100: THE SUN PART 1 – PRE-LAB READING

1. Structure of the Sun

From a combination of observations and theory, a picture of the interior structure, surface and atmosphere of the Sun has emerged (see Figure 1):

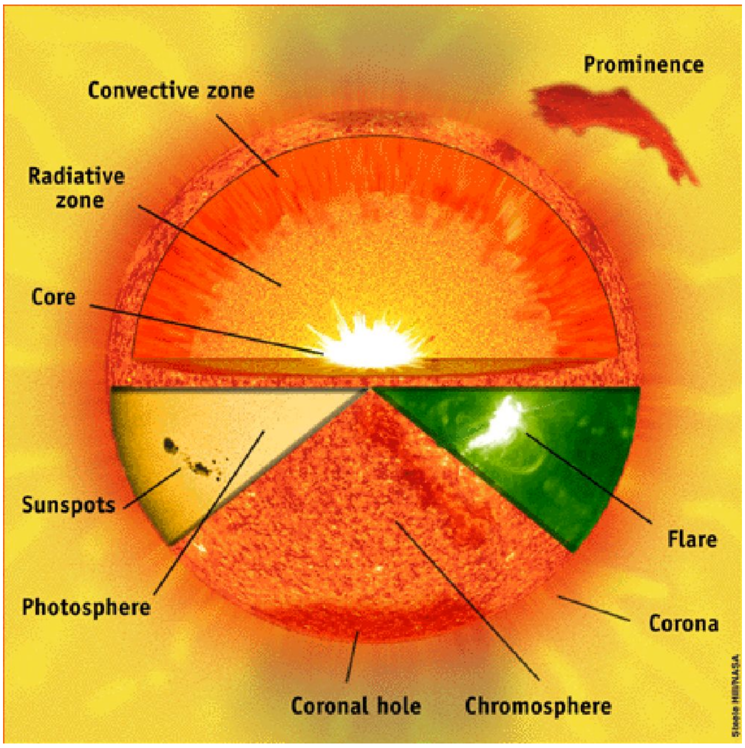

Figure 1. Image reproduced from *SOHO* website - http://sohowww.nascom.nasa.gov/

We can divide the Sun up into a number of distinct regions:

The Core: The power source for the Sun is the fusion of four protons to form helium (the proton-proton reaction). High temperatures, pressures and densities ($T \approx 15 \times 10^6$ K, $p \approx 10^9$ atm and $\rho \approx 160$ g cm^{-3}) are necessary for this reaction to proceed.

The Radiative Zone: Here energy from the core is transported predominantly in the form of photons and energetic particles ($T \approx 9 \times 10^6$ K, $\rho \approx 2 \times 10^{-2}$ g cm^{-3})

The Convection Zone: Energy is transported mostly by circulatory or convective motions of the gas ($T \approx 6 \times 10^5$ to 1×10^4 K, $\rho \approx 2 \times 10^{-2}$ to 1×10^{-7} g cm^{-3})

The Photosphere: Lies at the top of the convective layer. It is the source of most of the visible light from the Sun; effectively the surface of the Sun. Sunspots and granulation appear here. ($T \approx 5 \times 10^3$ K, $\rho \approx 5 \times 10^{-8}$ g cm^{-3})

The Chromosphere: Extends a few thousand km above the photosphere. Spicules, plages and filaments appear here. ($T \approx 5\text{-}6 \times 10^3$ K, $\rho \approx 5 \times 10^{-11}$ g cm^{-3})

The Corona: Tenuous outer atmosphere of the Sun. Very faint and very hot ($T \approx 1\text{-}2 \times 10^6$ K). Coronal loops and holes appear here.

The Solar wind: As a result of coronal heating, the Sun continuously blows off a low-density magnetized plasma (mostly electrons and protons) at speeds of ~400 km/s known as the **solar wind**. The corona is permeated by magnetic fields that in some regions form closed loops and in others open almost radially to space. The open magnetic field regions are cooler and appear darker than the closed ones; they are called **coronal holes**. These holes are the source of fast (~800 km/s) solar winds, which can reach the Earth in as little as 2 days.

