The Sun: Our Thermonuclear Furnace

Analogies are useful for analysis in unexplored fields. By means of analogies an unfamiliar system may be compared with one that is better known. The relations and actions are more easily visualized, the mathematics more readily applied, and the analytical solutions more readily obtained in the familiar system.

-- Harry F. Olson

- **One of the biggest scientific and technological achievements of the 20th century was the development of nuclear energy. One of the biggest scientific milestones in 20th century astronomy was the discovery that the Sun has been generating its energy for 5 billion years by converting hydrogen to helium in a self-regulating thermonuclear reactor. This is the same process that powers almost all of the stars that glow in the night sky.**

Key Physical Concepts to Understand:

thermonuclear fusion, hydrostatic equilibrium, the Sun as a self-regulating reactor, how energy is transported through the Sun, potential and kinetic energy

Historical Perspective: the solar energy problem

- In order for a star to shine for billions of years, it requires production of enormous amounts of energy.
- In the 19th century, bit was supposed that the Sun's luminosity was produced by chemical burning
- In the early part of the 20th Lord Kelvin of England and Heinrich Helmholtz of Germany proposed that the Sun could be powered by slow gravitational collapse.
- Inadequate to power the Sun over its estimated life of 4.6 billion years.
- In the 1930s it was proposed that the core conditions of the Sun were sufficient for thermonuclear fusion
- Fusion could sustain the Sun's current energy output for at least 10 billion years.

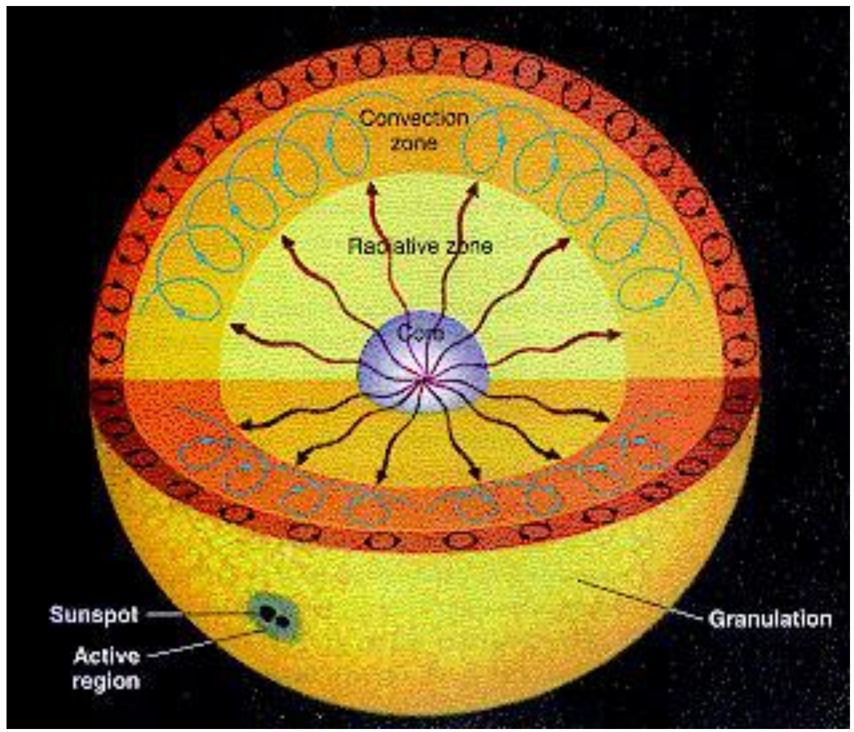
Potential Solar Energy Sources

Candidate Energy Source	**Lifetime of Solar Energy at Sun’s Current Luminosity**
Accretion of Comets	Insignificant
Chemical Burning	5000 years
Stored Heat, Cooling Off	2 ´ 10^{7} years
Gravitational Collapse	2 ´ 10^{8} years
Nuclear Fusion	1 ´ 10^{10} years

