Where Does the Sun Get Its Energy?

- Life time is related to source of energy
  - life time = (energy available) / (luminosity)
- Gravitational Contraction?
  - Contraction due to gravity releases energy
  - Total energy due to contraction $10^{48}$ ergs from Newton’s Laws
  - life time = $(10^{48}$ ergs)/(4x$10^{33}$ erg/sec) = 10$^7$ years
- Radioactive decay, similar to heating of Earth?
  - Mostly H and He which do not decay, need heavy nuclei
  - Even if solid uranium it would produce 1/2 of energy seen

Where Does the Energy Come From?

- **Mass is converted directly into energy**
  - Einstein’s Famous relationship
  - Mass and energy are the same thing!
  - The speed of light is very big so you get a lot of energy from a little bit of matter
- 4 H → 1 He
  - Mass of H = 1.67252x10$^{-24}$ gm
  - Mass of He = 6.64258x10$^{-24}$ gm
  - 4xH - He = 0.04750x10$^{-24}$ gm
  - E = mc$^2$ = 4.75x10$^{-26}$ gm
  - $E = (3x10^{10} \text{cm/sec})^2 = 4.5x10^{-5}$ ergs

Nuclear Fusion

- Several light nuclei (H) collide and combine to form a heavier nucleus (He)
- Energy is released
- Need **high temperature and densities**
  - Must overcome electrostatic repulsion of like charged atomic nuclei
  - Core of Sun is 15,000,000 K
  - Density is 150,000 kg/m$^3$

Mass Number

- $m_p = 1.672623 \times 10^{-24}$ g
- $m_n = 1.674929 \times 10^{-24}$ g
- $m_e = 9.109390 \times 10^{-28}$ g

$$m_p \sim m_n \sim m_e \gg m_a$$

A = mass number

Nuclear Physics

- Elements specified by
  - Atomic number: Z = # of protons
  - Protons have positive charge = +e
  - Neutral atoms: #protons = #electrons
- Isotope specified by # of neutrons, N
  - Neutrons electrically neutral
  - All isotopes of a given element have same Z
- Mass number: A=Z+N
  - A gives the number of nucleons
  - Good indicator of mass

Structure of Matter

- Baryons: heavy particles
  - Neutrons, Protons
    - Finite size
    - Made of quarks
- Leptons: light particles
  - Electrons, Neutrinos
    - Low rest mass
    - Unresolved in size
    - Not made up of quarks

- Quarks & Leptons fundamental particles
Fundamental Forces

- Forces are exchanged by virtual particles → bosons
  - Gravity - long range - gravitons
  - Electromagnetic - long range - photons
  - Strong - short range - mesons
  - Weak - short range - weakons

Strong Force

- Binds together n & p
- Short range ~10^{-13} cm
- Mediated by mesons
  - Quark - anti-quark pair
  - II meson - up/down quark, anti-quark pair

Weak Force

- Protons & Neutrons interact via force
  - Important for nuclear reactions in stars
- Mediated by weakons or intermediate vector bosons
- Range ~ 10^{-15} cm
- Converts proton into neutron & vice versa
  \[ ^1_0n \rightarrow ^1_1p + 0^{-1}e + 0^0\nu \]
- Beta Decay
  - Conserves charge, baryons, leptons

Energy From Fusion

- Converting Mass directly into energy is the most efficient way to get energy from matter
- If 10% of solar Hydrogen is converted into He the Sun will shine at its current rate for 10 Billion Years

Binding Energy

- Amount of Energy needed to break nucleus apart into constituent p & n

Coulomb Barrier

- Coulomb-interaction (1/4)
- Strong nuclear potential
Proton-Proton Chain

CNO CYCLE

1. $^3\text{He} + ^1\text{H} \rightarrow ^4\text{He} + \gamma$
2. $^4\text{He} \rightarrow ^1\text{H} + ^3\text{H} + \gamma$
3. $^3\text{He} + ^1\text{H} \rightarrow ^4\text{He} + \gamma$
4. $^4\text{He} + ^1\text{H} \rightarrow ^5\text{Li} + \gamma$
5. $^5\text{Li} + ^1\text{H} \rightarrow ^6\text{Li} + \gamma$
6. $^6\text{Li} + ^1\text{H} \rightarrow ^7\text{Be} + \gamma$

Plus ENERGY

Triple Alpha Reactions

Helium burning begins when Temp > $10^8$ K

$^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be} + \gamma$
$^4\text{He} + ^8\text{Be} \rightarrow ^{12}\text{C} + \gamma$

$^8\text{Be}$ is unstable and decays into 2 He nuclei (alpha particles in $2.6 \times 10^{-16}$ sec)

To produce C requires the almost simultaneous collision of 3 alpha particles

Need high cross section

Fusion of Heavier Elements

- To fuse heavier elements you need hotter temperatures to overcome Coulomb barriers
  $T \sim 4 Z_1^2 Z_2^2 e^4 \mu / 3 k T^2$

