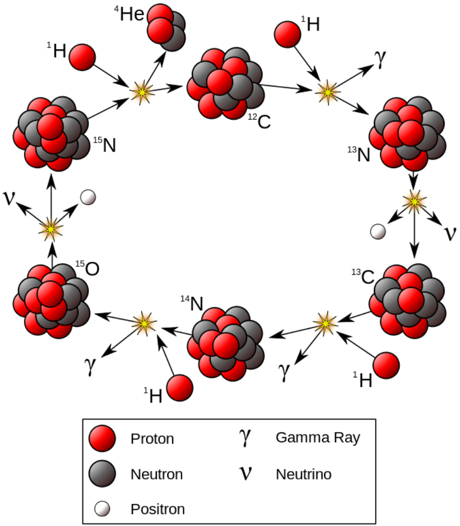
In more massive stars...

- Energy output comes from the carbon (or CNO) cycle
- CNO cycle comprises following sequence of reactions:

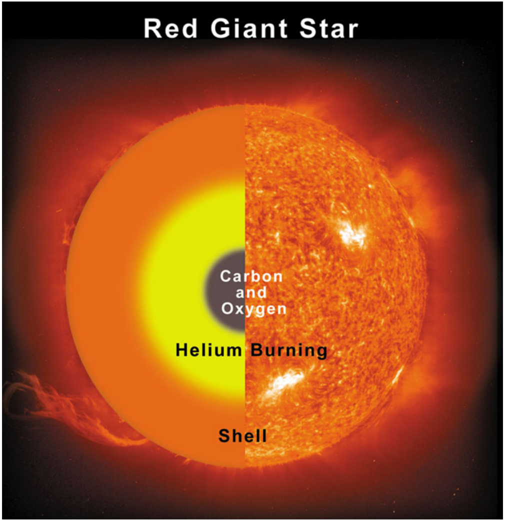
$$
\begin{aligned}
{}^{12}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} &\to {}^{13}_{7}\mathrm{N} + \gamma \\
{}^{13}_{7}\mathrm{N} &\to {}^{13}_{6}\mathrm{C} + e^{+} + \nu \\
{}^{13}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} &\to {}^{14}_{7}\mathrm{N} + \gamma \\
{}^{14}_{7}\mathrm{N} + {}^{1}_{1}\mathrm{H} &\to {}^{15}_{8}\mathrm{O} + \gamma \\
{}^{15}_{8}\mathrm{O} &\to {}^{15}_{7}\mathrm{N} + e^{+} + \nu \\
{}^{15}_{7}\mathrm{N} + {}^{1}_{1}\mathrm{H} &\to {}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He}
\end{aligned}
$$

- No carbon is consumed in this cycle (see first and last equations)
- Net effect is the same as the pp cycle
- Theory of the pp and CNO cyles first worked out by Bethe in 1939

Nuclear Burning



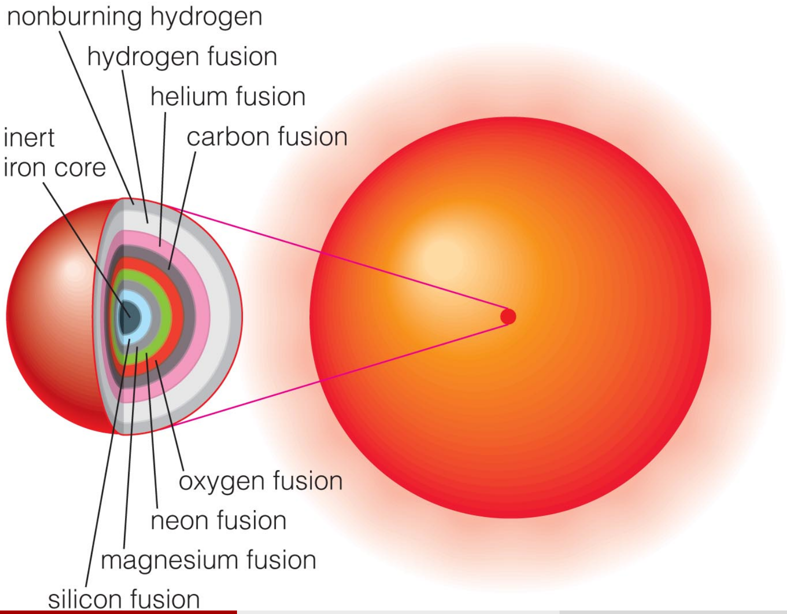
- Further fusion reactions are possible ☞ ${}^{4}_{2}$He fusing with ${}^{12}_{6}$C to form ${}^{16}_{8}$O.
- In very massive stars ☞ higher Z elements (e.g. ${}^{20}_{10}$Ne or ${}^{24}_{12}$Mg) can be made