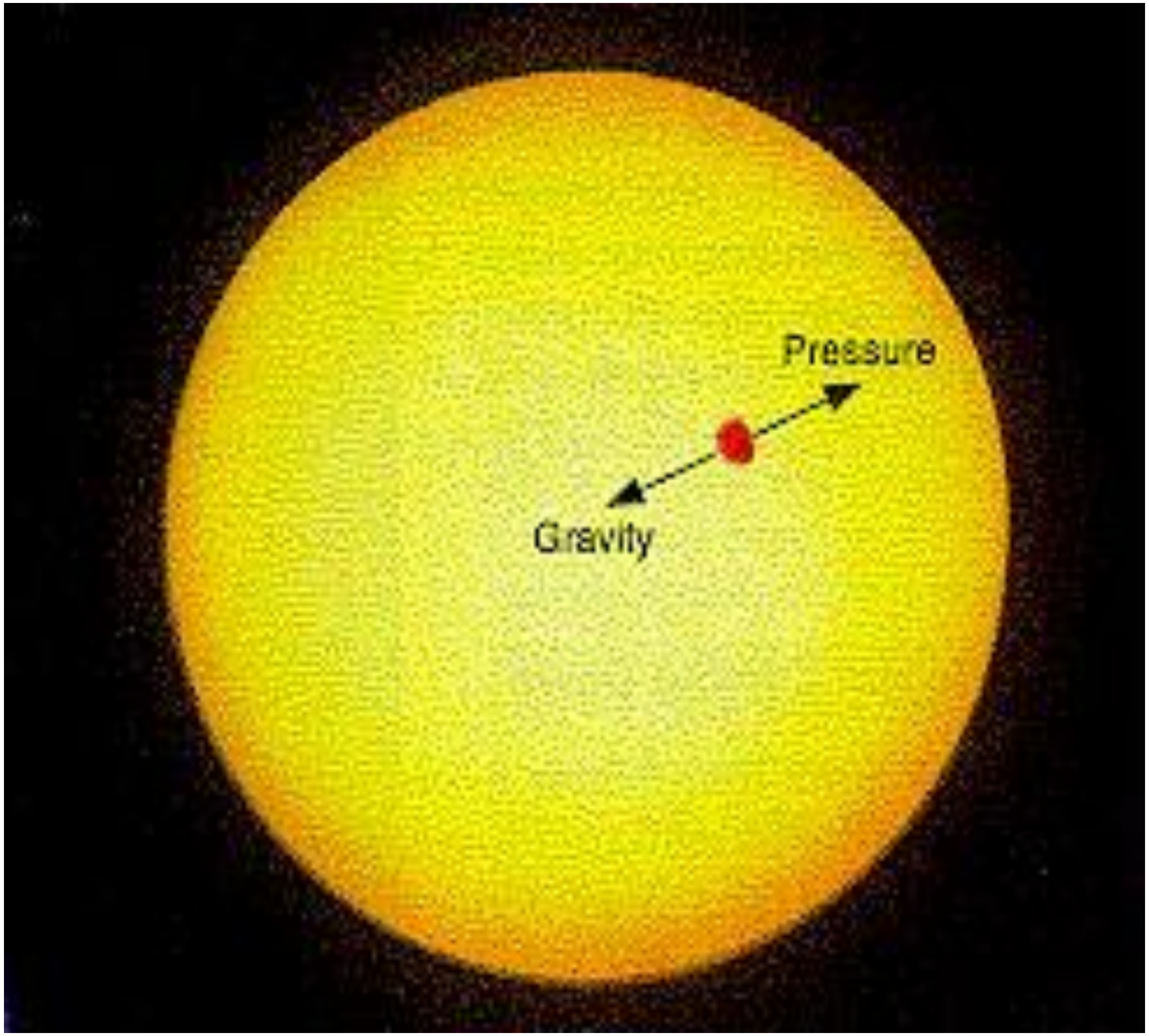
Nuclear Fusion and Stellar Structure

- A star is a hot, glowing sphere of gas, powered by thermonuclear fusion, usually of hydrogen into helium.
- The interior structure of the Sun, or any star, is determined by the balance in the gas between gravity which tries to collapse the gas and the energy source at the center of the star, which heats it and attempts to expand the gas.