- Alpha Reactions
- Carbon, Oxygen, Silicon fusion

Alpha Reactions

- During He burning some of C produced reacts with He to form O which in turn reacts to form Ne, then Mg......
- Reactions rare and not major source of energy generation
- Examples:
  $^{12}\text{C} + ^4\text{He} \rightarrow ^{16}\text{O} + \gamma$
  $^{16}\text{O} + ^4\text{He} \rightarrow ^{20}\text{Ne} + \gamma$
  $^{20}\text{Ne} + ^4\text{He} \rightarrow ^{24}\text{Mg} + \gamma$

Carbon Burning

When He in core is gone
Temperature $\sim 5-8 \times 10^8$ K

$^{12}\text{C} + ^{12}\text{C} \rightarrow ^{16}\text{O} + 2^4\text{He}$
  $\rightarrow ^{20}\text{Ne} + ^4\text{He}$
  $\rightarrow ^{22}\text{Ne} + p$
  $\rightarrow ^{22}\text{Mg} + n$
  $\rightarrow ^{24}\text{Mg} + \gamma$
Oxygen Burning

\[ T \sim 10^9 \text{ K} \]

\[ ^{16}\text{O} + ^{16}\text{O} \rightarrow ^{28}\text{Mg} + 2^4\text{He} \]
\[ ^{28}\text{Si} + ^{6}\text{He} \]
\[ ^{30}\text{P} + ^{3}\text{He} \]
\[ ^{30}\text{S} + n \]
\[ ^{30}\text{S} + \gamma \]

Silicon Burning

\[ ^{28}\text{Si} + ^{28}\text{Si} \rightarrow ^{56}\text{Ni} + \gamma \]
\[ ^{56}\text{Ni} \rightarrow ^{56}\text{Fe} + 2\epsilon^+ + 2\nu_\epsilon \]

At \( T > 10^9 \text{ K} \), photon energies are large enough to destroy certain nuclei.

Photonuclear reactions or photodissociations

Formation of Heavier Elements

Formation of elements heavier than Fe require an input of energy and cannot be produced by thermonuclear reactions.

Produced almost exclusively by neutron capture during final violent stages of stellar evolution (e.g. supernovae).

Solar Neutrinos

- 3 different neutrino experiments are sensitive to neutrinos from different nuclear reactions.
- The measured points do not agree very well with the predicted number of each type of neutrino.
- There is a problem with the Standard Model.

Solar Neutrinos

- Neutrinos:
  - Very low mass particles produced as a side product of nuclear fusion.
  - They hardly interact with matter so they can travel completely out of the Sun undisturbed.
- Detection of Neutrinos:
  - Difficult since they interact so weakly with matter.
  - Takes very large detectors.
  - Several have been built to detect different types of neutrinos from inside the sun.

K. Langanke

Nuclear burning stages

- For all energy sun
- For all energy sun
- For all energy sun
- For all energy sun
- For all energy sun
- For all energy sun
- For all energy sun
- For all energy sun
- For all energy sun
- For all energy sun

Bar graph comparison of neutrino experiments:

- SAGE
- Homestake
- Gallex
- SuperKamiokande
The Main Sequence Revisited

- All Stars are made up of mostly H
- Core burning of H will continue for long time
- Structure will change slowly
  - HYDROSTATIC EQUILIBRIUM

The Main Sequence Revisited

- All stars arrange themselves to balance the force of gravity and their interior pressure
  - As mass increases gravity increases
    - Differential Pressure increases inside stars
    - Energy generation + luminosity increases
    - Temperature + size increase to let increased energy out
- This equilibrium sequence of mass is the Main Sequence

The Main Sequence Revisited

- Mass Limits
  - \( M < 0.08 \, M_{\odot} \)
    - No Fusion
  - \( M > 90 \, M_{\odot} \)
    - Radiation Pressure dominates Gravity

Question

- Remember that the luminosity of a star was found be to closely related to its mass \((L \propto M^4)\). Now we know that stars get their energy by converting their mass directly into energy so the total amount of energy a star has is proportional to its mass \((E \propto M)\). Will a massive star live a longer or shorter time than a low mass star?

The Main Sequence Revisited

- Like the Sun all stars arrange themselves to balance the force of gravity and their interior pressure
  - As mass increases gravity increases
    - Pressure increases inside stars
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Energy Transport

Massive Stars $M > 1.2 M_{\odot}$
- Core:
  - CNO cycle
  - Convective core
  - Steep thermal gradient
  - Energy generation rate changes quickly
  - Radiation no efficient enough to transport out all energy being released
- Outside Core:
  - Radiation carries energy

Energy Transport

Low Mass Stars $M < 1.2 M_{\odot}$
- Core:
  - PP Chain
  - Small thermal gradient
  - Radiative transport efficient
- Near Surface:
  - H- opacity becomes large - Temp low enough for H to be partially ionized
  - Increase in opacity makes convection more efficient
  - Convection zones

Energy Transport

Low Mass Stars
As mass decreases, H-zone moves deeper into star due to lower Temperatures
$M < 0.3 M_{\odot}$ Fully convective