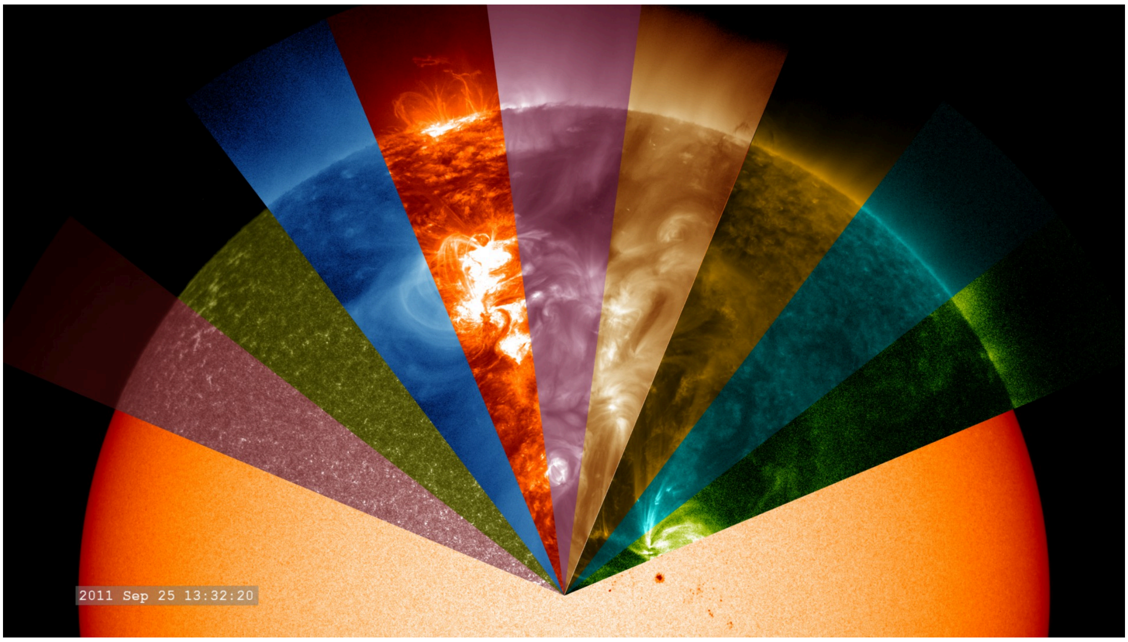
Heliophysics

The Science of Heliophysics: Where Light Begins

(Atufa Vora, MacroEdTech)

Heliophysics is one of the disciplines of physics specifically introduced by remarkable physicist **Eugene Parker** to study the Sun and its influence across the solar system. The Sun is a high-powered star in the centre of our solar system, Its humongous gravitational pull binds all the planets, comets, and asteroids in their orbits. The Sun acts as a unique and powerful natural test center for physics, where the immense conditions of temperature, density, and magnetic fields allow scientists to study processes like nuclear fusion and plasma dynamics which are impossible to replicate on Earth. The light and energy produced by the Sun are directly connected to human life and technology. Solar radiation is the greatest source of solar energy which is a power house of renewable sources and sustainable energy. Furthermore, the variation of solar output is deeply affected by Earth's climate, as it balances the energy that controls the temperature and long-term weather patterns. The scientist studies the solar Interior and atmosphere, solar wind and interplanetary space, and space weather. This allows scientists to protect Earth's infrastructure from the solar wind and to understand the elemental stellar physics.



Structure of Sun

The Sun is an imperfectly spherical shaped star with layers in its structure, each layer of the sun plays a crucial role in energy generation and transport. The temperature increases as moving farther from the core and the pressure decreases drastically.

Core

- **Location:** The very centre of the Sun
- **Temperature:** Approximately 15 million Kelvin
- **Pressure:** Approximately 2.65×10^{11} bar(250 billion times Earth's atmospheric pressure)
- **Activity:** Nuclear fusion takes place here which converts hydrogen into helium and releases vast amounts of energy. This process powers the entire Sun.