Cross-section of the Sun



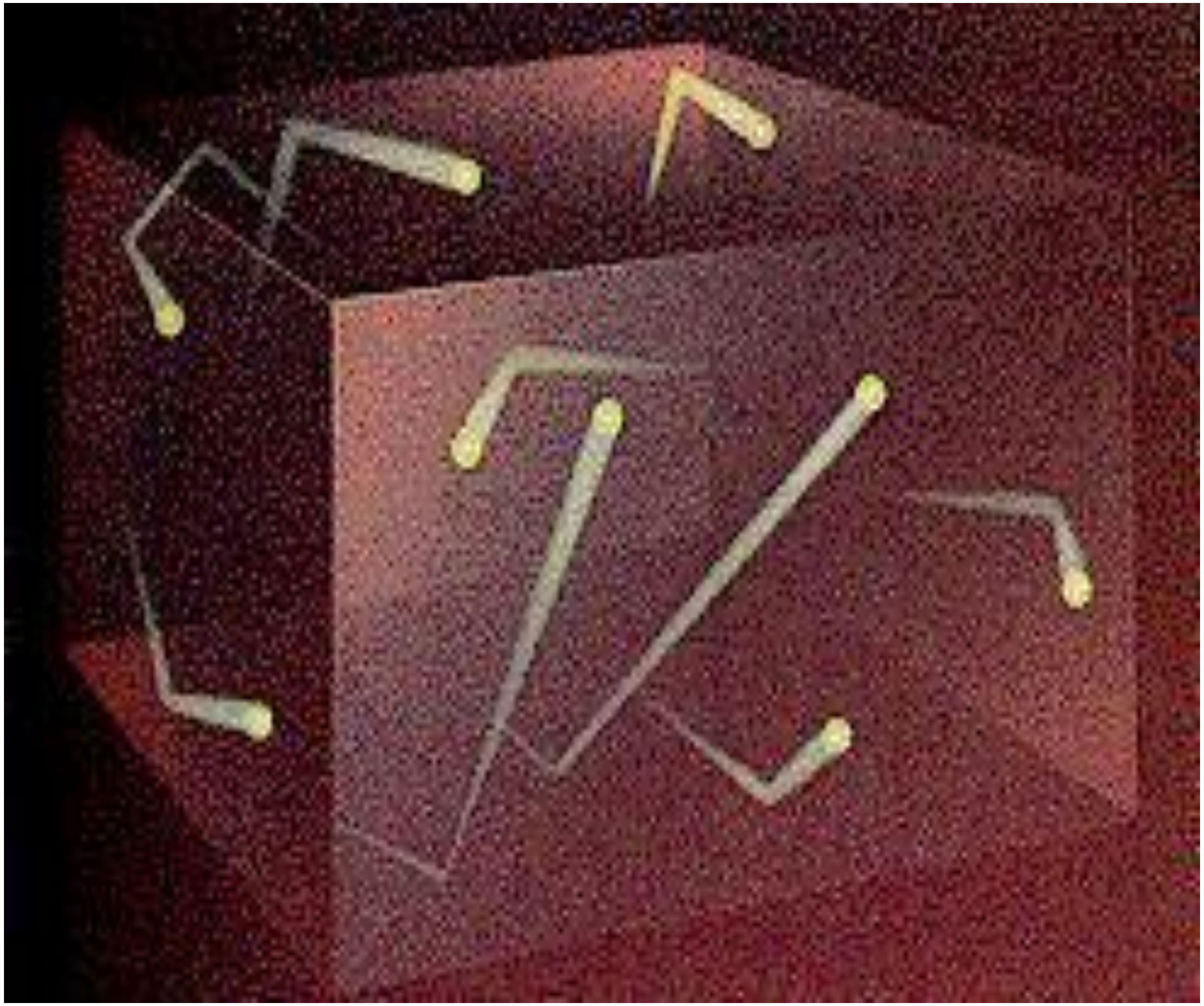
Hydrostatic Equilibrium



Pressure in the Sun's Interior

- **Consider the cross-section of the Sun in <u>the previous slide</u>.**
- **A small volume at the surface of the Sun is attracted to the center by all matter lying below**
- **It pushes down on the gas below it with the force of its weight.**
- **The gas at any point inside the Sun is supporting the weight of a column of gas above it. Like a diver in a swimming pool.**
- **Pressure is the amount of force distributed over a unit of surface area. This can be measured in pounds per square foot (English) or in Newtons per square meter (metric)**

Gas Pressure



How does the Sun Generate That Much Pressure

- This weight of solar gas must be counterbalanced by an equal an opposite force or this mass will begin to move (Figure 3).
- In this case the opposite force is the pressure within this volume of gas.
- If the gas pressure of a volume of gas is less than the weight of the overlying material, then the gas collapses.
- If the gas pressure is greater than the weight of the overlying material, then the gas expands.
- The pressure near the center of the star must support the weight of the entire star. At the center of the Sun p is about 20 billion pounds per square inch.

Balloon Model of the Sun

- **The pressure in a gas is proportional to Density ´ Temperature. A rubber balloon has a balance between the elastic tension in the plastic or rubber out of which the balloon is made, along with the gas pressure of the outside air, and the outward pressure of the gas filling the balloon.**
- **At the Sun's center, the temperature at the center must be 10 to 15 million K and the density 100,000 kg/m^3 to support the weight above. This a gas with a density over 10 times greater than steel.**
