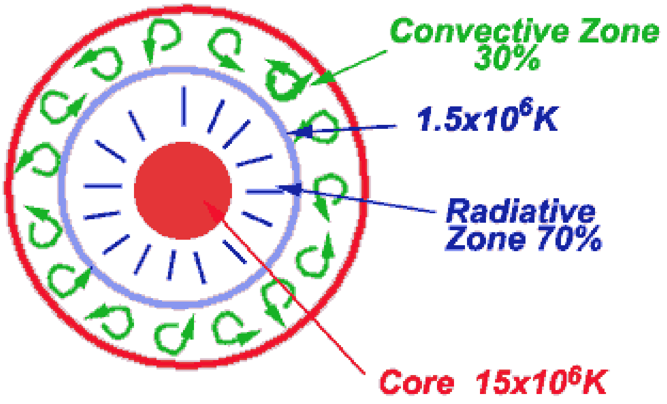
1. Basic Structure of the Sun

For this course we only look at the basic structure of the Sun (there are other courses at UCL dealing with Solar Physics) in order to understand where the solar wind comes from. You can get further information on the Web. Details of NASA's "Roadmap" for research into Sun-Earth connections, for example, can be found on this link.

The Sun is a "standard" G2 type star, unremarkable in most senses. It is largely gaseous, though the gases composing it are mostly at immense pressure and temperature. It does not rotate as a solid body, though the inner and outer parts are "coupled" by convective and radiative transfer. The main parts of the Sun's structure are:

- The core, where fusion occurs of Hydrogen to form Helium - temperature around 15 10^6K
- Radiation zone - out to about 70% of the Sun's radius. The temperature falls with radius down to c. 1.5 10^6K
- Convection zone - as the atmosphere becomes more opaque it cannot sustain the intensity of radiation needed to transfer the heat so the large temperature gradient has to be maintained by convection from radiative zone to photosphere
- Photosphere - the "visible" surface of the sun c 6000K
- Chromosphere - above the photosphere, the temperatsphere, the temperature drops away from the surface to c 4500K and then rises to 8500K. Because it is initially cooler that the photosphere below it, it is marked by the presence of absorption lines in the solar spectrum - particularly the main transitions in the Hydrogen atom like the Lyman and Balmer lines. Noted particularly for H-alpha at 656.3nm
- Corona - from a process still not completely understood, the "atmosphere" above the chromosphere is heated to temperatures around 10^6K - this region is the corona. The chemical composition of the upper solar atmosphere is variable and different from that of the surface layers of the Sun.
- Magnetic field - the sun's magnetic field is generated by dynamo action, though the details are still not entirely understood.



The sun is believed to be made up of the following proportions of elements:

- 92.1% H
- 7.8%He
- 0.061% O
- 0.030% C
- 0.0084% N
- 0.0076% Ne
- 0.0037% Fe
- 0.0031% Si
- 0.0024% Mg
- 0.0015% S
- 0.0015% All Others

The sun gets its energy from the conversion of Hydrogen to Helium. This take s place via two main pathways, one of them catalysed by an intermediate product:

Reactive pathway 1:: The proton-proton chain

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p  + p  -->  $^{2}$H + e$^{+}$ + (e-)neutrino
 $^{2}$H + p --> $^{3}$He + gamma-ray
 $^{3}$He + gamma-ray
 $^{3}$He + $^{3}$He --> $^{4}$He + 2p + gamma-ray
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Reactive pathway 2:: Carbon cycle

