CHAPTER 1

Introduction

1.1 Solar Irradiance:

The sun is source of electromagnetic energy which is emitted in various wavelength bands. The solar energy emitted by sun is measured at a distance of 1AU from sun in watts/m^2/sec which is called as “solar constant” or “total solar irradiance (TSI)” (fig 1A upper part).

Over a period of many solar cycle the nature of this solar constant is studied by various solar missions like VIRGO, ACRIM I, II, SOVA2, ERBS etc & a composite of these data is prepared which is called as “composite total solar irradiance (CTSI)” (fig 1A lower part & fig 1B).

Fig 1A

Total Solar Irradiance: Original Data (top) and Composite (bottom)

Days (Beginning January 1, 1980)

Fig 1B

Solar Irradiance (W m^-2)

Year

1978-1999
The Sun is a G-type main sequence star. The visual brightness of sun is \( V \) - 26.74, absolute magnitude 4.83, belongs to spectral classification G2V, metallicity \( Z \) is 0.0122 & angular size is 31.6' - 32.7'.

The Sun's orbital characteristics are mean distance 2.5e+17 km (ie 26000 light years) from milky way. Galactic period 2.25 to 2.50e+8 years, velocity 220 km/s to orbit around the centre of the galaxy, 20 km/s relative to average velocity of stars in stellar neighbourhood.

Rotational characteristics are obliquity 7.25° to the elliptic, 67.23° to the galactic plane, right ascension of north pole 286.13°, declination of north pole 63°52' north, sidereal rotation at equator 25.05 days, at 16° latitude 25.38 days, at poles 34.4 days, rotational velocity at equator 7.189e+3 km/hour.

Physical characteristics are mean diameter is 1.392e+6 km, equitorial radius is 6.955e+5 km, surface area 6.0877e+12 km², volume 1.412e+18 km³, average density 1.408e+3 kg/m³, equitorial surface gravity 27.4 m/sec², escape velocity 617.7 km/sec, temperature of center (modeled) 1.57e+7 K, photosphere 5778K, corona 5e+6 K. It is a near perfect sphere with flattening (oblateness) 9e-6 which means that its polar diameter differs from its equatorial diameter by only 10 km (6 mi). Luminosity 3.846e+26 watts, 3.75e+28 lumen, mean intensity 2.009e+7 w/m²/sr.

As the Sun exists in a plasmatic state and is not solid, it rotates faster at its equator than at its poles. This behavior is known as differential rotation. The period of this actual rotation is approximately 25.6 days at the equator and 33.5 days at the poles. However, due to our constantly changing vantage point from the Earth as it orbits the Sun, the apparent rotation of the sun at its equator is about 28 days.[24]
Sun's colour is white although from the surface of the earth it may appear yellow because of atmospheric scattering. Majority of its radiations are in yellow-green portion of visible spectrum. G2 indicates a surface temp of 5510 °C, V in spectral classification indicates that the sun like most of the stars is a main sequence star, generates its energy by nuclear fusion of hydrogen into helium.

The Sun is composed of elements hydrogen and helium; they account for 74.9% and 23.8% of the mass of the Sun in the photosphere, respectively. All heavier elements, called metals in astronomy, account for less than 2% of the mass. The most abundant metals are oxygen (roughly 1% of the Sun's mass), carbon (0.3%), neon (0.2%), and iron (0.2%).

The Sun has inherited its chemical composition from the interstellar medium out of which it is formed. The hydrogen and helium in the Sun were produced by Big Bang nucleosynthesis. The metals were produced by stellar nucleosynthesis in generations of stars which completed their stellar evolution and returned their material to the interstellar medium prior to the formation of the Sun.

The chemical composition of the photosphere is normally considered representative of the composition of the primordial Solar System. However, since the Sun formed, the helium and heavy elements have settled out of the photosphere. Therefore, the photosphere now contains slightly less helium and only 84% of the heavy elements than the protostellar Sun did; the protostellar Sun was 71.1% hydrogen, 27.4% helium, and 1.5% metals.

In the inner portions of the Sun, nuclear fusion has modified the composition by converting hydrogen into helium, so the innermost portion of the Sun is now roughly 60% helium, with the metal abundance unchanged. Because the interior of the Sun is radiative, not convective none of the fusion products from the core have risen to the photosphere.

The solar heavy-element abundances described above are typically measured both using spectroscopy of the Sun's photosphere and by measuring abundances in meteorites that have never been heated to melting temperatures. These meteorites are thought to retain the composition of the protostellar Sun and thus not affected by settling of heavy elements. The two methods generally agree well.

1.2 Fraunhofer lines:

In physics and optics, the Fraunhofer lines are a set of spectral lines named for the German physicist Joseph von Fraunhofer (1787-1826). The lines were originally observed as dark features (absorption lines) in the optical spectrum of the Sun. The English chemist William Hyde Wollaston was in 1802 the first person to note the appearance of a number of dark features in the solar spectrum. In 1814, Fraunhofer independently rediscovered the lines and began a systematic study and careful measurement of the wavelength of these features. In all, he mapped over 570 lines, and designated the principal features with the letters A through K, and weaker lines with other letters. Modern observations of sunlight can detect many thousands of lines. About 45 years later Kirchhoff and Bunsen noticed that several Fraunhofer lines coincide with characteristic emission lines identified in the spectra of heated elements. It was correctly deduced that dark lines in the solar spectrum are caused by absorption by chemical elements in the Solar atmosphere. Some of
the observed features were identified as telluric lines originating from absorption in oxygen molecules in the Earth's atmosphere.

**Fig 1c: Fraunhofer lines**

The Fraunhofer lines are typical spectral absorption lines. These dark lines are produced whenever a cold gas is between a broad spectrum photon source and the detector. In this case a decrease in the intensity of light is seen as the photons are absorbed, then re-emitted in random directions, which are mostly in directions different from the original one. This results in an absorption line. Absorption lines are produced even during reflection from an illuminated cold gas, since after reflection there is still the opportunity for a selective absorption (and re-scatter) between the point of reflection and the detector.

By contrast, if the detector sees photons emitted directly from a glowing gas, by emission processes in atoms in the hot gas, resulting in an emission line. In the Sun, Fraunhofer lines are seen from gas in the outer regions of the Sun, which are too cold to directly produce emission lines of the elements they represent. The Fraunhofer C, F, G', and h lines correspond to the alpha, beta, gamma and delta lines of the Balmer series of emission lines of the hydrogen atom. The D1 and D2 lines form the well-known "sodium doublet", the centre wavelength of which (589.29 nm) is given the designation letter "D". The D1 and D2 lines correspond to the fine splitting of the excited P-state of the alkali.

Note that there is disagreement in the literature for some line designations; e.g., the Fraunhofer d-line may refer to the cyan iron line at 466.814 nm, or alternatively to the yellow helium line (also labeled D3) at 587.5618 nm. Similarly, there is ambiguity with reference to the e-line, since it can refer to the spectral lines of both iron (Fe) and mercury (Hg). In order to resolve ambiguities that arise in usage, ambiguous Fraunhofer line designations are preceded by the element with which they are associated (e.g., Mercury e-line and Helium d-line).

Because of their well defined wavelengths, Fraunhofer lines are often used to characterize the refractive index and dispersion properties of optical materials. The major Fraunhofer lines, and the elements they are associated with, are shown in the following table
The Sun is a Population I, or heavy element-rich, \textsuperscript{[note 1]} star.\cite{26} The formation of the Sun may have been triggered by shockwaves from one or more nearby supernovae.\cite{27}

This is suggested by a high abundance of heavy elements in the Solar System, such as gold and uranium, relative to the abundances of these elements in so-called Population II (heavy element-poor) stars. These elements could most plausibly have been produced by endergonic nuclear reactions during a supernova, or by transmutation via neutron absorption inside a massive second-generation star.\cite{26}\cite{27}

The Sun does not have a definite boundary as rocky planets do, and in its outer parts the density of its gases drops approximately exponentially with increasing distance from its center.\cite{28} Nevertheless, it has a well-defined interior structure, described below. The Sun’s radius is measured from its center to the edge of the photosphere. This is simply the layer above which the gases are too cool or too thin to radiate a significant amount of light, and is therefore the surface most readily visible to the naked eye.\cite{29}\cite{28} The solar interior is not directly observable.