- **At the solar "surface" the temperature is about 5,800 K and the density is much lower than the Earth's atmosphere.**
- **A star of 10 to 20 solar masses has a more extensive mass problem than the Sun, so it requires an even greater central pressure and internal temperature.**
- **In order for a star to remain stable the central pressure must always balance the weight of the star.**
- **What happens if the pressure force exceeds the force of gravity? The star will expand until the gas pressure force equals the gravitational force.**
- **This balance in a star between gas pressure and gravity is known as hydrostatic equilibrium.**

Potato Model of a Star

- **Imagine a hot potato, cooling, just out of the oven.**
- **The surface cools by radiating thermal energy into space, like a blackbody, and by convection from the surface of the potato into the air.**
- **As the surface cools energy flow rom the hotter center to the cooler outside.**
- **This latter process occurs by conduction, the flow of heat in a body from a hot region to a cooler region.**
- **Heat is simply the fast atomic motion in matter.**
- **As a molecule starts to vibrate or move more rapidly, we say that its temperature has gone up.**
- **In a potato, the hot, fast vibrating molecules in the inside set into more rapid vibration cooler, slowly vibrating neighbors.**
- **Then heat flows to the cooler molecules and their temperature rises.**

Potato Model continued

- **The Sun loses energy from its photosphere by radiating light into space like a blackbody.**
- **The net effect of this energy loss is that the photosphere (at 5800 K) has become a lot cooler than the center of the Sun (10 to 15 million K) like the potato.**
- **Without a central heat engine, the Sun, as any other star, would steadily contract, generating the necessary energy for sunlight by a continuous gravitational contraction.**