Radiative Zone

- **Location:** Surrounding the Core
- **Temperature:** Decreases from approximately 7 million Kelvin to 2 million Kelvin.
- **Activity:** Energy is transported outward by photons which are the packets of light energy that are continuously absorbed and re-emitted by the dense plasma. This is a very slow process and takes hundreds of thousands of years for energy to pass through.

Convective Zone

- **Location:** Above the radiative zone, extending to the visible surface.
- **Temperature:** From ~2 million Kelvin at its base down to ~5,800 Kelvin at the top (photosphere interface).
- **Activity:** Energy transport by convection currents which is hot plasma that rises, cools, sinks creates the motion seen at the surface.

Photosphere

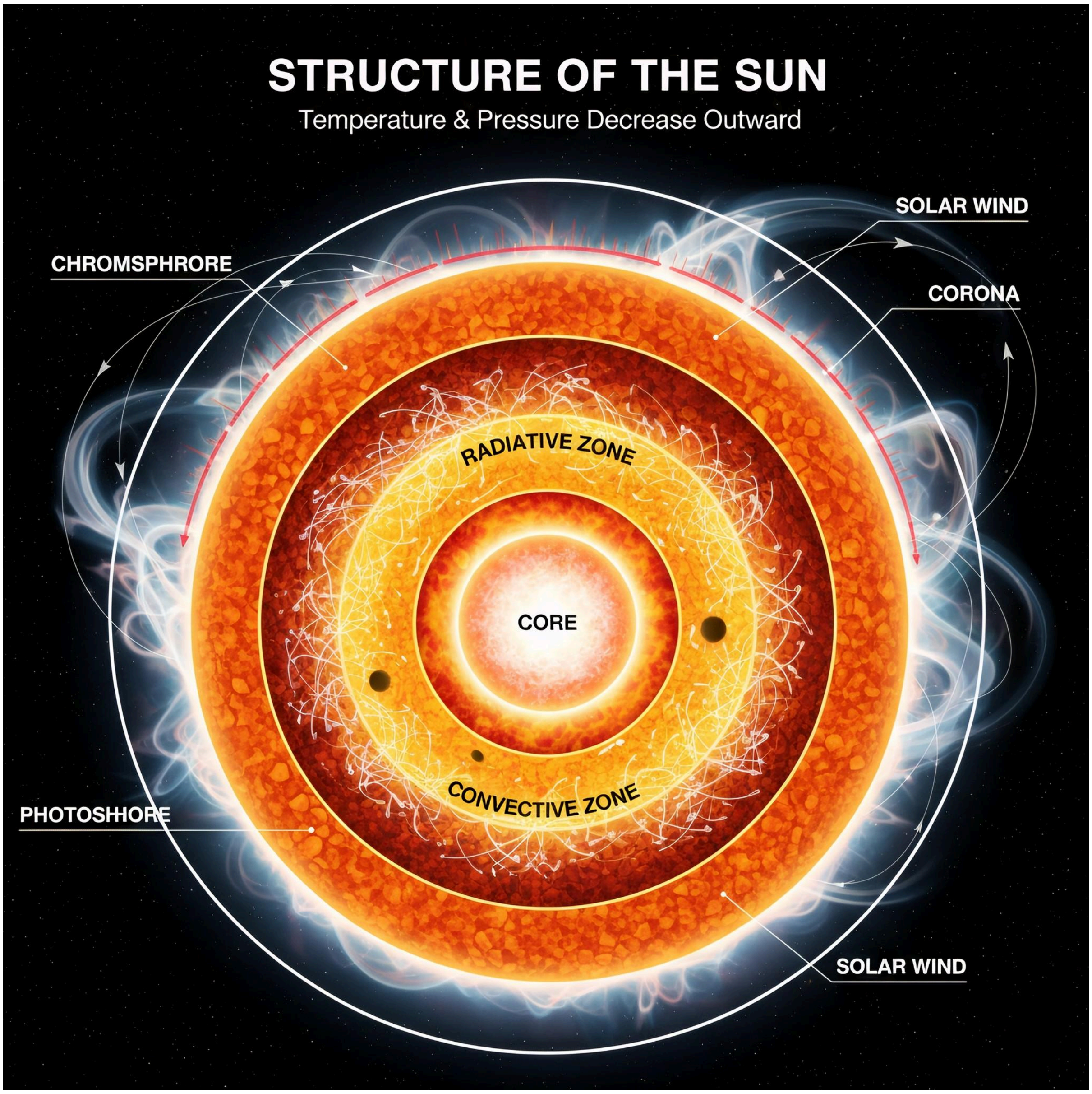
- **Location:** The visible "surface" of the Sun (though not a solid surface).
- **Temperature:** ≈ 5,800 K (or about ~5,700 K) for the photosphere.
- **Activity:** The light we see from the Sun comes from this layer. The surface looks grainy because of rising and sinking hot gases, and dark spots called sunspots can also be seen here.

