The Age of the Sun and Energy Transport in Stars

Astronomy 101
Why do stars shine?

• Stars shine because they are *hot*.
  – emit thermal (~blackbody) radiation
  – heat “leaks” out of their photospheres.

• Luminosity = rate of energy loss.

• To *stay* hot, stars must make up for the lost energy, otherwise they would go out.
Case Study: The Sun

• **Question:**
  How long can the Sun shine?

• **Answer:**
  Consider the **internal heat content** of the Sun.
  Luminosity = rate of heat loss.

  \[
  \text{Lifetime} = \frac{\text{Internal Heat}}{\text{Luminosity}}
  \]
What if no source of energy?

- The Sun’s Luminosity losses would not be balanced by input of new internal heat.
  - The Sun would steadily cool off & fade out.
- 18th Century:
  - Assumed a solid Sun (iron & rock)
  - Found Lifetime ~ 10 Million Years
- No Problem:
  Earth was thought to be thousands of years old.
The Age Crisis: Part I

• Late 1800s:
  – Geologists: Earth was *millions* of years old.
  • How can Earth be older than the Sun?
    – Astronomers: The Sun is a big ball of gas in *Hydrostatic Equilibrium*.

• Kelvin & Helmholtz proposed *Gravitational Contraction* as a source of energy.
Kelvin-Helmholtz Mechanism

• Luminosity radiates away heat
  – Outer layers of the Sun cool at little, lowering the gas pressure.
  – Lower Pressure means Gravity gets the upper hand and the star contracts a little.
  – Contraction compresses the core, heating it up a little, adding heat to the Sun.

• Sun could shine for ~100 Million years
Gravity & Pressure in Equilibrium
Luminosity radiates away heat & Pressure

Drops
Balance tips in favor of gravity, Sun shrinks.
Contraction makes core heat up, increasing the internal Pressure.
Balance restored, but with higher gravity, pressure & temperature than before...

Starts the cycle all over again...
The Age Crisis: Part II

• **Early 1900s:**
  • Geologists show that the Earth is $>2 \text{ Billion}$ years old.

• **Kelvin Says:**
  *The Geologists are wrong.*

• **Nature Says:**
  *Kelvin is wrong...* There is new physics.
Nuclear Fusion

• **1905:**
  Einstein demonstrates that Mass and Energy are equivalent: $E=mc^2$

• **1920s:**
  Eddington noted that 4 protons have 0.7% more mass than 1 Helium nucleus (2p+2n).
  If 4 protons fuse into 1 Helium nucleus, the remaining 0.7% of mass is converted to **energy**.
Fusion Energy

- Fuse 1 gram of Hydrogen into 0.993 grams of Helium.
- Leftover 0.007 grams converted into Energy:
  - $E = mc^2 = 6.3 \times 10^{18}$ ergs
- Enough energy to lift 64,000 Tons of rock to a height of 1 km.
Hydrogen Fusion

• **Question:**
  How do you fuse $4 \, ^1\text{H} \,(p)$ into $^4\text{He} \,(2p+2n)$?

• **Issues:**
  Four protons colliding at once is unlikely.
  Must turn 2 of the protons into neutrons.
  Must be hot: >10 Million K to get protons close enough to fuse together.
Proton-Proton Chain:

\[ p + p \rightarrow ^2H + e^+ + \nu_e \ (\text{twice}) \]
\[ ^2H + p \rightarrow ^3\text{He} + \gamma \ (\text{twice}) \]
\[ ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + p + p \]

3-step Fusion Chain
positron neutrino

$^2\text{H}$

$^3\text{He}$

$^4\text{He}$

photon
The Bottom Line

• Fuse 4 protons ($^1\text{H}$) into one $^4\text{He}$ nucleus.
• Release energy in the form of:
  – 2 Gamma-ray photons
  – 2 neutrinos that leave the Sun
  – 2 positrons that hit nearby electrons, creating two more Gamma-ray photons
  – Motions (heat) of final $^4\text{He}$ and 2 protons.
The Age Crisis: Averted

- Luminosity of the Sun is \(\sim 4 \times 10^{33}\) erg/sec
  - Must fuse \(\sim 600\) Million Tons of H into He every second.
  - \(\sim 4\) Million tons converted to energy per second.
  - Sun contains \(\sim 10^{21}\) Million Tons of Hydrogen
  - Only \(\sim 10\%\) is hot enough for fusion to occur.

- Fusion Lifetime is \(\sim 10\) Billion Years.
Test: Solar Neutrinos

• **Question:**
  How do we **know** that fusion is occurring in the core of the Sun?

• **Answer:**
  Look for the **neutrinos** created in Step 1 of the Proton-Proton chain.
What are Neutrinos?

- Massless, weakly interacting neutral particles.
- Travel at the speed of light.
- Can pass through a block of lead 1 parsec thick!

- Any neutrinos created by nuclear fusion in the Sun’s core would stream out of the Sun at the speed of light.
Solar Neutrinos: Observed!

• Detection of neutrinos is very hard:
  – Need massive amounts of detector materials
  – Work underground to shield out other radiation

• Answer:
  – We detect neutrinos from the P-P chain in all the experiments performed to date!

• Success! But...
The Solar Neutrino Problem

• We detect only \(\sim 1/3\) of the number expected...

• Why?
  – Is our solar structure model wrong?
  – Is the subatomic particle theory of neutrinos wrong?