Once was regarded as a small and relatively insignificant star, but now presumed to be brighter than 85% of the stars in galaxy, most of which are dwarfs (with magnitudes around 4.8. The Sun’s hot corona continuously expands in space creating the solar wind, a hypersonic stream of charged particles that heliopause at roughly 100AU.

The interstellar medium formed by the solar wind, the heliosphere, is the largest continuous structure in solar system. The Sun is currently traveling through the local interstellar cloud in the local bubble zone, within the inner rim of the Orion arm of the Milky Way galaxy. Of the 50 nearest stellar...
systems within 17 light years from the earth, the sun ranks 4th in mass. The sun orbits the center of the Milky Way galaxy at a distance of approximately 24,000-26,000 light years from the galactic center, completing one clockwise orbit as viewed from the galactic north pole in 225-250 million years. The mean distance of the sun from the earth is approximately 149.6 million km (1AU). Though this varies as earth moves from perihelion in January to aphelion in July. At this average distance, light travels from sun to the earth 8 min 19 sec.

Just as seismology uses waves generated by earthquakes to reveal the interior structure of the Earth, the discipline of helioseismology makes use of pressure waves (infrasound) traversing the Sun’s interior to measure and visualize the star’s inner structure. Computer modeling of the Sun is also used as a theoretical tool to investigate its deeper layers.

1.3 The Solar Interior The solar interior is mainly separated into four regions by the different processes that occur there. Energy is generated in the core, the innermost 25%. This energy diffuses outward by radiation (mostly gamma-rays and x-rays) through the radiative zone and by convective fluid flows (boiling motion) through the convection zone, the outermost 30%. The thin interface layer (the "tachocline") between the radiative zone and the convection zone is where the Sun’s magnetic field is thought to be generated.

To study various solar aspects in detail, sun can be divided into following layers:
1) Core
2) Radiative zone 2a) Tachocline region (the interface region)
3) Convective zone
4) Photosphere
5) Chromosphere
6) Transition region
7) Corona
8) Heliosphere

**A) Core**: The core of the Sun extends about 0.2 to 0.25 solar radii. It has a density of up to 150 g/cm³ (150 times the density of water on Earth) and a temperature of close to 13,600,000 kelvins (by contrast, the surface of the
sun is around 5,800 kelvins). Recent analysis of SOHO mission data favors a faster rotation rate in the core than in the rest of the radiative zone.\textsuperscript{[11]} Through most of the Sun’s life, energy is produced by nuclear fusion through a series of steps called the p-p (proton-proton) chain; this process converts hydrogen into helium.\textsuperscript{[12]} Less than 2% of the helium generated in the Sun comes from the CNO cycle.

The core is the only location in the Sun that produces an appreciable amount of heat via fusion: the rest of the star is heated by energy that is transferred outward from the core. All of the energy produced by fusion in the core must travel through many successive layers to the solar photosphere before it escapes into space as sunlight or kinetic energy of particles.\textsuperscript{[31]} The proton-proton chain occurs around \(9.2 \times 10^37\) times each second in the core of the Sun.

Since this reaction uses four protons, it converts about \(3.7 \times 10^{38}\) protons (hydrogen nuclei) to helium nuclei every second (out of a total of \(~8.9 \times 10^{56}\) free protons in the Sun), or about \(6.2 \times 10^{11}\) kg per second.\textsuperscript{[31]} Since fusing hydrogen into helium releases around 0.7% of the fused mass as energy,\textsuperscript{[32]} the Sun releases energy at the matter-energy conversion rate of 4.26 million metric tons per second, 383 yottawatt (3.83\times10^{26} W),\textsuperscript{[34]} or \(9.15 \times 10^{10}\) megatons of TNT per second.

The rate of nuclear fusion depends strongly on density and temperature, so the fusion rate in the core is in a self-correcting equilibrium: A slightly higher rate of fusion would cause the core to heat up more and expand slightly against the weight of the outer layers, reducing the fusion rate and correcting the perturbation; and a slightly lower rate would cause the core to cool and shrink slightly, increasing the fusion rate and again reverting it to its present level.\textsuperscript{[38]}\textsuperscript{[39]}
The high-energy photons (gamma rays) released in fusion reactions are absorbed in only a few millimeters of solar plasma and then re-emitted again in random direction (and at slightly lower energy)—so it takes a long time for radiation to reach the Sun’s surface. The “photon travel time” range between 10,000 and 170,000 years.\textsuperscript{[40]} After a final trip through the convective outer layer to the transparent “surface” of the photosphere, the photons escape as visible light. Each gamma ray in the Sun’s core is converted into several million visible light photons before escaping into space. Neutrinos are also released by the fusion reactions in the core, but unlike photons they rarely interact with matter, so almost all are able to escape the Sun immediately. For many years measurements of the number of neutrinos produced in the Sun were lower than theories predicted by a factor of 3. This discrepancy was recently resolved through the discovery of the effects of neutrino oscillation: the Sun in fact emits the number of neutrinos predicted by the theory, but neutrino detectors were missing \( \frac{2}{3} \) of them because the neutrinos had changed flavor.\textsuperscript{[41]}
In stars like the Sun the nuclear burning takes place through a three step process called the proton-proton or pp chain. In the first step two protons collide to produce deuterium, a positron, and a neutrino. In the second step a proton collides with the deuterium to produce a helium-3 nucleus and a gamma ray. In the third step two helium-3s collide to produce a normal helium-4 nucleus with the release of two protons. In this process of fusing hydrogen to form helium, the nuclear reactions produce elementary particle called neutrinos. These elusive particles. The number of neutrinos we detect is but a fraction of the number we expected. This problem of the missing neutrinos was one of the great mysteries of solar astronomy but now appears to be solved by the discovery of neutrino masses.

B) The Radiative Zone
The radiative zone extends outward from the outer edge of the core to the interface layer or tachocline at the base of the convection zone (from 25% of the distance to the surface to 70% of that distance). The radiative zone is characterized by the method of energy transport - radiation. The energy generated in the core is carried by light (photons) that bounces from particle to particle through the radiative zone.

The Interface Layer (Tachocline)
The interface layer lies between the radiative zone and the convective zone. The fluid motions found in the convection zone slowly disappear from the top of this layer to its bottom where the conditions match those of the calm radiative zone. This thin layer has become more interesting in recent years as more details have been discovered about it. It is now believed that the Sun’s magnetic field is generated by a magnetic dynamo in this layer. The changes in fluid flow velocities across the layer (shear flows) can stretch magnetic field lines of force and make them stronger. This change in flow velocity gives this layer its alternative name - the tachocline. There also appears to be sudden changes in chemical composition across this layer. pass right through the overlying layers of the Sun and, with some effort can be detected here on Earth.
Between the radiative zone and the convection zone is a transition layer called the tachocline. This is a region where the sharp regime change between the uniform rotation of the radiative zone and the differential rotation of the convection zone results in a large shear—a condition where successive horizontal layers slide past one another.\textsuperscript{[14]} The fluid motions found in the convection zone above, slowly disappear from the top of this layer to its bottom, matching the calm characteristics of the radiative zone on the bottom. Presently, it is hypothesized (see Solar dynamo), that a magnetic dynamo within this layer generates the Sun’s magnetic field.\textsuperscript{[33]}

Tachocline layer location is 0.693(eq),0.717(high lat.) solar radii, thickness 0.04 times solar radius. The geometry and width of tachocline plays an important role in the solar dynamo by winding up a weaker poloidal field to create a much stronger toroidal field. The term tachocline was coined in a paper by EDWARD SPIGEL & JEAN-PAUL ZAHN in 1992 (astronomy and astrophysics,265,1992,106) by analogy to oceanic thermocline.