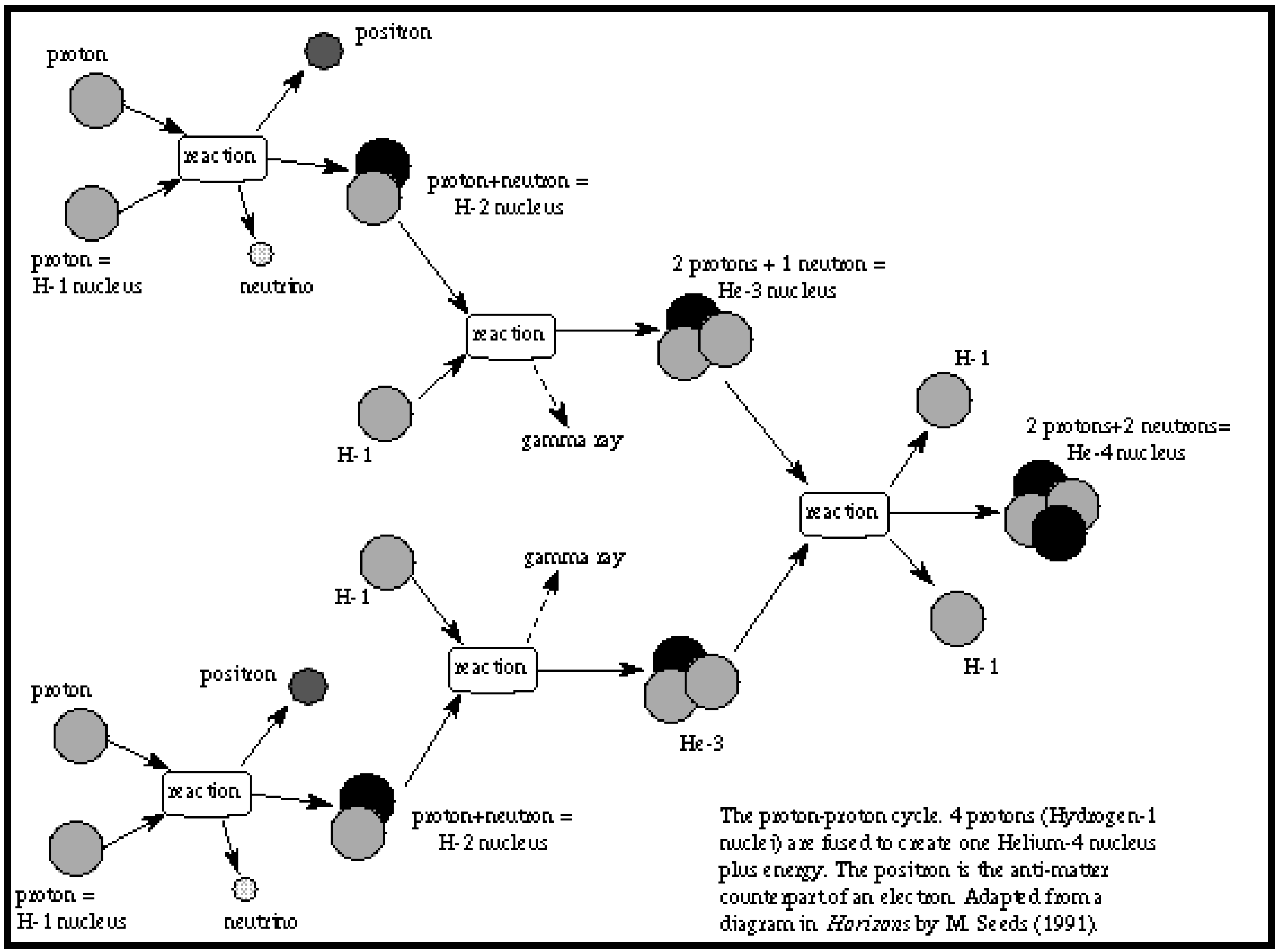
What Powers the Sun?

