PHY2003 ASTROPHYSICS I

Lecture 5. The Sun

The Sun is a yellow dwarf star located at the center of the Solar System. The Sun is the nearest star to Earth, and controls the dynamics of the Solar System through its gravity. It is also the largest source of thermal energy within the Solar System, heating the Earth's atmosphere to a temperature conducive to life and liquid water on Earth's surface.

The Sun

Differential rotation, mean period 27 days.

Mean Distance of Sun $d = 1.4985 \times 10^8$km.

($\equiv 1$ Astronomical Unit (au))

Radius of Sun $R_\odot = 6.95 \times 10^5$km

Mass of Sun $M_\odot = 1.99 \times 10^{30}$kg

Mean Density of Sun $\overline{\rho_\odot} = 1400$kg/m^3

Total EM flux measured at the earth $F_\odot = 1368$ J/s/m^2

Therefore the total luminosity of the Sun is

$$L_\odot = 4\pi\Delta^2 F_\odot = 3.8 \times 10^{26}\ \mathrm{J/s}$$

Energy emitted per unit area per second

$$= \frac{L_\odot}{4\pi R_\odot^2} = 6.3 \times 10^7\ \mathrm{J/s/m^2}$$

Surface temperature is therefore

$$T_\odot = \left(\frac{E}{\sigma}\right)^{1/4} = 5770\,\mathrm{K}$$

Spectra of the Sun show many numerous absorption lines caused by gases in its outermost layers. Detailed modelling shows a composition of $\sim 75\%$ H and $\sim 25\%$ He by mass.

Internal Structure of the Sun

For all Main Sequence stars, including the Sun, the temperature and density in their cores are so great that Hydrogen atoms combine to make Helium atoms and release energy, a process known as thermonuclear fusion. The Sun is hydrostatic equilibrium with nuclear fusion of hydrogen is producing enough outward pressure to balance gravitational collapse.

The Sun's interior has three layers. Moving from the center outwards they are the:

1. **Core** - $0 \leq r \leq 0.25R_\odot$ - Where nuclear fusion occurs. Energy is produced by hydrogen atoms (H) being converted into nuclei of helium (He).
2. **Radiative zone** - $0.25 \leq r \leq 0.7R_\odot$ - Region in which most energy is transported through radiation. Ions of hydrogen and helium emitting photons that travel a short distance before being reabsorbed by other ions. Photons follow a random-walk through scattering by ions.
3. **Convective zone**- $0.7 \leq r \leq 1.0R_\odot$ - Region in which most energy is transported through convection. Top of the convective zone is the photosphere

The Photosphere and Beyond

The parts of the Sun directly visible form Earth can be split into three regions, denoted by their height, temperature and density.

The Photosphere

The Sun is entirely gaseous, with a density decreasing as one travels outwards from the core. The apparent surface at visual wavelengths is called the Photosphere, and is simply the radius where the plasma becomes rarified enough that photons do not suffer collisions with ions. This means that they can then travel in straight lines and reach us undeflected. The Photosphere is $\sim$100 km deep and is the visible layer of the Sun/the Sun's visible surface . It is the top of the convective zone.

Sunspots are large, dark areas in the photosphere. Darkness is a contrast effect - Sunspots are 1000K–2000K cooler than surrounding surface. They last from a couple of days to several weeks, but are continuously evolving.

Spectra show Zeeman splitting of lines, implying intense magnetic fields breaking the Solar surface. Generally come in pairs, with opposite alignment of magnetic fields. Loops of magnetic field lie between them.

The position and number of sunspots varies on an 11-year Solar cycle. Every 11-years the number of Sunspots reaches a maximum. 5.5 years later there are hardly any.

At Solar maximum, spots are concentrated at mid-latitudes. As the the numbers die away, they move towards the equator. After Solar minimum, they are near the poles, and the polarity is reversed!

Faculae are small bright areas. These contain intense magnetic fields, concentrated in smaller areas than sunspots. At Solar maximum, faculae out number spots, and make Sun 0.1% brighter than average.

Granulation is the name for cellular features about ~ 1000 km across, covering the Photosphere. They normally exist for ~ 20 minutes.

Granules are the tops of convection cells in the atmosphere. Flow within granules can reach supersonic speeds, generating sound shockwaves (important later).

Flares are large explosions on the surface of the Sun. They normally last a few minutes, but heat the surrounding plasma up to several million K.

The energy released is $\sim 10^{20}$ J/s, with the largest flares emitting $\sim 10^{25}$ J in total.

Flares often occur near sunspots, and are somehow caused by the sudden release of stored magnetic energy.

The Chromosphere

This is the layer a few thousand km above photosphere, optically visible by Hα ($n = 3 \rightarrow 2$) emission. Due to its low density, 10^{-4} times that of the photosphere,it is relatively transparent, resulting in the photosphere being regarded as the visual surface of the Sun. The chromosphere is visible by eye as thin red band around Moon during a Total Solar Eclipse, or with a telescope that isolates the Hα emission.

The chromosphere is a few thousand K hotter than photosphere. It is filled with spicules - thin jets of plasma 500km diameter and 5000km long, extending from the photosphere upwards. The chromosphere may play a role in conducting heat from the interior of the sun to its outermost layer, the corona.

The chromosphere is shaped by the magnetic field lines emerging from the photosphere that shepherd the electrically charged solar plasma. **Prominences** are plasma-filled magnetic field structures, often in loop form.They extend from the photosphere through the chromosphere.

The Corona

Outermost atmosphere of the Sun, observed during Solar Eclipses or from spacecraft. It appears as white halo of small plumes/jets of ionized gas that flow outward from the Sun.

Temperatures of $> 10^6$ K are present within the corona. Why the corona is up to 300 times hotter than the photosphere is an active area of research. The corona is furthest from the Sun's core, and thus it would be expected that the temperate would decrease as you move further from the heat source. This is referred to as the Solar Corona Heating Problem and has remained unsolved for over 30 years. Somehow there must be a transport of energy from the photosphere to the corona. Magnetic fields may play a role. Two leading theories: **nanoflares** (tiny explosions in the photosphere ranging from a billion to a million times smaller than a regular solar flare. It is proposed that nanoflares may erupt thousands of times every second releasing energy into the chromosphere and corona) or via **plasma waves** (Alfvén waves or electromagnetic-hydrodynamic waves) may be the source of extra heating in the corona.

Coronal Streamers is the name given to the outward-flowing plasma fro the corona shaped by Sun's magnetic field lines into tapered forms/jets which extend millions of miles into space.

Coronal mass ejections (CMEs) are a large clouds of plasma and magnetic fields expelled outwards from the corona through the Solar System, interacting with any spacecraft, planets, and planetesimals in its path. CMEs travel outward from the Sun at speeds about $\sim$250 km/s to $\sim$3000 km/s. CMEs can reach the Earth 15-18 hours, producing dramatic aurorae. CMEs often occur after the sudden release of energy from solar flare outbursts, but CMEs can occur as isolated events without previous solar flares.

The corona contains particles and magnetic fields carried continuously outwards from the Sun, called the **Solar Wind**. The solar wind transports a million tons of matter from the Sun into space every second. The average wind speed at the Earth is ~ 500 km/sec. The average particle density at the Earth is roughly $n_e = n_p = 5$ cm^{-3}.Particles leak through the poles of the Earth's magnetic field to create the aurora.