![FIG 1G: temp profile](image)

**C) Convective zone:** The convection zone is the outer-most layer of the solar interior. It extends from a depth of about 200,000 km right up to the visible surface. At the base of the convection zone the temperature is about 2,000,000°C. This is “cool” enough for the heavier ions (such as carbon, nitrogen, oxygen, calcium, and iron) to hold onto some of their electrons. This makes the material more opaque so that it is harder for radiation to get through. This traps heat that ultimately makes the fluid unstable and it starts to “boil” or convect. Convection occurs when the temperature gradient (the rate at which the temperature falls with height or radius) gets larger than the adiabatic gradient (the rate at which the temperature would fall if a volume of material were moved higher without adding heat). Where this occurs a volume of material moved upward will be warmer than its surroundings and will continue to rise further. These convective motions carry heat quite rapidly to the surface. The fluid expands and cools as it rises. At the visible surface the temperature has dropped to 5,700°K and the density is only 0.0000002 gm/cm$^3$
The convective motions themselves are visible at the surface as granules and supergranules.

In the Sun’s outer layer, from its surface down to approximately 200,000 km (or 70% of the solar radius), the solar plasma is not dense enough or hot enough to transfer the heat energy of the interior outward via radiation (in other words it is opaque enough). As a result, thermal convection occurs as thermal columns carry hot material to the surface (photosphere) of the Sun. Once the material cools off at the surface, it plunges back downward to the base of the convection zone, to receive more heat from the top of the radiative zone. At the visible surface of the Sun, the temperature has dropped to 5,700° K and the density to only 0.2 g/m³ (about 1/10,000th the density of air at sea level). The thermal columns in the convection zone form an imprint on the surface of the Sun, in the form of the solar granulation and supergranulation.

The turbulent convection of this outer part of the solar interior gives rise to a "small-scale" dynamo that produces magnetic north and south poles all over the surface of the Sun. The Sun’s thermal columns are Bénard cells and therefore tend to be hexagonal.

**Photosphere:** The effective temperature, or black-body temperature, of the Sun (5777 K) is the temperature a black body of the same size must have to yield the same total emissive power. The visible surface of the Sun, the photosphere, is the layer below which the Sun becomes opaque to visible light. Above the photosphere, visible sunlight is free to propagate into space, and its energy escapes the Sun entirely. The change in opacity is due to the decreasing amount of H⁻ ions, which absorb visible light easily. Conversely, the visible light we see is produced as electrons react with hydrogen atoms to produce H⁻ ions. The photosphere is actually tens to hundreds of kilometres thick, being slightly less opaque than air on Earth. Because the upper part of the photosphere is cooler than the lower part, an image of the Sun appears brighter in the center than on the edge or limb of the solar disk, in a phenomenon known as limb darkening. Sunlight has approximately a black-body spectrum that indicates its temperature is about 6,000 K, interspersed with
atomic absorption lines from the tenuous layers above the photosphere. The photosphere has a particle density of \( \sim 10^{23} \text{ m}^{-3} \) (this is about 1% of the particle density of Earth’s atmosphere at sea level).[42] During early studies of the optical spectrum of the photosphere, some absorption lines were found that did not correspond to any chemical elements then known on Earth. In 1868, Norman Lockyer hypothesized that these absorption lines were because of a new element which he dubbed "helium", after the Greek Sun god Helios. It was not until 25 years later that helium was isolated on Earth.[43] The coolest layer of the Sun is a temperature minimum region about 500 km above the photosphere, with a temperature of about 4,100 K.[44] This part of the Sun is cool enough to support simple molecules such as carbon monoxide and water, which can be detected by their absorption spectra.[45].

**E) chromosphere:**

![FIG 1: solar chromosphere](image)

Above the temperature minimum layer is a layer about 2,000 km thick, dominated by a spectrum of emission and absorption lines.[46] It is called the chromosphere from the Greek root chroma, meaning color, because the chromosphere is visible as a colored flash at the beginning and end of total eclipses of the Sun.[47] The temperature in the chromosphere increases gradually with altitude, ranging up to around 20,000 K near the top.[48] In the upper part of the chromosphere helium becomes partially ionized.[49] Taken by Hinode’s Solar Optical Telescope on January 12, 2007, this image of the Sun reveals the filamentary nature of the plasma connecting regions of different magnetic polarity.

The gases which extend away from the photosphere make up the chromosphere. These gases are transparent to most visible radiation. The chromosphere is about 2,500 km thick. The density of the gases decreases as you move away from the photosphere into the chromosphere, but the temperature increases! From the bottom to the top of the chromosphere, the average temperature goes from 4500 to 10,000 Kelvin! Needless to say, this rise was not anticipated by scientists when they first measured it. Throughout the rest of the Sun, temperature decreases as you move further away from the core.

<table>
<thead>
<tr>
<th>Chromosphere thickness:</th>
<th>~2,000 - 10,000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density:</td>
<td>( \sim 1 \text{E-13 g/cm}^3 )</td>
</tr>
<tr>
<td>Top of chromosphere:</td>
<td>at the steep rise of temperature</td>
</tr>
<tr>
<td>Temperature at 1,000 km elevation:</td>
<td>8,000 K</td>
</tr>
<tr>
<td>Temperature at top of chromosphere:</td>
<td>20,000 - 40,000 K</td>
</tr>
</tbody>
</table>
**Chromospheric Features**

a) **Spicules/Mottles**: Altitude of basis: 1,000 km, Diameter at basis: 500 - 1,000 km, Height: 3,000 - 10,000 km, Location: at the border of supergranules, About 100,000 - 1E6 spicules active at the same time, Type I: generated by sound waves, Upward velocity: 20 km/s, Lifetime: 5 - 10 min, Type II: generated by Alfvén waves, Lifetime: 10 - 60 sec.

Spicules live for about 5 - 10 minutes; at the solar limb they appear elongated (if seen on the disk, they are known as "mottles" or "fibrils"). They are usually associated with regions of high magnetic flux; their mass flux is about 100 times that of the solar wind. At any one time there are around 60,000 to 70,000 active spicules on the Sun; an individual spicule typically reaches 3,000 - 10,000 km altitude above the photosphere.

b) **The Chromospheric Network**: Magnetic field: 25 G, Location: at the border of supergranules, Intra-network region: Lower part (<1000 km): "canopy" Canopy temperature: 3000K, Upper part (>1000 km): coronal conditions. The chromospheric network is a web-like pattern most easily seen in the emissions of the red line of hydrogen (H-alpha) and the ultraviolet line of calcium (Ca II K - from calcium atoms with one electron removed).
network outlines the supergranule cells and is due to the presence of bundles of magnetic field lines that are concentrated there by the fluid motions in the supergranules.

**FIG 1M**

**c) Filaments/Quiescent prominences & Plages**: Thickness: 5,000 km, Height: 50,000 km, Length: 200,000 km, Density: 2E-13 g/cm³, Temperature: ~10,000 K, Location: along PIL of decayed AR, Lifetime: days to months, Magnetic field: 10-100 G Filaments are dark, thread-like features seen in the red light of hydrogen (H-alpha). These are dense, somewhat cooler, clouds of material that are suspended above the solar surface by loops of magnetic field. Plage, the French word for beach, are bright patches surrounding sunspots that are best seen in H-alpha emissions that characterize the chromosphere.
Prominences are dense clouds of material suspended above the surface of the Sun by loops of magnetic field. Prominences and filaments are actually the same things except that prominences are seen projecting out above the limb, or edge, of the Sun. Both filaments and prominences can remain in a quiet or quiescent state for days or weeks. However, as the magnetic loops that support them slowly change, filaments and prominences can erupt and rise off of the Sun over the course of a few minutes or hours.