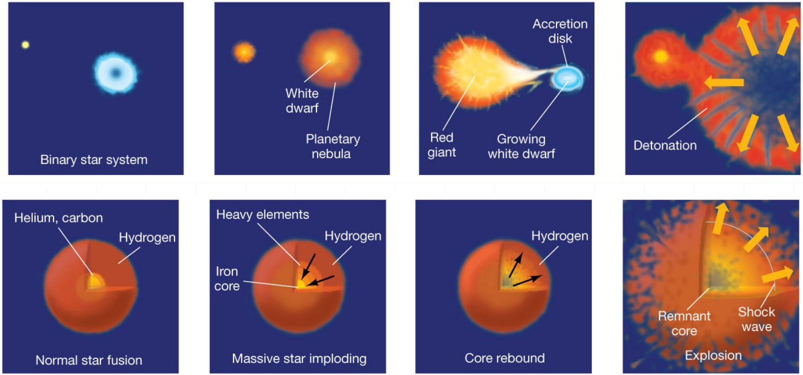
Red supegiants

- As massive red supergiants age
  stars produce "onion layers" of heavier elements in their interiors
- @ $T = 5 \times 10^9$ K nuclei as heavy as $^{56}_{26}$Fe and $^{56}_{28}$Ni can be made
- Average binding energy per nucleon
  begins to decrease beyond iron group of isotopes
- Formation of heavy nuclei by fusion ends at iron group
- As a consequence
  core of iron builds up in centers of massive supergiants
- Process of creating heavier nuclei from lighter ones
  or by absorption of neutrons at higher Z
  is called nucleosynthesis

Red Supergiant



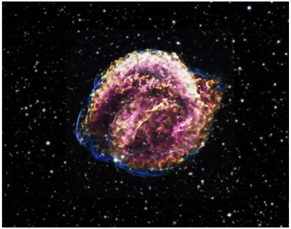
- Supernovae are massive explosions
  that take place at end of star's life cycle
- They can be triggered by one of two basic mechanisms:
  - I by sudden re-ignition of nuclear fusion in degenerate star
  - II by the sudden gravitational collapse of massive star's core



Supernova explosion

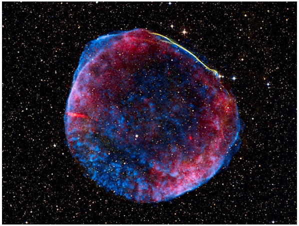
Pulsars

SN1604 (Kepler)



SNR-0509-67.5 (LMC)