• The last seems most plausible
  – recent evidence neutrinos have mass
  – question for the physics of 21st century!
Putting Stars Together

• Physics needed to describe how stars work:
  • Law of Gravity
  • Equation of State ("gas law")
  • Principle of Hydrostatic Equilibrium
  • Source of Energy (e.g., Nuclear Fusion)
  • Movement of Energy through star
Hydrostatic Equilibrium

• Balance between Pressure & Gravity.
  – If Pressure dominates, the star expands.
  – If Gravity dominates, the star contracts.

• Sets up a Core-Envelope Structure:
  – Hot, dense, compact core.
  – Cooler, low-density, extended envelope.
Energy Generation

• *Stars shine because they are hot.*
• To *stay* hot stars must make up for the energy lost by shining.
• Two Energy sources available:
  – Gravitational Contraction (Kelvin-Helmholtz)
    • Only available if star is NOT in equilibrium
  – Nuclear Fusion in the hot core.
Main-Sequence Stars

• Generate energy by fusion of $4\, ^1\text{H}$ into $1\, ^4\text{He}$.

• **Proton-Proton Chain:**
  – Relies on proton-proton reactions
  – Efficient at low core Temperature ($T_C<18\text{M K}$)

• **CNO Cycle:**
  – Carbon acts as a *catalyst*
  – Efficient at high core Temperature ($T_C>18\text{M K}$)
Proton-Proton Chain:

\[
p + p \rightarrow ^2\text{H} + e^+ + \nu_e \text{ (twice)}
\]

\[
^2\text{H} + p \rightarrow ^3\text{He} + \gamma \text{ (twice)}
\]

\[
^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + p + p
\]
CNO Cycle:

\[ ^{12}\text{C} + p \rightarrow ^{13}\text{N} + \gamma \]

\[ ^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu_e \]

\[ ^{13}\text{C} + p \rightarrow ^{14}\text{N} + \gamma \]

\[ ^{14}\text{N} + p \rightarrow ^{15}\text{O} + \gamma \]

\[ ^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ + \nu_e \]

\[ ^{15}\text{N} + p \rightarrow ^{12}\text{C} + ^4\text{He} \]
Controlled Nuclear Fusion

• Fusion reactions are *Temperature sensitive*:
  – Higher Core Temperature = More Fusion
  – $\varepsilon(\text{PP}) \sim T^4$
  – $\varepsilon(\text{CNO}) \sim T^{18}$

• BUT,
  – More fusion makes the core *hotter*,
  – *Hotter* core leads to even more fusion, ...

• Why doesn’t it blow up like an H-Bomb?
Hydrostatic Thermostat

• If fusion reactions run too fast:
  – core *heats up*, leading to *higher pressure*
  – pressure *increase* makes the core *expand*.
  – expansion *cools* core, *slowing* fusion.

• If fusion reactions run too slow:
  – core *cools down*, leading to *lower pressure*
  – pressure *drop* makes the core *contract*.
  – contraction *heats* core, *increasing* fusion.
Thermal Equilibrium

• Heat always flows from hotter regions into cooler regions.

• In a star, heat must flow:
  – from the hot core,
  – out through the cooler envelope,
  – to the surface where it is radiated away as light.
Energy Transport

• There are 3 ways to transport energy:
  • 1) Radiation:
    Energy is carried by photons
  • 2) Convection:
    Energy carried by bulk motions of gas
  • 3) Conduction:
    Energy carried by particle motions
Radiation

• Energy is carried by photons.
  – Photons leave the core
  – Hit an atom or electron within ~1cm and get scattered.
  – Slowly stagger to the surface ("random walk")
  – Break into many low-energy photons.

• Takes ~1 Million years to reach the surface.
Random Walk
Convection

- Energy carried by bulk motions of the gas.
- Analogy is water boiling:
Conduction

• Heat is passed from atom-to-atom in a dense material from hot to cool regions.

• **Analogy:**
  Holding a spoon in a candle flame, the handle eventually gets hot.
Energy Transport in Stars

• **Normal Stars:**
  – A mix of Radiation & Convection transports energy from the core to the surface.
  – Conduction is inefficient (density is too low).

• **White Dwarfs:**
  – Ultra-dense stars
  – Conduction dominates energy transport.
Summary:

• Stars shine because they are hot.
  – need an energy source to stay hot.

• Kelvin-Helmholtz Mechanism
  – Energy from slow Gravitational Contraction
  – Cannot work to power the present-day Sun

• Nuclear Fusion Energy
  – Energy from Fusion of $4^1$H into $1^4$He
  – Dominant process in the present-day Sun
Summary:

• Energy generation in stars:
  – Nuclear Fusion in the core.
  – Controlled by a Hydrostatic “thermostat”.

• Energy is transported to the surface by:
  – Radiation & Convection in normal stars
  – Conduction in white dwarf stars

• With Hydrostatic Equilibrium, these determine the detailed structure of a star.
Questions

• Do other stars also produce energy by nuclear fusion?
• Why doesn’t the Sun explode?
• How long can other stars last?
• Are there other objects that “shine” via gravitational contraction?
Questions

• Which stars generate energy primarily via the CNO cycle and which by the PP cycle?
• Why are MV stars less luminous than GV stars? OV more luminous?
• What will happen when a star runs out of fuel?
• What is going on in Supergiants? Giants?