Sunspots - Basic Physics

The basic origin of a sunspot is as follows:

- The photospheric gas is quite highly ionised
- Forms a plasma - +ve ions and -ve electrons free to move and can be deflected by a magnetic field.
- Magnetic field acting on hot plasma rising in a convection cell deflects it producing a local region of cool gas - a sunspot.

A sunspot group resembles a giant bar magnet, with a north pole at one end and a south pole at the other.

Observations of the properties of many groups shows they are all correlated...

Observations at any given instant show that in the northern hemisphere of the Sun that the magnetic fields in all groups of sunspots are aligned.

This is in the sense that the leading or *preceding* members all have the same polarity (N *or* S), while the trailing or *following* members have the opposite polarity.

This behaviour is seen in reverse in the Southern hemisphere of the Sun.

In both cases the polarity follows that of the Sun as a whole (i.e. North pole in the North hemisphere leads to the preceding members of a sunspot group having North poles).

Observations show that the polarity of the Sun flips every 11 years (so unlike the Earth, which is far more stable).

Babcock's Magnetic-Dynamo Model

So how do we understand the full **22 year** solar cycle?

The best idea was proposed by Babcock in 1960.

The combination of convection and differential rotation causes the initial simple magnetic field of the Sun to become distorted.

Differential rotation causes the magnetic field to become concentrated at certain latitudes as it is 'frozen' into the motions of the photosphere.

Convection then creates tangles and kinks in the field which erupt through the surface as sunspots.

Differential rotation eventually undoes the 'damage'. Preceding members migrate to the equator where they cancel out, while following members congregate at the poles where they act to reverse the polarity of the Sun.

More on the Magnetic Field

As plasma is pushed to the sides of (super) granules the motion of charged particles also generates a magnetic field - it is this that powers spicules.

The magnetic field of the Sun is thought to extend to a relatively thin boundary layer between the convective and radiative zones, and is found to extend 10,000's km into the Corona.

Magnetic fields in the Corona form huge arch like structures which channel plasma from the surface of the Sun. These structures can interact and when they do they sometimes 'short circuit'.

In doing so they release huge amounts of energy which acts to heat the Corona.

Magnetic fields account for many other surface/Coronal phenomena:

Plages: Bright, hot regions of the Chromosphere, which are found to occur just before new sunspots appear. They are thought to form due to upwelling magnetic fields compressing and heating gas above them in the Chromosphere.

Dark streaks called **Filaments**, which are cool dense regions of the photosphere where material is raised to higher altitudes by magnetic fields.

They appear dark against the surface of the Sun but against the background of space they appear as bright **Prominences**.
These extend for 10,000s km above the photosphere and may last for hours to months.

Flares and CME's

Finally, magnetic fields likely play an important role in generating **Solar Flares**, which tend to orginate in complex sunspot groups.
In a few mins gas temps. can rise to 5×10^6K and vast quantities of radiation and particles are ejected into space. The energy released (10^{30}J) is equivalent to that released by a 100 million million one megaton bombs...
This is dwarfed by **Coronal Mass Ejections**, in which $\sim 10^{12}$kg of material may be ejected with velocities of 100s km/s. These appear to be associated with large scale restructuring of the Sun's magnetic field and can occur every few months.
The Sun therefore appears to be a rather active ball of gas, when observed across the EM spectrum.

The Solar Interior

So far we have constructed theoretical models for the interior of the Sun and have observed the outer layers, but can we observe the interior *directly*?
The answer is yes - by **Helioseismology** and observing the *Neutrino flux.*
Helioseismology works by listening to the way the Sun wobbles.
In 1960, Robert Leighton discovered that part of the Sun's surface oscillates up and down 10m every 5 min.
Other periods were subsequently found, with periods between 20-160mins.
These pulsations are exactly analagous to sound waves and seismic waves in the Earth's interior generated by earthquakes.
In the same way that geologists use seismic waves to study the structure of the Earth, so we may probe the Sun's interior by the way it vibrates.
This is because changes in the internal properties of the Sun such as density affect the way these 'sound waves' propagate.
This has enabled us to refine estimates of the quantity of He present in the Solar Core and convective zone, as well as determining the thickness of the transitional zone between the radiative and convective zones (where the magnetic field is thought to form).

Solar Neutrinos

Remember our discussion of the p-p chain? One of the by-products of the fusion of H→He was the production of *neutrinos* - ghostly particles with almost no mass that interact *very* weakly with matter.
Each second the Sun produces 10^{38} neutrinos, which escape from the Sun without undergoing the random walk of the photons. Consequently, if we could detect these particles, we would directly probe the conditions in the Sun's core.
Despite the fact we might expect 10^{14} neutrinos per second to pass though every square metre of the Earth, it's still *very difficult* to detect *any.*
One possible detection process is
neutrino+neutron→proton+electron
The Davis experiment in the 1960s used a huge tank of C_2Cl_4 and this reaction to detect neutrinos.