2. Observed Phenomena

Some of the more prominent phenomena observable in the Sun's outer layers are:

Sunspots: A temporary disturbed area in the solar photosphere that appears dark because it is cooler than the surrounding areas. Sunspots consist of concentrations of strong magnetic flux. They usually occur at lower latitudes and in pairs or groups of opposite magnetic polarity that move in unison across the face of the Sun as it rotates.

Plages: Bright areas seen near sunspots in the chromosphere, particularly in Hα light.

Filaments: A structure in the corona consisting of cool plasma supported by magnetic fields. Filaments are dark structures when seen against the bright solar disk, but appear bright when seen over the solar limb. Filaments seen over the limb are also known as prominences.

Prominences: A structure in the corona consisting of cool plasma supported by magnetic fields. Prominences are bright structures when seen over the solar limb, but appear dark when seen against the bright solar disk. Prominences seen on the disk are also known as filaments.

Coronal Holes: An area of the corona which appears dark in X-rays and ultraviolet light. The magnetic field lines in a coronal hole extend out into the solar wind rather than coming back down to the Sun's surface as they do in other parts of the Sun.

Coronal Mass Ejections: A huge magnetic bubble of plasma that erupts from the Sun's corona and travels through interplanetary space at high speed.

Flares: Rapid release of energy from a localized region on the Sun in the form of electromagnetic radiation, energetic particles, and mass motions. They are thought to arise when individual magnetic field lines reconnect.

3. Probing the structure of the Sun at different wavelengths

Imaging of the solar disk through narrowband filters allows the Sun to be studied in the light of particular spectral lines. Some lines may be more prominent in particular layers of the Sun's atmosphere and hence let us examine that layer. For example, Hα, a strong absorption line of neutral Hydrogen at 6563 Å, is formed between 1200 and 1800 km above the visible surface of the Sun. It emits in chromospheric regions that are being heated, generally due to the presence of interacting magnetic fields. It also shows many dark filamentary structures on the solar disk, which correspond to magnetic loops reaching up into the solar corona. These features tend to be cooler than the surrounding corona and permit Hα absorption to take place, thus their darker appearance.

In general, the hotter layers of the Sun can be linked to emission from higher excitation lines or higher ionisation states. For example, coronal temperatures of some 10^6 K correspond to X rays given off by ionised coronal gas. In contrast, the photosphere at ~5800 K appears dark at X-ray wavelengths, but bright at visible wavelengths. Polarisation measurements can be related back to the Zeeman splitting of spectral lines to map magnetic field strength.

4. *Limb Darkening*

The brightness of the solar disk decreases towards the edge; this is called **limb darkening**. It is due to the fact that we see deeper, hotter layers looking directly at the centre of the solar disk and higher, cooler layers looking near the edge or limb, assuming that we can only see a fixed distance *d* through the solar atmosphere.

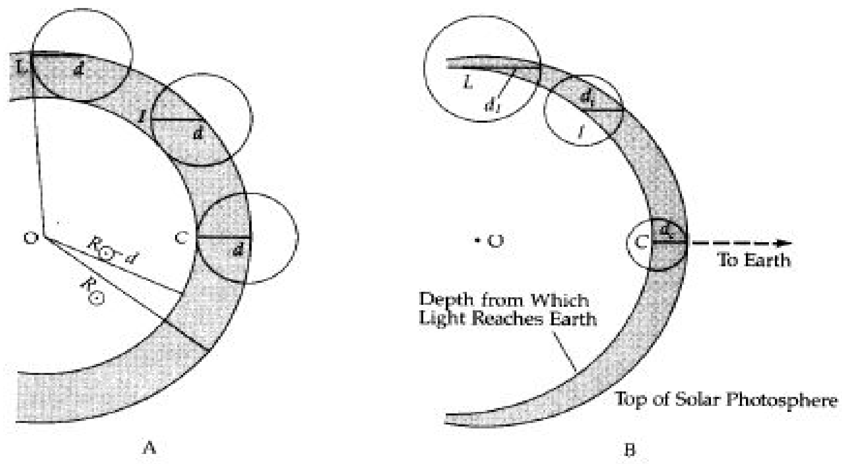

Figure 2. Image reproduced from Zeilik & Gregory, *Introductory Astronomy & Astrophysics*