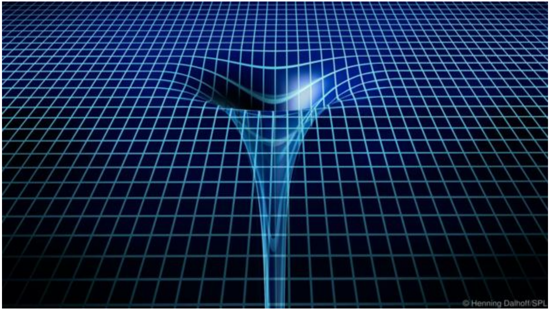
SN1006

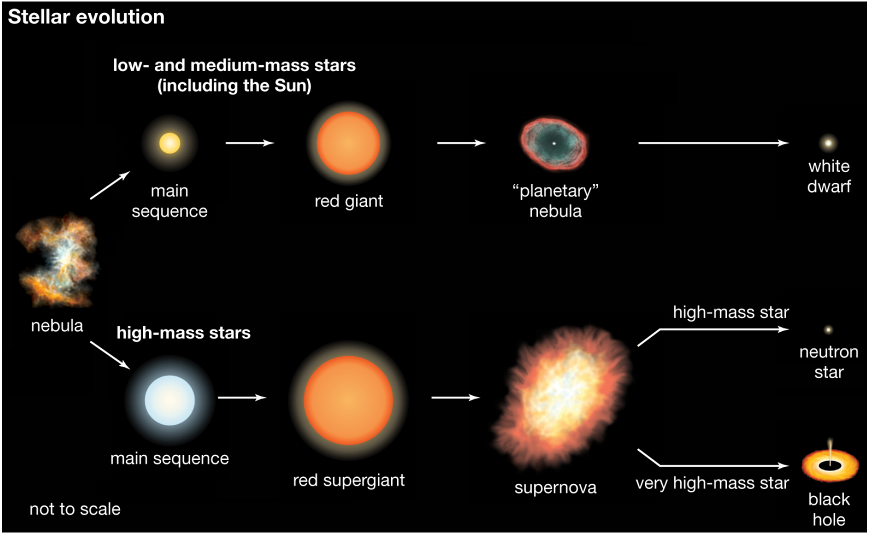


- Core of collapsed star contracts until all nuclei are touching
- Forces are so great that all the nuclei disintegrate into their constituents (neutrons and protons)
- Protons combine with electrons to leave dense core of neutrons (star is about as large as Boston)
- Newly born neutron star (or pulsar) ☞ rotates madly about its axis emitting energy at a billion times rate of Sun

Black Holes

- If neutron star mass $> 3M_\odot$ ☞ star further contracts under gravity
- As density increases
  paths of light rays emitted from star are bent
  and eventually wrapped irrevocably around star
- This is called a black hole ☞ because no light escapes “the star”



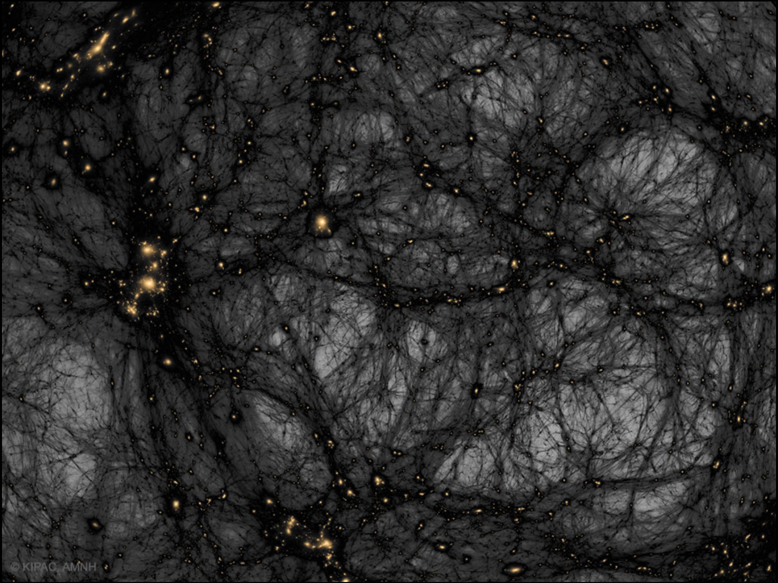


✧ Star form when gaseous (mostly ^{1}H) clouds contract due to pull of gravity

✧ Energy releasy in ^{1}H fusion reactions

produces outward pressure to halt inward gravitational contraction

Happy Halloween



Is our universe haunted? It might look that way on this dark matter map. The gravity of unseen dark matter is the leading explanation for why galaxies rotate so fast, why galaxies orbit clusters so fast, why gravitational lenses so strongly deflect light, and why visible matter is distributed as it is both in the local universe and on the cosmic microwave background. The featured image from the American Museum of Natural History's Hayden Planetarium Space Show Dark Universe highlights one example of how pervasive dark matter might haunt our universe. In this frame from a detailed computer simulation, complex filaments of dark matter, shown in black, are strewn about the universe like spider webs, while the relatively rare clumps of familiar baryonic matter are colored orange. These simulations are good statistical matches to astronomical observations. In what is perhaps a scarier turn of events, dark matter – although quite strange and in an unknown form – is no longer thought to be the strangest source of gravity in the universe. That honor now falls to dark energy, a more uniform source of repulsive gravity that seems to now dominate the expansion of the entire universe.

Illustration by Tom Abel and Ralf Kaehler