**Transition region:**
- Thickness: \( \sim 100 \) km
- Density range: \([1 \text{E}-13, 1 \text{E}-15]\) g/cm\(^3\)
- Temperature range: \([\sim 20,000, 1 \text{E}6]\) K

**Transition Region Explosions:**
- Frequency: \(1/40 \text{ s-1}\)
- Speed of the jet of plasma: \(100-400 \text{ km/s}\)
- Location: at the border of supergranules
- Blinkers (He II bright spots): Identified regions: \(\sim 3000\)
- Frequency of brightening: \(1/10 \text{ min-1}\)

The transition region is a thin and very irregular layer of the Sun’s atmosphere that separates the hot corona from the much cooler chromosphere. Heat flows down from the corona into the chromosphere and in the process produces this thin region where the temperature changes rapidly from 1,000,000°C (1,800,000°F) down to about 20,000°C (40,000°F). Hydrogen is ionized (stripped of its electron) at these temperatures and is therefore difficult to see. Instead of hydrogen, the light emitted by the transition region is dominated by such ions as C IV, O IV, and Si IV (carbon, oxygen, and silicon each with three electrons stripped off) spectrum that is only accessible from space.

**FIG 1R: carbon IV emission**

**FIG 1Q: Sulfur VI emission**

Above the chromosphere there is a thin (about 200 km) transition region in which the temperature rises rapidly from around 20,000 K in the upper chromosphere to coronal temperatures closer to 10,000,000 K. The temperature increase is facilitated by the full ionization of helium in the transition region, which significantly reduces radiative cooling of the plasma. The transition region does not occur at a well-defined altitude. Rather, it forms a kind of nimbus (halo) around chromospheric features such as spicules and filaments, and is in constant, chaotic motion. The transition region is not easily visible.
from Earth’s surface, but is readily observable from space by instruments sensitive to the extreme ultraviolet portion of the spectrum.\cite{51}

The transition region has been studied from space using instruments on several spacecraft including the Solar Maximum Mission and the Solar and Heliospheric Observatory. The Transition Region and Coronal Explorer (TRACE) mission is now actively acquiring data on the structure and dynamics of the transition region. The images to the left are from the SUMER instrument on the SOHO Mission. The images are emission from Carbon IV at temperatures of about 100,000°C & Sulfur VI at temperatures of about 200,000°C.

G) corona

\[\text{FIG 15 : solar corona}\]

Density in the lower corona: \(\sim 1\times 10^{-15}\ \text{g/cm}^3\), temperature: 1-3\(\times 10^6\ \text{K}\), extension in white light: 30 solar radii and more, Proposed heating mechanisms: by acoustic and Alfven waves, by reconnections in the magnetic carpet (nano flares).

During a total solar eclipse, the solar corona can be seen with the naked eye. The parts of the Sun above the photosphere are referred to collectively as the solar atmosphere.\cite{45,49} They can be viewed with telescopes operating across the electromagnetic spectrum, from radio through visible light to gamma rays, and comprise five principal zones: the temperature minimum, the chromosphere, the transition region, the corona, and the heliosphere.\cite{45} The heliosphere, which may be considered the tenuous outer atmosphere of the Sun, extends outward past the orbit of Pluto to the heliopause, where it forms a sharp shock front boundary with the interstellar medium. The chromosphere, transition region, and corona are much hotter than the surface of the Sun.\cite{45} The reason why has not been conclusively proven; evidence suggests that Alfven waves may have enough energy to heat the corona.\cite{49}

The corona is the extended outer atmosphere of the Sun, which is much larger in volume than the Sun itself. The corona continuously expands into the space forming the solar wind, which fills all the Solar System.\cite{52} The lower corona, which is very near the surface of the Sun, has a particle density around 10\(^{-15}\) - 10\(^{-16}\) m\(^{-3}\).\cite{51,49} The average temperature of the corona and solar wind is about 1-2 million kelvins, however, in the hottest regions it is 8-20 million kelvins.\cite{52} While no complete theory yet exists to account for the temperature of the corona, at least some of its heat is known to be from magnetic reconnection.\cite{52,54}
a) The white light corona
The Corona is the Sun's outer atmosphere. It is visible during total eclipses of the Sun as a pearly white crown surrounding the Sun. The corona displays a variety of features including streamers, plumes, and loops. These features change from eclipse to eclipse and the overall shape of the corona changes with the sunspot cycle. However, during the few fleeting minutes of totality few, if any changes are seen in these coronal features.

![FIG 1T: White light corona](image)

b) The Emission Line Corona
Early observations of the visible spectrum of the corona revealed bright emission lines at wavelengths that did not correspond to any known materials. This led astronomers to propose the existence of "coronium" as the principal gas in the corona. The true nature of the corona remained a mystery until it was determined that the coronal gases are superheated to temperatures greater than 1,000,000°C (1,800,000°F). At these high temperatures both hydrogen and helium (the two dominant elements) are completely stripped of their electrons. Even minor elements like carbon, nitrogen, and oxygen are stripped down to bare nuclei. Only the heavier trace elements like iron and calcium are able to retain a few of their electrons in this intense heat. It is emission from these highly ionized elements that produces the spectral emission lines that were so
mysterious to early astronomers. We can now produce artificial eclipses in coronagraphs that cover the disk of the Sun and filter out everything except the emission due to these coronal ions. These coronagraphs produce images of the "emission line corona." Examples of these observations can be seen at the National Solar Observatory's Coronal Data page.

c) The X-Ray Corona

The corona shines brightly in x-rays because of its high temperature. On the other hand, the "cool" solar photosphere emits very few x-rays. This allows us to view the corona across the disk of the Sun when we observe the Sun in X-rays. To do this we must first design optics that can image x-rays and then we must get above the Earth's atmosphere.

![X-ray corona](image1)

In the early 70's Skylab carried an x-ray telescope that revealed coronal holes and coronal bright points for the first time. During the last decade Yohkoh provided a wealth of information and images on the sun's corona. Today we have the SOHO and TRACE satellites obtaining new and exciting observations of the Sun's corona, its features, and its dynamic character. During a total solar eclipse, the solar corona can be seen with the naked eye, during the brief period of totality.

The temperature variation of various solar layers is as depicted below.

![Temperature profile](image2)
1.4 coronal holes: These regions appear dark in coronographs or during total solar eclipse. They show a void in x-ray & extreme ultra violet images. They have very low density about 100 times lower than that of rest of corona. They are open magnetic field structures. The open magnetic field lines originating from them extend to infinity instead of looping back to photosphere. The solar charged particles escape from sun (because of these open magnetic field lines) producing solar wind. During solar minima coronal holes are confined to polar regions, while during solar maxima at any solar latitude they can open up.

Alfven waves: open magnetic field lines originating from coronal holes have large fluctuations, known as alfven waves. Field lines originating from center of hole have large fluctuations compared to those originating from the sides.

Fig 1Y: coronal hole

FIG 1Z: Alfven waves

The magnetic fields from the center of coronal holes in the sun's atmosphere have large fluctuations known as Alfvén waves, while those from the sides have smaller fluctuations. The side fields do not transfer energy as well from the sun to Earth's magnetosphere.