- **The source of energy from the Sun is explained by Einstein's famous equation from his theory of special relativity: $E = mc^2$**
- This equation describes the allowed conversion of mass into energy.
- stored energy is called potential energy.
- energy of motion is called kinetic energy.
- neither energy nor mass by itself is conserved, but energy *plus* mass is conserved. Energy can be converted into mass and mass into energy.
- The conversion is described by $E = mc^2$; if an amount of mass, m, is destroyed, it is converted to an equivalent energy E.
- If one *gram* of matter could be completely converted into energy it would produce an equivalent energy to 5 million *kilograms* of coal.
- Conversion of mass to energy can supply the Sun with the energy for its current luminosity for billions of years.

Nuclear Energy Generation

- **Mass is converted into energy, and vice versa, in ordinary chemical reactions.**
- **The energy produced in a nuclear reaction is much greater than that produced in an ordinary chemical reaction**
- **An example is the thermonuclear fusion of hydrogen nuclei into a helium nucleus.**
- **Two hydrogen nuclei and two neutrons can fuse together to liberate 0.7% of their mass as energy.**
- **Is hydrogen fusion sufficient for powering the Sun? If all of the hydrogen in the Sun were fused into helium the Sun could appear at its current luminosity for 100 billion years.**
- **The process that powers the Sun and most other stars with the conversion of hydrogen to helium is called the proton-proton chain.**

The Proton-Proton Reaction



The proton-proton cycle. 4 protons (Hydrogen-1 nuclei) are fused to create one Helium-4 nucleus plus energy. The positron is the anti-matter counterpart of an electron. Adapted from a diagram in *Horizons* by M. Seeds (1991).

The Sun as a Fusion Reactor

- **What is required for fusion to occur? Fusion is difficult to control.**
- **The tremendous gravitational forces in stars allows them to be held together at these incredible temperatures.**
- **In jump-starting fusion in a gas, high temperatures and densities are required.**
- **The fusion of hydrogen into helium gets started when two hydrogen nuclei bang together and stick, forming a more massive nucleus.**
- **Once placed together, the nuclear strong force, which holds protons and neutrons together in an atomic nucleus.**
- **However the strong force has a short range and is only significant over a very short range, 10^{-15} m.**

Sun as a Fusion Reactor Cont'd

- **in gases at millions of Kelvins, nuclei are stripped of their electrons and bang together at such high velocities that they can get close enough for the strong force to hold protons together in a combined nucleus.**
- **When this happens, the resulting nucleus is often less massive than the individual components; as a result, energy is created from mass.**
- **In the Sun, energy is produced in a self-sustained chain reaction.**
- **In a nuclear chain reaction, the energy produced by an individual fusion reaction producing a single nucleus is enough to keep the temperature high enough in its neighborhood to produce multiple nuclear fusions nearby.**
- **High gas densities are required for a chain reaction for there to be enough reactions per unit volume in order to sustain a high temperature.**
- **once the center of the Sun has reached a temperature and density great enough for high-velocity particles to fuse frequently, the energy produced by this fusion will maintain conditions (high T and P) for sustained fusion**

What regulates solar fusion?

- **Why doesn't the Sun simply explode like a gigantic hydrogen bomb? The Sun has its own natural thermostat for regulating nuclear fusion. This thermostat is hydrostatic equilibrium, the balance between gravity a rise in gas pressure.**
- **Thus, the Sun's hydrostatic equilibrium holds its thermonuclear fusion rate, its size, and its energy output steady.**
- **Self-regulating reactor keeps a star at constant size and constant energy (corresponding to the Earth's biological record).**

- The Sun’s temperature runs from 10-15 million K at the center to 5800 K in the photosphere.
- thermonuclear fusion in the Sun is temperature sensitive, fusion of hydrogen to helium in the Sun takes place in a rather small core volume.
- Only about 10% of the Sun’s hydrogen is available for fusion.
- This still provides the Sun with enough hydrogen to hold it at its present luminosity for another 5 billion years.
- Since the Earth and Sun are estimated to be 4.6 billion years old, the Sun will have a total lifetime of about 10 billion years.
- one-thousandth of the volume of the Sun lies within the inner 10% of the Sun’s radius. More than half of the Sun’s energy is generated in this small volume.