Chromosphere

- **Location:** Thin layer just above the photosphere..
- **Temperature:** Increases from about ~4,000 Kelvin near the base to ~20,000 Kelvin.
- **Activity:** This layer gives off a red glow during a solar eclipse. Tiny jets of gas called spicules and large loops of gas called prominences start here. The temperature increases as you move higher up in this layer.

Corona

- **Location:** The outermost layer of the Sun's atmosphere, extending far into space.
- **Temperature:** Very hot, ranging from ~1–2 million Kelvin.
- **Activity:** This layer releases the solar wind that flows through space. It can only be seen during a total solar eclipse or with special instruments. Scientists are still studying why it is much hotter than the layers below it.


STRUCTURE OF THE SUN
Temperature & Pressure Decrease Outward
SOLAR WIND
CHROMSPHRORE
CORONA
RADIATIVE ZONE
CORE
CONVECTIVE ZONE
PHOTOSHORE
SOLAR WIND

Physics of Energy Generation

The intense energy radiating from the Sun, born in its core through thermonuclear fusion reactions. The major process responsible for converting mass into energy in stars like our Sun is the proton-proton (p-p) chain.

The Proton-Proton Chain Reaction

This chain reaction takes four different hydrogen nuclei (^1H, or protons) and fuses them producing one helium nucleus (^4He). The whole process can be represented by the following equation:

$$4\,^1\mathrm{H} \rightarrow \,^4\mathrm{He} + 2e^+ + 2\nu_e + 2\gamma$$

Where:

- $4\,^1\mathrm{H}$ represents four protons (hydrogen nuclei).
- $^4\mathrm{He}$ represents the final helium nucleus.
- $2e^+$ represents two positrons (antimatter electrons).
- $2\nu_e$ represents two electron neutrinos.
- 2γ Energy is released primarily in the form of gamma-ray photons.

The Mass-Energy Conversion

The reason behind the immense energy release is the difference between the initial and final mass. The total mass of the four initial protons is slightly greater than the final mass of the helium nucleus and its byproducts, and that small amount of missing mass is not loss, it is changed into an immense amount of energy (E) according to Einstein's famous mass-energy equivalence equation:

$$E=mc^2$$

Where c is the speed of light, the square of speed of light c^2 is such a large number that even the tiniest loss of mass results in a big release of energy. The Sun converts about 4 million metric tons of matter into energy every second through this process.

Solar Radiation and Spectrum

The energy released from the Sun's core reaches the photosphere which is the surface of our Star, then emitted into space as electromagnetic radiation. The characteristics of this radiation can be found using fundamental laws of thermal physics.

Blackbody Radiation

Blackbody radiation is the thermal electromagnetic radiation around a body which is in thermodynamic equilibrium with its environment, emitted by a black body, defined by the specific solar spectrum which depends on the body's temperature. The photosphere of the Sun is a blackbody radiator that continuously emits the light creating a solar spectrum that is regulated by the surface temperature.