Coronal holes seem to be responsible for minimizing the southward direction of the interplanetary magnetic field as well. The solar wind's magnetic fields oscillate on the journey from the sun to Earth. These fluctuations are known as Alfvén waves. The wind coming out of the centers of the coronal holes have large fluctuations, meaning that the southward magnetic component -- like that in all the directions -- is fairly large. The wind that comes from the edges, however, has smaller fluctuations, and comparably smaller southward components. So, once again, coronal holes at lower latitudes would have a better chance of connecting with Earth's magnetosphere and causing geomagnetic effects, while mid-latitude holes would be less effective. Credit: Karen C. Fox, NASA's Goddard Space Flight Center news, NASA/Park

e) Heliospheric current sheet extends to the outer reaches of the Solar System, and results from the influence of the Sun's rotating magnetic field on the plasma in the interplanetary medium.\(^{[23]}\)

H) Heliosphere: The heliosphere, which is the cavity around the Sun filled
with the solar wind plasma, extends from approximately 20 solar radii (0.1 AU) to the outer fringes of the Solar System. Its inner boundary is defined as the layer in which the flow of the solar wind becomes supersonic—that is, where the flow becomes faster than the speed of Alfvén waves.[5] Turbulence and dynamic forces outside this boundary cannot affect the shape of the solar corona within, because the information can only travel at the speed of Alfvén waves. The solar wind travels outward continuously through the heliosphere, forming the solar magnetic field into a spiral shape,[54] until it impacts the heliopause, more than 50 AU from the Sun. In December 2004, the Voyager 1 probe passed through a shock front that is thought to be part of the heliopause.

![Heliosphere Diagram](image)

**FIG 1AA: heliosphere**

"Changes in the Sun’s magnetic field are carried outward through the heliosphere by the solar wind," explains Steve Suess, another solar physicist at the Marshall Space Flight Center. "It takes about a year for disturbances to propagate all the way from the Sun to the outer bounds of the heliosphere." Because the Sun rotates (once every 27 days) solar magnetic fields corkscrew outwards in the shape of an Archimedian spiral. Far above the poles the magnetic fields twist around like a child’s Slinky toy.

### 1.5 Solar Magnetic Field

The heliospheric current sheet extends to the outer reaches of the Solar System, and results from the influence of the Sun’s rotating magnetic field on the plasma in the interplanetary medium.[57] The Sun is a magnetically active star. It supports a strong, changing magnetic field that varies year-to-year and reverses direction about every eleven years around solar maximum.[58] The Sun’s magnetic field gives rise to many effects that are collectively called solar activity, including sunspots on the surface of the Sun, solar flares, and variations in solar wind that carry material through the Solar System.[59] Effects of solar activity on Earth include auroras at moderate to high latitudes, and the disruption of radio communications and electric power.
Solar activity is thought to have played a large role in the formation and evolution of the Solar System. Solar activity changes the structure of Earth's outer atmosphere. Both of the Voyager probes have recorded higher levels of energetic particles as they approach the boundary. All matter in the Sun is in the form of gas and plasma because of its high temperatures. This makes it possible for the Sun to rotate faster at its equator (about 25 days) than it does at higher latitudes (about 35 days near its poles). The differential rotation of the Sun's latitudes causes its magnetic field lines to become twisted together over time, causing magnetic field loops to erupt from the Sun's surface and trigger the formation of the Sun's dramatic sunspots and solar prominences (see magnetic reconnection). This twisting action gives rise to the solar dynamo and an 11-year solar cycle of magnetic activity as the Sun's magnetic field reverses itself about every 11 years. The solar magnetic field extends well beyond the Sun itself. The magnetized solar wind plasma carries Sun's magnetic field into the space forming what is called the interplanetary magnetic field. Since the plasma can only move along the magnetic field lines, the interplanetary magnetic field is initially stretched radially away from the Sun.

**1.6 Solar and planetary mass fractionation relationship:**

Because the fields above and below the solar equator have different polarities pointing towards and away from the Sun, there exists a thin current layer in the solar equatorial plane, which is called the heliospheric current sheet. At the large distances the rotation of the Sun twists the magnetic field and the current sheet into the Archimedean spiral structure called the Parker spiral. The interplanetary magnetic field is much stronger than the dipole component of the solar magnetic field. The Sun's 50–400 μT (in the photosphere) magnetic dipole field reduces with the cube of the distance to about 0.1 nT at the distance of the Earth. However, according to spacecraft observations the interplanetary field at the Earth's location is about 100 times greater at around 5 nT.
Various authors have considered the existence of a mass fractionation relationship between the isotopic compositions of solar and planetary noble gases, for example correlations between isotopic compositions of planetary and that it was the fractionation in the Sun itself that caused the fractionation relationship between the isotopic compositions of planetary and solar wind implanted noble gases. Nevertheless, the belief that the whole Sun has the same composition as the solar atmosphere was still widespread, at least until 1983. In 1983, it was claimed when observing the Sun with appropriate filtration, the most immediately visible features are usually its sunspots, which are well-defined surface areas that appear darker than their surroundings because of lower temperatures. Sunspots are regions of intense magnetic activity where convection is inhibited by strong magnetic fields, reducing energy transport from the hot interior to the surface.

**Solar cycle (Sunspots and the sunspot cycle):**

1. **Measurements of solar cycle variation during the last 30 years**

The magnetic field gives rise to strong heating in the corona, forming active regions that are the source of intense solar flares and coronal mass ejections. The largest sunspots can be tens of thousands of kilo metres across. The number of sunspots visible on the Sun is not constant, but varies over an 11-year cycle known as the solar cycle. At a typical solar minimum, few sunspots are visible, and occasionally none at all can be seen. Those that do appear are at high solar latitudes. As the sunspot cycle progresses, the number of sunspots increases and they move closer to the equator of the Sun, a phenomenon described by Spörer’s law. Sunspots usually exist as pairs with opposite magnetic polarity. The magnetic polarity of the leading sunspot alternates every solar cycle, so that it will be a north magnetic pole in one solar cycle and a south magnetic pole in the next. History of the number of observed sunspots during the last 250 years, which shows the ~11-year solar cycle.

The solar cycle has a great influence on space weather, and is a significant influence on the Earth’s climate since luminosity has a direct relationship with magnetic activity. Solar activity minima tend to be correlated with colder temperatures, and longer than average solar cycles tend to be correlated with hotter temperatures. In the 17th century, the solar cycle appears to have stopped entirely for several decades; very few sunspots were observed during this period. During this era, which is known as the Maunder minimum or Little Ice Age, Europe experienced very cold temperatures. Earlier extended minima have been discovered through analysis of tree rings and also appear to have coincided with lower-than-average global temperatures.

1. **Possible long-term cycle**

A recent theory claims that there are magnetic instabilities in the core of the Sun that cause fluctuations with periods of either 41,000 or 100,000 years. These could provide a better explanation of the ice ages than the Milankovitch cycles.

1. **Life cycle**

The Sun was formed about 4.57 billion years ago when a hydrogen molecular cloud collapsed. Solar formation is dated in two ways: the Sun’s current main sequence age, determined using computer models of stellar evolution and nucleocosmochronology, is thought to be about 4.57 billion years. This is in close accord with the radiometric date of the oldest
Solar System material, at 4.567 billion years ago. The Sun is about halfway through its main-sequence evolution, during which nuclear fusion reactions in its core fuse hydrogen into helium. Each second, more than 4 million tons of matter are converted into energy within the Sun’s core, producing neutrinos and solar radiation; at this rate, the Sun will have so far converted around 100 Earth-masses of matter into energy. The Sun will spend a total of approximately 10 billion years as a main sequence star. The Sun does not have enough mass to explode as a supernova. Instead, in about 5 billion years, it will enter a red giant phase, its outer layers expanding as the hydrogen fuel in the core is consumed and the core contracts and heats up. Helium fusion will begin when the core temperature reaches around 100 million kelvins and will produce carbon, entering the asymptotic giant branch phase. Earth’s fate is precarious. As a red giant, the Sun will have a maximum radius beyond the Earth’s current orbit, 1 AU (1.5×10¹¹ m), 250 times the present radius of the Sun. However, by the time it is an asymptotic giant branch star, the Sun will have lost roughly 30% of its present mass due to a stellar wind, so the orbits of the planets will move outward. If it were only for this, Earth would probably be spared, but new research suggests that Earth will be swallowed by the Sun owing to tidal interactions.