In Figure 2B above, each circle corresponds to the same optical depth, while in Figure 2A each circle corresponds to the same distance through the atmosphere. In reality, we can only see into the solar atmosphere to the depth from which a photon can escape unhindered. Below that the photons are continuously absorbed and re-emitted by atoms and ions. Astronomers usually define this absorption in terms of the **optical depth**, τ_λ, which is a function of the opacity of the solar atmosphere. The chromosphere, for example, has a very low optical depth, so most radiation from the photosphere below passes right through it.

5. Sunspots and solar activity

Sunspots occur in the photosphere and appear as darker regions. A lighter region with radial filamentary structure (penumbra) usually surrounds the darkest, central region (umbra). The parts of a sunspot are all transient magnetic structures. They are basically bundles of magnetic field lines filling the region and fanning out above it. A given sunspot has an associated magnetic polarity, so we usually find two sunspots of complementary polarity. Counts of sunspot numbers reveal an 11-year cycle during which sunspots move from high latitudes to low latitudes, but individual lifetimes only range from a few days to a few months. Sunspot polarity reverses each cycle, so in reality we should speak of a 22-year cycle. The general trend in sunspot numbers is shown in Figure 3, along with a "butterfly diagram" illustrating the changing latitudes of sunspots over a cycle.

Increasing sunspot number corresponds to increasing solar activity. Accompanying each sunspot group is a large active region, called a Bipolar Magnetic Region (BMR), where the magnetic activity is concentrated. These magnetic fields produce regions of enhanced density and temperature in the chromosphere above, called plages, as well as streamers and large ejections of mass in the corona. Other markers of active regions are long dark filaments or prominences sometimes looping back to the surface and lasting from hours to weeks.

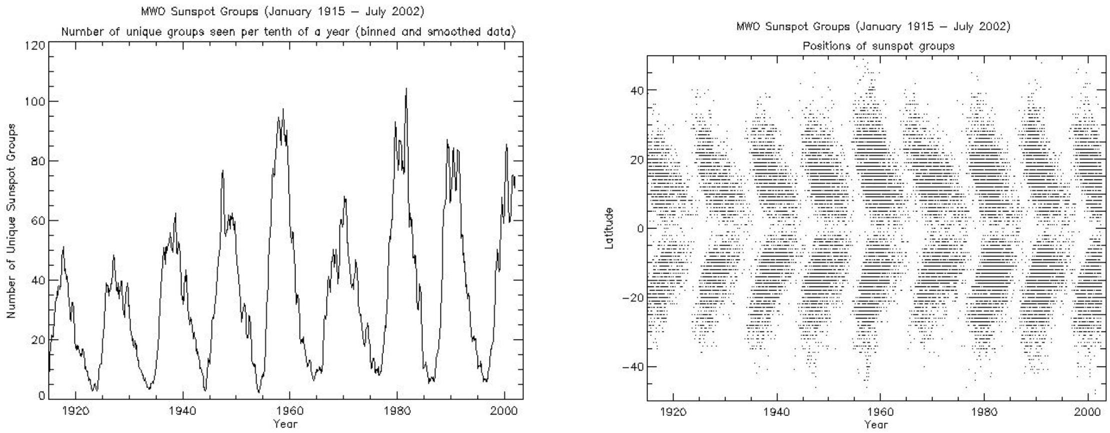

Figure 3. Images reproduced from Mt Wilson Solar Observatory website; http://www.astro.ucla.edu/~obs/150_data.html#spotplots

6. Differential rotation and the Solar Dynamo

The Sun has a north and south pole, just like the Earth, and rotates on its axis. However, unlike the Earth, which rotates rigidly at all latitudes every 23 hours and 56 minutes, the Sun rotates every 25 days at the equator and takes progressively longer to rotate at higher latitudes, up to 38 days at the poles. This is known as **differential rotation** and arises because the Sun is a sphere of gas, not a solid body.