Wien's Displacement Law

Wien's displacement law states that the wavelength at which the emission of a blackbody is maximum is inversely proportional to its absolute temperature.

$$\lambda_{\text{max}} = \frac{b}{T}$$

λ_{max} = wavelength peak
b = constant of proportionality
T = absolute temperature

The Sun's photosphere temperature of approximately 5,800 Kelvin which correlates with the peak emission wavelength of around 500 nm, which falls in the visible yellow-green portion of the spectrum, making the Sun appear yellow-white.

Stefan–Boltzmann Law

Stefan–Boltzmann law states that the total energy radiated per unit surface area of a blackbody per unit time is directly proportional to the fourth power of its absolute temperature. This means a small increase in the Sun's temperature would result in a huge increase in the energy that radiates from it which is also increasing the star's luminosity.

$$j^\star = \sigma T^4$$

$j^\star$ = black-body radiant emittance

σ = Stefan-Boltzmann constant

T = thermodynamic temperature

Magnetic Fields and Solar Activity

The Sun is a highly magnetized star. Its complex and constantly shifting magnetic fields are the cause of all extreme solar activity, collectively known as Space Weather. The sunspots are the regions on the Sun's photosphere that appear darker because they are cooler formed where the extremely strong magnetic fields emerge from the Sun's interior. The solar flares are the sudden bursts of electromagnetic radiation (X-rays and gamma rays) from the solar atmosphere when magnetic field lines above sunspot groups suddenly reconnect and release immense amounts of stored energy in minutes. Coronal Mass Ejections (CMEs) are the massive eruptions of plasma (hot, charged particles) and associated magnetic fields that are ejected from the Sun's corona and hurled into space.

The solar magnetic cycle is of approximately 11-year cycle with the variations of sunspots, flares, and CMEs fluctuates from a minimum (few sunspots) to a maximum (many sunspots). Every 11 years, the Sun's global magnetic field completely reverses its polarity (North becomes South and vice-versa). The full magnetic cycle, before the original polarity is restored, is therefore about 22 years.

The CMEs and solar flares can cause electronic damage and increase atmospheric drag which shortens the lifespan of satellites and disrupts signal transmission. Increased ionization in the ionosphere causes signal fading and scintillation, severely degrading GPS and high-frequency radio reliability. Rapid changes in Earth's magnetic field induce geomagnetically induced currents (GICs) in long conductors, which can overload and damage transformers in power distribution networks.

Impact on Earth

A continuous stream of charged particles (plasma) and magnetic fields flowing outward from the Sun's corona at high speed is known as solar wind. Earth is protected by its global magnetic field, which deflects most of the solar wind around the planet called the magnetosphere. Only a small fraction of particles manages to enter the magnetosphere, mostly near the poles causing auroras. The magnetic field lines and collide with gases in the Earth's upper atmosphere (oxygen and nitrogen), these collisions excite the atmospheric gases, causing them to emit light, resulting in the spectacular displays known as the auroras (Aurora Borealis in the North, Aurora Australis in the South).

Space weather forecasting is the arrival and intensity of events like CMEs and solar flares is crucial for mitigation which allows operators to put satellites into "safe mode" or orient them to protect sensitive electronics and enables mission control to instruct astronauts on the International Space Station (ISS) to shelter in heavily shielded areas to minimize radiation exposure.

Recommended Resources

- *European Space Agency (ESA). The Structure of the Sun (Booklet). PDF*.
- *National Aeronautics and Space Administration (NASA). "Layers of the Sun". Web article.*
- *International Atomic Energy Agency (IAEA). Solar and Space Physics: A Science for a Technological Society. PDF.*
- *LibreTexts. "The Structure and Composition of the Sun". Web section*.
- *Living Reviews in Solar Physics. Open-access journal on solar/heliospheric physics*.
- *Mechanism of spontaneous formation of stable magnetic structures on the Sun (arXiv). Research paper you can reference for the magnetic field & solar activity section.*