Even if Earth would escape incineration in the Sun, still all its water will be boiled away and most of its atmosphere would escape into space. In fact, even during its current life in the main sequence, the Sun is gradually becoming more luminous (about 10% every 1 billion years), and its surface temperature is slowly rising. The Sun used to be fainter in the past, which is possibly the reason why life on Earth has only existed for about 1 billion years on land. The increase in solar temperatures is such that already in about a billion years, the surface of the Earth will become too hot for liquid water to exist, ending all terrestrial life. Following the red giant phase, intense thermal pulsations will cause the Sun to throw off its outer layers, forming a planetary nebula. The only object that will remain after the outer layers are ejected is the extremely hot stellar core, which will slowly cool and fade as a white dwarf over many billions of years. This stellar evolution scenario is typical of low- to medium-mass stars.

### 1.10 Sunlight

Sunlight is Earth’s primary source of energy. The solar constant is the amount of power that the Sun deposits per unit area that is directly exposed to sunlight. The solar constant is equal to approximately 1,368 W/m² (watts per square meter) at a distance of one astronomical unit (AU) from the Sun (that is, on or near Earth). Sunlight on the surface of Earth is attenuated by the Earth’s atmosphere so that less power arrives at the surface—closer to 1,000 W/m² in clear conditions when the Sun is near the zenith. Solar energy can be harnessed via a variety of natural and synthetic processes—photosynthesis by plants captures the energy of sunlight and converts it to chemical form (oxygen and reduced carbon compounds), while direct heating or electrical conversion by solar cells are used by solar power equipment to generate electricity or to do other useful work. The energy stored in petroleum and other fossil fuels was originally converted from sunlight by photosynthesis in the distant past.

### 1.11 Motion and location within the galaxy

The Sun’s motion about the centre of mass of the Solar System is complicated by perturbations from the planets. Every few hundred years this motion switches...
between prograde and retrograde. The Sun lies close to the inner rim of the Milky Way Galaxy’s Orion Arm, in the Local Fluff or the Gould Belt, at a hypothesized distance of 7.5–8.5 kpc (25,000–28,000 lightyears) from the Galactic Center, contained within the Local Bubble, a space of rarefied hot gas, possibly produced by the supernova remnant, Geminia. The distance between the local arm and the next arm out, the Perseus Arm, is about 6,500 light-years. The Sun, and thus the Solar System, is found in what scientists call the galactic habitable zone. The Apex of the Sun’s Way, or the solar apex, is the direction that the Sun travels through space in the Milky Way. The general direction of the Sun’s galactic motion is towards the star Vega near the constellation of Hercules, at an angle of roughly 60 sky degrees to the direction of the Galactic Center. If one were to observe it from Alpha Centauri, the closest star system, the Sun would appear to be in the constellation Cassiopeia. The Sun’s orbit around the Galaxy is expected to be roughly elliptical with the addition of perturbations due to the galactic spiral arms and non-uniform mass distributions. In addition the Sun oscillates up and down relative to the galactic plane approximately 2.7 times per orbit. This is very similar to how a simple harmonic oscillator works with no drag force (damping) term. It has been argued that the Sun’s passage through the higher density spiral arms often coincides with mass extinctions on Earth, perhaps due to increased impact events. It takes the Solar System about 225-250 million years to complete one orbit of the galaxy (a galactic year), so it is thought to have completed 20–25 orbits during the lifetime of the Sun. The orbital speed of the Solar System about the center of the Galaxy is approximately 251 km/s. At this speed, it takes around 1,400 years for the Solar System to travel a distance of 1 light-year, or 8 days to travel 1 AU.

1.1 Theoretical problems:

a) Solar neutrino problem: For many years the number of solar electron neutrinos detected on Earth was one third to one half of the number predicted by the standard solar model. This anomalous result was termed the solar neutrino problem. Theories proposed to resolve the problem either tried to reduce the temperature of the Sun’s interior to explain the lower neutrino flux, or posited that electron neutrinos could oscillate—that is, change into undetectable tau and muon neutrinos as they traveled between the Sun and the Earth. Several neutrino observatories were built in the 1980s to measure the solar neutrino flux as accurately as possible, including the Sudbury Neutrino Observatory and Kamiokande. Results from these observatories eventually led to the discovery that neutrinos have a very small rest mass and do indeed oscillate. Moreover, in 2001 the Sudbury Neutrino Observatory was able to detect all three types of neutrinos directly, and found that the Sun’s total neutrino emission rate agreed with the Standard Solar Model, although depending on the neutrino energy as few as one-third of the neutrinos seen at Earth are of the electron type. This proportion agrees with that predicted by the Mikheyev-Smirnov-Wolfenstein effect (also known as the matter effect), which describes neutrino oscillation in matter, and it is now considered a solved problem.

b) Coronal heating problem: The optical surface of the Sun (the photosphere) is known to have a temperature of approximately 6,000 K. Above it lies the solar corona, rising to a temperature of 1-2 million K. The high
It is thought that the energy necessary to heat the corona is provided by turbulent motion in the convection zone below the photosphere, and two main mechanisms have been proposed to explain coronal heating. The first is wave heating, in which sound, gravitational or magneto hydrodynamic waves are produced by turbulence in the convection zone. These waves travel upward and dissipate in the corona, depositing their energy in the ambient gas in the form of heat. The other is magnetic heating, in which magnetic energy is continuously built up by photospheric motion and released through magnetic reconnection in the form of large solar flares and myriad similar but smaller events—nanoflares. Currently, it is unclear whether waves are an efficient heating mechanism. All waves except Alfvén waves have been found to dissipate or refract before reaching the corona. In addition, Alfvén waves do not easily dissipate in the corona. Current research focus has therefore shifted towards flare heating mechanisms.

c) Faint young Sun problem: Theoretical models of the Sun’s development suggest that 3.8 to 2.5 billion years ago, during the Archean period, the Sun was only about 75% as bright as it is today. Such a weak star would not have been able to sustain liquid water on the Earth’s surface, and thus life should not have been able to develop. However, the geological record demonstrates that the Earth has remained at a fairly constant temperature throughout its history, and in fact that the young Earth was somewhat warmer than it is today. The consensus among scientists is that the young Earth’s atmosphere contained much larger quantities of greenhouse gases (such as carbon dioxide, methane and/or ammonia) than are present today, which trapped enough heat to compensate for the smaller amount of solar energy reaching the planet.

d) Present anomalies: The Sun is presently behaving unexpectedly in a number of ways. It is in the midst of an unusual sunspot minimum, lasting far longer and with a higher percentage of spotless days than normal; since May 2008, predictions of an imminent rise in activity have been regularly made and as regularly confuted. It is measurably dimming; its output has dropped 0.02% at visible wavelengths and 6% at EUV wavelengths in comparison with the levels at the last solar minimum. Over the last two decades, the solar wind’s speed has dropped 3%, its temperature 13%, and its density 20%. Its magnetic field is at less than half strength compared to the minimum of 22 years ago. The entire heliosphere, which fills the Solar System, has shrunk as a result, resulting in an increase in the level of cosmic radiation striking the Earth and its atmosphere.