7. Coronal Mass Ejections

A coronal mass ejection (CME) occurs when a significant amount of relatively cool, dense, ionized gas escapes from the normally closed, confining, low-level magnetic fields of the Sun's atmosphere to streak out into interplanetary space. In other words, a large quantity of mass is accelerated by the magnetic field of the corona and travels through space, sometimes towards the Earth. Eruptions of this sort can produce major disruptions in the near-Earth environment, affecting communications, navigation systems and even power grids. We do not yet really understand why CMEs occur and how to predict them. One important aspect of current research is to measure the velocity of CMEs and their acceleration as they leave the Sun. This is done by tracing features in the CME and measuring their positions as a function of time.

One of the main ways we observe CMEs is with **coronagraphs**; telescopes which simulate total solar eclipses by blocking out the disk of the Sun so we can see its fainter outer atmosphere, the corona. Coronagraphs can also be used to block out the central light of more distant stars to reveal close-in orbiting exoplanets and dusty circumstellar disks.

8. Data sources - the SOHO satellite

Overview

Today, one of the primary sources of solar observations is the *SOHO* satellite. A satellite is the easiest way to obtain high spatial resolution observations of the Sun, free of distortions from the Earth's atmosphere and, more importantly, diurnal data gaps. A joint NASA/ESA mission, the *SOHO* (*Solar and Heliospheric Observatory*) spacecraft was launched in December 1995 from the Kennedy Space Center. It is designed to study the internal structure of the Sun, its extensive outer atmosphere and the origin of the solar wind. *SOHO* has helped solar physicists understand some of the most perplexing riddles about the Sun, including the heating of the solar corona, the acceleration of the solar wind, and the physical conditions of the solar interior. It has given us the first long term, uninterrupted view of the Sun.

A total of 11 instruments were included on the spacecraft. Brief descriptions of some of the primary instruments are included below. The remainder are described on the *SOHO* home page (http://sohowww.nascom.nasa.gov/).

Instruments

EIT (Extreme Ultraviolet Imaging telescope): The *SOHO* EIT is able to image the solar transition region and inner corona in four, selected bandpasses in the extreme ultraviolet (EUV); Fe IX/X, 171 Å, Fe XII, 195 Å, Fe XV, 284 Å and He II, 304 Å. Using either full-disk or subfield images, the EIT can image active regions, filaments and prominences, coronal holes, coronal "bright points," polar plumes, and a variety of other solar features. The instrument was designed to be used in conjunction with other *SOHO* instruments, as well as with ground-based instruments.

MDI (Michelson Doppler Imager): The *SOHO* MDI is designed to study the interior structure and dynamics of the Sun using the tools of helioseismology. The MDI Observables are (a) Spectral Intensity in the Ni I photospheric absorption line at 6767.8 Å, (b) Line Depth in the Ni-I absorption line, (c) Continuum Intensity near the Ni-I absorption line, (d) Doppler Shift (Velocity), and (e) Zeeman Splitting.

LASCO (Large Angle and Spectrometric COronagraph): The LASCO instrument is a set of three coronagraphs that image the solar corona from 1.1 to 32 solar radii. One solar radius is about 700,000 km or 16 arc minutes. A coronagraph is a telescope that is designed to block light coming from the solar disk, in order to see the extremely faint emission from the region around the sun, called the corona. The essential questions of solar physics addressed by LASCO are: How is the corona heated? Where and how is the solar wind accelerated? What causes coronal transients, and what role do they play in the evolutionary development of large-scale coronal patterns?

9. Other Data Sources

Frequent, multi-wavelength solar images are available from ground-based and satellite observatories all over the world. See, for example https://umbra.nascom.nasa.gov/images/ , https://solarmonitor.org and https://www.sws.bom.gov.au/Solar/3/3/1 (Space Weather Service).