Every now and again a neutrino will react with a neutron in the ^{37}Cl atoms, producing a proton and hence a radioactive atom of Argon (^{37}Ar).
The rate of production of ^{37}Ar is therefore proportional to the flux of neutrinos - by measuring one we may infer the other.
Big problem: The flux of solar neutrinos was only 1/3rd of that expected from theory... the *Solar Neutrino Problem.*

The Solar Neutrino Problem

How do we resolve this?

- The Solar model is wrong. The rate of production of neutrinos is sensitive to the internal conditions of the Sun. If the core temp was 10% lower the problem would disappear - however the Sun's size and surface temp would then differ from that observed.
- Neutrinos 'oscillate'. Neutrinos come in 3 flavours, and the Davis experiment is only sensitive to one flavour. If neutrinos can change flavour (i.e. oscillate) from a detectable to non-detectable type between the Sun and Earth the problem would be solved.

Newer experiments such as Super-Kamiokande & Sudbury Neutrino Observatory suggest that the latter may be the correct explanation.

Part II: The Stars

Much of our detailed knowledge about the Sun is due to its proximity - and hence our ability to resolve and study surface features.
Until the last few years the Sun has been the only star for which this is possible - although the recent development of new observational techniques such as IR interferometry now permits us to resolve a small subset of nearby stars.
Nevertheless, despite the apparently limited information we have on the vast majority of stars, we may still determine a number of their fundamental parameters.

Part II: Basic stellar properties

Some of the fundamental parameters and properties of stars are:
(1) Distance
(2) Luminosity
(3) Surface (or effective) temperature
(4) Internal structure and rotation
(5) Mass
(6) Chemical composition
(7) Nuclear energy sources
(8) Evolutionary state and history
(9) Mode of formation
(10) Final fate
Of these we have already encountered 1-3 last term, while the internal structure and its dependance on rotation is largely beyond the scope of this course (and only dramatically affects massive stars).
Hence, for the remainder of the course we will concern ourselves with the remaining 6 properties.

Part II: Stellar Masses

Determining the masses of stars is difficult, since it requires the observation of binary systems (See term 1 for details).
Despite the difficulty of this process over the years it has been possible to build up a dataset on the masses of stars of a given luminosity and temperature.
This data has shown a strong **Mass Luminosity Relationship** to exist for most types of star.
Roughly, for H burning stars this relationship is

$$L \propto M^3$$

i.e if you increase the mass of a star by a factor of 10, its luminosity increases by a factor of 1000.
Since we known that for H burning stars there is also a relationship between luminosity and temperature it also follows that there must be a relationship between masss and temperature (e.g. Fig. 19-22 & 19-23).
Note that if you examine the Mass-Luminoisty relationship closely, it's really only complete for stars up to about $20\,\mathrm{M}_\odot$ - why is this?

- The rarity of massive stars
- The problems of observing them through significant quantities of interstellar dust and gas
- The intrinsic difficulty of the observations.

At large distances it is very unlikely that we could detect the motion of a visual binary.
Also, if a star is very massive it needs a binary companion that is massive and/or very close for its orbital motion to be spectroscopically detectable.

The H-R Diagram

Stars that lie on the Main Sequence are called Main Sequence stars and are found to make up 90% of the stars in the sky.
Local examples include the Sun, Vega and Barnard's star...
Some (less numerous) appear to be overluminous for their temperature, when compared to the Main Sequence. These can be:

(a) Red Giants (Arcturus, Aldebaran)
(b) Red Supergiants (Betelgeuse, Antares)
(c) Blue Supergiants (Rigel, Deneb)

About 1% of the stars in the sky are Red giants or supergiants.
The various 'boxes of stars' contain stars of the same effective temperature but which have very different radii...(Fig 19-15).

(i) Red Giants have $\mathrm{R}_* = 10R_\odot$
(ii) Red Supergiants have $\mathrm{R}_* = 100 - 1000R_\odot$
(iii) Blue Supergiants have $\mathrm{R}_* = 50 - 100R_\odot$
(iv) White Dwarfs have $\mathrm{R}_* = 0.01R_\odot$

We can thus identify a sequence of luminosity classes, and these are denoted with Roman Numerals:
Main Sequence is denoted by V-IV (IV=subgiants)
Giants by III-II
Supergiants Ib-Ia
where in each case we move from less luminous to more luminous stars (fig. 19-17).
Thus a star might finally be classified in detail as a G2V star (e.g. the Sun) or K5 III (e.g. Aldebaran; a Red Giant L$\sim 370L_\odot$, T$\sim$4000K) or B7V (Regulus L$\sim 140L_\odot$, T$\sim$12000K)
Note that the H-R diagram can also be used to estimate the distance to a star. Once we assign a spectral type we can locate the star on the H-R diagram and estimate its luminosity. From its apparent brightness and our luminosity estimate we may also estimate its distance.

(Note that we may determine the luminosity class from subtle differences in the shape of absorption lines).
This method is called **Spectroscopic parallax** and distances to most stars are measured in this manner, to an accuracy of ∼10%.