e) History of observation: The Trundholm Sun chariot pulled by a horse is a sculpture believed to be illustrating an important part of Nordic Bronze Age mythology. Humanity’s most fundamental understanding of the Sun is as the luminous disk in the sky, whose presence above the horizon creates day and whose absence causes night. In many prehistoric and ancient cultures, the Sun was thought to be a solar deity or other supernatural phenomenon. Worship of the Sun was central to civilizations such as the Inca of South America and the Aztecs of what is now Mexico. Many ancient monuments were constructed with solar phenomena in mind; for example, stone megaliths accurately mark the
summer or winter solstice (some of the most prominent megaliths are located in Nabta Playa, Egypt, Mnajdra, Malta and at Stonehenge, England); Newgrange, a prehistoric human-built mount in Ireland, was designed to detect the winter solstice; the pyramid of El Castillo at Chichén Itzá in Mexico is designed to cast shadows in the shape of serpents climbing the pyramid at the vernal and autumn equinoxes. During the Roman era the Sun's birthday was a holiday celebrated as Sol Invictus (literally "unconquered sun") soon after the winter solstice which may have been an antecedent to Christmas. With respect to the fixed stars, the Sun appears from Earth to revolve once a year along the ecliptic through the zodiac, and so Greek astronomers considered it to be one of the seven planets (Greek planeteis, "wanderer"), after which the seven days of the week are named in some languages.\[119\][120][121]

f) Development of scientific understanding: One of the first people to offer a scientific or philosophical explanation for the Sun was the Greek philosopher Anaxagoras, who reasoned that it was a giant flaming ball of metal even larger than the Peloponnesus, and not the chariot of Helios.\[116\] For teaching this heresy, he was imprisoned by the authorities and sentenced to death, though he was later released through the intervention of Pericles. Eratosthenes estimated the distance between the Earth and the Sun in the 3rd century BCE as "of stadia myriads 400 and 80000", the translation of which is ambiguous, implying either 4,080,000 stadia (755,000 km) or 804,000,000 stadia (148-153 million km); the latter value is correct to within a few percent. In the 1st century CE, Ptolemy estimated the distance as 1,210 times the Earth radius.\[123\] Medieval Arabic contributions include Albatenius discovering that the direction of the Sun's eccentric is changing,\[124\] and Ibn Yunus observing more than 10,000 entries for the Sun's position for many years using a large astrolabe.\[125\] The theory that the Sun is the center around which the planets move was apparently proposed by the ancient Greek Aristarchus as well as several ancient Babylonian, ancient Indian and medieval Arab astronomers (see Heliocentrism). This view was revived in the 16th century by Nicolaus Copernicus. In the early 17th century, the invention of the telescope permitted detailed observations of sunspots by Thomas Harriot, Galileo Galilei and other astronomers. Galileo made some of the first known Western observations of sunspots and posited that they were on the surface of the Sun rather than small objects passing between the Earth and the Sun.\[126\] Sunspots were also observed since the Han dynasty and Chinese astronomers maintained records of these observations for centuries. In 1672 Giovanni Cassini and Jean Richer determined the distance to Mars and were thereby able to calculate the distance to the Sun. Isaac Newton observed the Sun's light using a prism, and showed that it was made up of light of many colors,\[127\] while in 1800 William Herschel discovered infrared radiation beyond the red part of the solar spectrum.\[128\] The 1800s saw spectroscopic studies of the Sun advance, and Joseph von Fraunhofer made the first observations of absorption lines in the spectrum, the strongest of which are still often referred to as Fraunhofer lines. When expanding the spectrum of light from the Sun, there are large number of missing colors can be found. In the early years of the modern scientific era, the source of the Sun's energy was a significant puzzle. Lord Kelvin suggested that the Sun was a gradually cooling liquid body that was radiating an internal store of heat.\[129\] Kelvin and Hermann von Helmholtz then proposed the Kelvin-Helmholtz mechanism to explain the energy output.
Unfortunately the resulting age estimate was only 20 million years, well short of the time span of at least 300 million years suggested by some geological discoveries of that time. In 1890 Joseph Lockyer, who discovered helium in the solar spectrum, proposed a meteoritic hypothesis for the formation and evolution of the Sun. Not until 1904 was a substantiated solution offered. Ernest Rutherford suggested that the Sun’s output could be maintained by an internal source of heat, and suggested radioactive decay as the source.

In 1890, Joseph Lockyer, who discovered helium in the solar spectrum, proposed a meteoritic hypothesis for the formation and evolution of the Sun. Not until 1904 was a substantiated solution offered. Ernest Rutherford suggested that the Sun’s output could be maintained by an internal source of heat, and suggested radioactive decay as the source.

However, it would be Albert Einstein who would provide the essential clue to the source of the Sun’s energy output with his mass-energy equivalence relation $E = mc^2$. In 1920, Sir Arthur Eddington proposed that the pressures and temperatures at the core of the Sun could produce a nuclear fusion reaction that merged hydrogen (protons) into helium nuclei, resulting in a production of energy from the net change in mass. The preponderance of hydrogen in the Sun was confirmed in 1925 by Cecilia Payne. The theoretical concept of fusion was developed in the 1930s by the astrophysicists Subrahmanyan Chandrasekhar and Hans Bethe. Hans Bethe calculated the details of the two main energy-producing nuclear reactions that power the Sun. Finally, a seminal paper was published in 1957 by Margaret Burbidge, entitled "Synthesis of the Elements in Stars". The paper demonstrated convincingly that most of the elements in the universe had been synthesized by nuclear reactions inside stars, some like our Sun.

### Solar space missions

The satellite is in an Earth-trailing orbit and is further from the Moon than the Earth is, the Moon appears smaller than the Sun. The first satellites designed to observe the Sun were NASA's Pioneers 5, 6, 7, 8 and 9, which were launched between 1959 and 1968. These probes orbited the Sun at a distance similar to that of the Earth, and made the first detailed measurements of the solar wind and the solar magnetic field. Pioneer 9 operated for a particularly long period of time, transmitting data until 1987. In the 1970s, two Helios spacecraft and the Skylab Apollo Telescope Mount provided scientists with significant new data on solar wind and the solar corona. The Helios 1 and 2 probes was a joint U.S.-German probe that studied the solar wind from an orbit carrying the spacecraft inside Mercury's orbit at perihelion. The Skylab space station, launched by NASA in 1973, included a solar observatory module called the Apollo Telescope Mount that was operated by astronauts resident on the station.

Skylab made the first time-resolved observations of the solar transition region and of ultraviolet emissions from the solar corona. Discoveries included the first observations of coronal mass ejections, then called "coronal transients", and of coronal holes, now known to be intimately associated with the solar wind. In 1980, the Solar Maximum Mission was launched by NASA. This spacecraft was designed to observe gamma rays, X-rays and UV radiation from solar flares during a time of high solar activity and solar luminosity. Just a few months after launch, however, an electronics failure caused the probe to go into standby mode, and it spent the next three years in this inactive state. In 1984 Space Shuttle Challenger mission STS-41C retrieved the satellite and repaired its electronics before re-releasing it into orbit. The Solar Maximum Mission subsequently acquired thousands of images of the solar corona before...
re-entering the Earth’s atmosphere in June 1989.\textsuperscript{[140]} Launched in 1991, Japan’s Yohkoh (Sunbeam) satellite observed solar flares at X-ray wavelengths. Mission data allowed scientists to identify several different types of flares, and also demonstrated that the corona away from regions of peak activity was much more dynamic and active than had previously been supposed. Yohkoh observed an entire solar cycle but went into standby mode when an annular eclipse in 2001 caused it to lose its lock on the Sun. It was destroyed by atmospheric reentry in 2005.\textsuperscript{[140]} One of the most important solar missions to date has been the Solar and Heliospheric Observatory, jointly built by the European Space Agency and NASA and launched on 2 December 1995.\textsuperscript{[141]} Originally intended to serve a two-year mission, SOHO is still in operation as of 2009. It has proven so useful that a follow-on mission, the Solar Dynamics Observatory, is planned for launch in November 2009. Situated at the Lagrangian point between the Earth and the Sun (at which the gravitational pull from both is equal), SOHO has provided a constant view of the Sun at many wavelengths since its launch.\textsuperscript{[141]} In addition to its direct solar observation, SOHO has enabled the discovery of large numbers of comets, mostly very tiny sungrazing comets which incinerate as they pass the Sun.\textsuperscript{[142]} All these satellites have observed the Sun from the plane of the ecliptic, and so have only observed its equatorial regions in detail. The Ulysses probe was launched in 1990 to study the Sun’s polar regions. It first traveled to Jupiter, to “slingshot” past the planet into an orbit which would take it far above the plane of the ecliptic. Serendipitously, it was well-placed to observe the collision of Comet Shoemaker-Levy 9 with Jupiter in 1994. Once Ulysses was in its scheduled orbit, it began observing the solar wind and magnetic field strength at high solar latitudes, finding that the solar wind from high latitudes was moving at about 750 km/s which was slower than expected, and that there were large magnetic waves emerging from high latitudes which scattered galactic cosmic rays.\textsuperscript{[143]} Elemental abundances in the photosphere are well known from spectroscopic studies, but the composition of the interior of the Sun is more poorly understood. A solar wind sample return mission, Genesis, was designed to allow astronomers to directly measure the composition of solar material. Genesis returned to Earth in 2004 but was damaged by a crash landing after its parachute failed to deploy on reentry into Earth’s atmosphere. Despite severe damage, some usable samples have been recovered from the spacecraft’s sample return module and are undergoing analysis.\textsuperscript{[141]} The Solar Terrestrial Relations Observatory (STEREO) mission was launched in October 2006. Two identical spacecraft were launched into orbits that cause them to (respectively) pull further ahead of and fall gradually behind the Earth. This enables stereoscopic imaging of the Sun and solar phenomena, such as coronal mass ejections.\textsuperscript{[144]}

**Observation and effect:** The Sun as it appears through a camera lens from the surface of Earth sunlight is very bright, and looking directly at the Sun with the naked eye for brief periods can be painful, but is not particularly hazardous for normal, non-dilated eyes.\textsuperscript{[141][145] Looking directly at the Sun causes phosphene visual artifacts and temporary partial blindness. It also delivers about 4 milli-watts of sunlight to the retina, slightly heating it and potentially causing damage in eyes that cannot respond properly to the brightness.\textsuperscript{[141][146]} UV exposure gradually yellows the lens of the eye over a period of years and is thought to contribute to the formation of cataracts, but this depends on general exposure to solar UV, not on whether one looks directly at
the Sun. Long-duration viewing of the direct Sun with the naked eye can begin to cause UV-induced, sunburn-like lesions on the retina after about 100 seconds, particularly under conditions where the UV light from the Sun is intense and well focused; conditions are worsened by young eyes or new lens implants (which admit more UV than aging natural eyes), Sun angles near the zenith, and observing locations at high altitude. Viewing the Sun through light-concentrating optics such as binoculars is very hazardous without an appropriate filter that blocks UV and substantially dims the sunlight. An attenuating (ND) filter might not filter UV and so is still dangerous. Attenuating filters to view the Sun should be specifically designed for that use: some improvised filters pass UV or IR rays that can harm the eye at high brightness levels. Unfiltered binoculars can deliver over 500 times as much energy to the retina as using the naked eye, killing retinal cells almost instantly (even though the power per unit area of image on the retina is the same; the heat cannot dissipate fast enough because the image is larger). Even brief glances at the midday Sun through unfiltered binoculars can cause permanent blindness. Partial solar eclipses are hazardous to view because the eye’s pupil is not adapted to the unusually high visual contrast: the pupil dilates according to the total amount of light in the field of view, not by the brightest object in the field. During partial eclipses most sunlight is blocked by the Moon passing in front of the Sun, but the uncovered parts of the photosphere have the same surface brightness as during a normal day. In the overall gloom, the pupil expands from ~2 mm to ~6 mm, and each retinal cell exposed to the solar image receives about ten times more light than it would looking at the non-eclipsed Sun. This can damage or kill those cells, resulting in small permanent blind spots for the viewer. The hazard is insidious for inexperienced observers and for children, because there is no perception of pain: it is not immediately obvious that one’s vision is being destroyed. During sunrise and sunset sunlight is attenuated due to Rayleigh scattering and Mie scattering from a particularly long passage through Earth’s atmosphere, and the Sun is sometimes faint enough to be viewed comfortably with the naked eye or safely with optics (provided there is no risk of bright sunlight suddenly appearing through a break between clouds). Hazy conditions, atmospheric dust, and high humidity contribute to this atmospheric attenuation. A rare optical phenomenon may occur shortly after sunset or before sunrise, known as a green flash. The flash is caused by light from the Sun just below the horizon being bent (usually through a temperature inversion) towards the observer. Light of shorter wavelengths (violet, blue, green) is bent more than that of longer wavelengths (yellow, orange, red) but the violet and blue light is scattered more, leaving light that is perceived as green. Ultraviolet light from the Sun has antiseptic properties and can be used to sanitize tools and water. It also causes sunburn, and has other medical effects such as the production of vitamin D. Ultraviolet light is strongly attenuated by Earth’s ozone layer, so that the amount of UV varies greatly with latitude and has been partially responsible for many biological adaptations, including variations in human skin color in different regions of the globe.

1.2 References:


18^ A Star with two North Poles, April 22, 2003, Science @ NASA


24^ Phillips, 1995, pp. 78-79


28^ Zirker, 2002, p. 11

29^ Phillips, 1995, p. 73


35^ Zirker, 2002, pp. 15-34


43^ ed. by Andrew M. Soward... (2005). "The solar tachocline: Formation, stability and its role in the solar dynamo". Fluid dynamics and dynamos in
astrophysics and geophysics reviews emerging from the Durham Symposium on
Astrophysical Fluid Mechanics, July 29 to August 8, 2002. Boca Raton: CRC


to Power the Solar Wind". Science 318 (5856): 1574-77.
doi:10.1126/science.1151747. PMID 18063784.
http://www.sciencemag.org/cgi/content/full/318/5856/1574.

doi:10.1126/science.263.5143.64.
http://www.sciencemag.org/cgi/content/abstract/263/5143/64.


Science 91 (5): 587-595. ISSN 0011-3891.

field: A tutorial". in Song, Paul; Singer, Howard J. and Siscoe, George L. (pdf).
Space Weather (Geophysical Monograph). American Geophysical Union. pp. 73-
ssc.igpp.ucla.edu/personnel/russell/papers/SolWindTutorial.pdf.


58. Zirker, 2002, pp. 119-120


66. Hansen, Kawaler & Trimble (2004, pp. 77-78)

Hansen, Kawaler & Trimble (2004, § 9.2.3)


Smith (1976 cited in Biemont 1978)


83. Zirker, 2002, pp. 7-8


92. "Construction of a Composite Total Solar Irradiance (TSI) Time Series from 1978 to present".

41


94 Phillips, 1995, pp. 319-321

95 Sun's retrograde motion and violation of even-odd cycle rule in sunspot activity, J. Javaraiah, 2005


104^ Leong, S. (2002). "Period of the Sun's Orbit around the Galaxy (Cosmic Year)." The Physics Factbook. 


http://adsabs.harvard.edu/abs/2004NJPh....6..121M.


110^ "Sudbury Neutrino Observatory First Scientific Results". 2001-07-03. 


115 Robert Zimmerman, "What's Wrong with Our Sun?", Sky and Telescope August 2009
116 http://science.nasa.gov/headlines/y2009/01apr_deepsolarminimum.htm

117 NASA, "The Sun's Sneaky Variability", October 27, 2009


151 Chou, B.R. (2005). "Eye Safety During Solar Eclipse". http://sunearth.gsfc.nasa.gov/eclipse/SEhelp/safety2.html. While environmental exposure to UV radiation is known to contribute to the accelerated aging of the outer layers of the eye and the development of cataracts, the concern over improper viewing of the Sun during an eclipse is for the development of "eclipse blindness" or retinal burns.


"Sol", Merriam-Webster online, accessed July 19, 2009