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     $^{12}$C + p --> $^{13}$N
         ^
         |
     ----  $^{13}$N --> $^{13}$C + e$^{+}$ + e-neutrino
     | $^{13}$C + p --> $^{14}$N
======>$^{14}$N + p --> $^{15}$O
||   |     $^{15}$O --> $^{15}$N + e$^{+}$ + e-neutrino
||   | $^{15}$N + p --> $^{12}$C + $^{4}$He
||   |               |
||   ---------------
||     $^{15}$N + p --> $^{16}$O
||     $^{16}$O + p --> $^{17}$F
||         $^{17}$F --> $^{17}$O + e$^{+}$ + e-neutrino
||     $^{17}$O + p --> $^{14}$N + $^{4}$He
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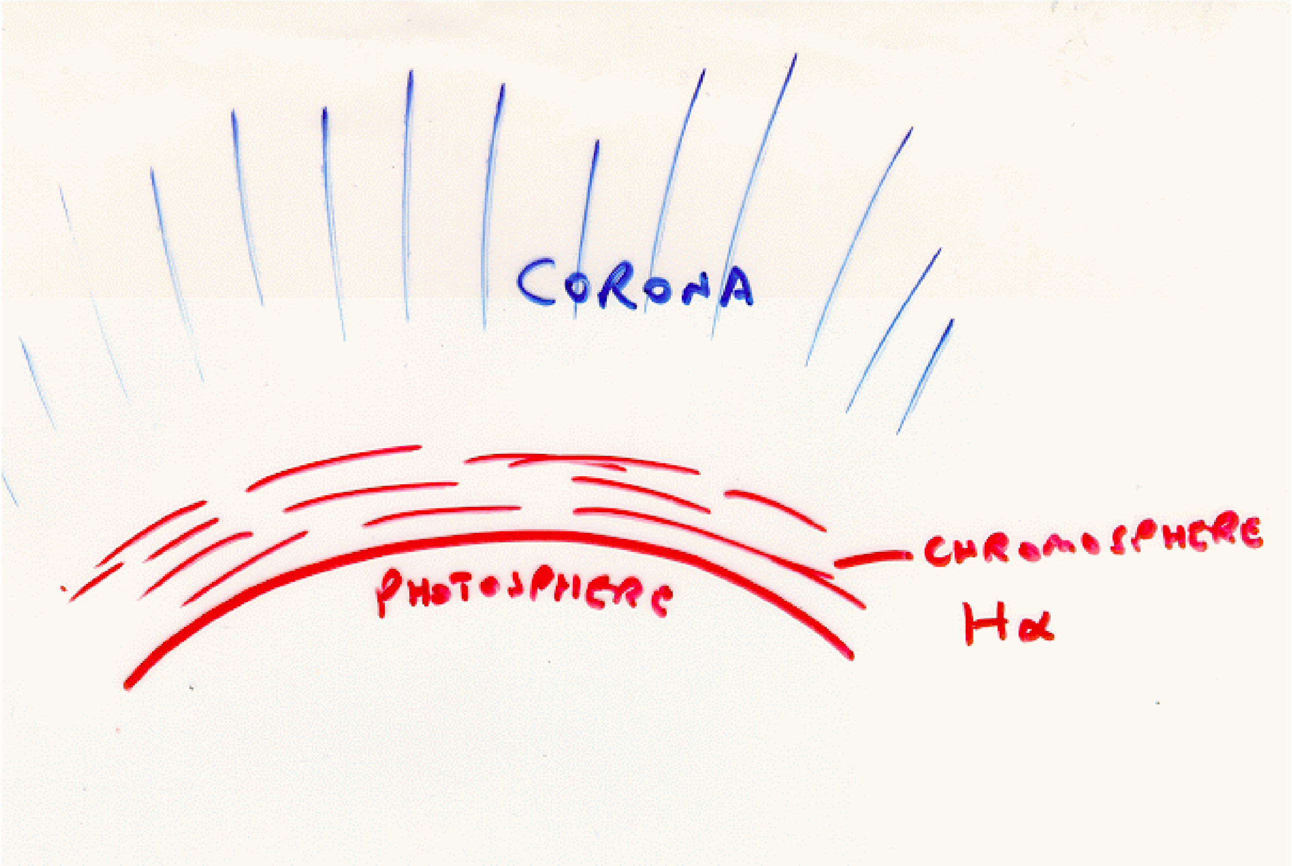
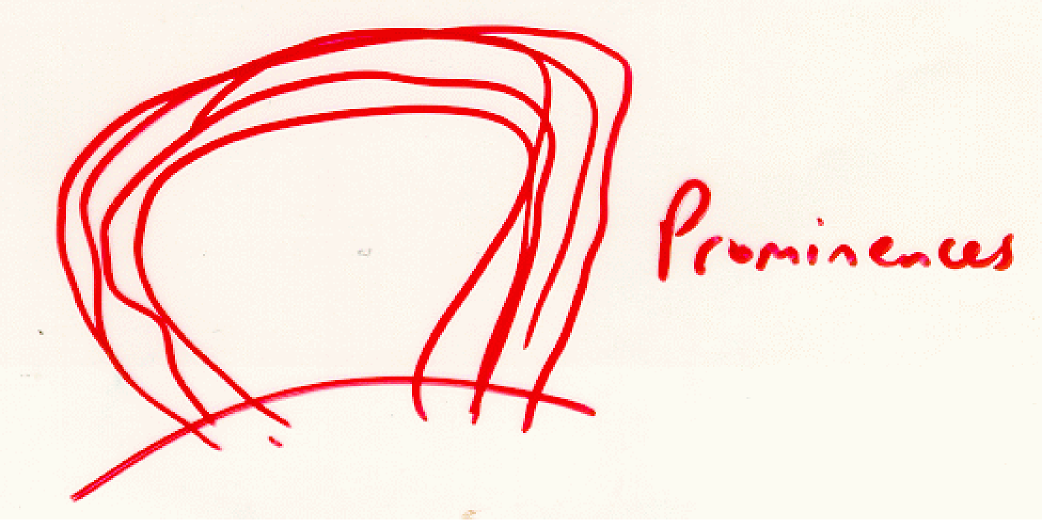
The structure of the surface and boundary layer into the sun's "atmosphere":



We see at the surface of the Sun a lot of structure. It is seen to be divided up into a complex ever-changing pattern of convection cells - "supergranulation". Some of the surface material breaks free of the surface and moves upwards. Often this is obviously under the control of magnetic fields that "organise" it in to magnetic arches or more complex structures. The rate of magnetic field emergence f of magnetic field emergence from the quiet regions of the Sun exceeds that of active regions (sunspot groups) though emerging active regions contribute to the large-scale magnetic structure. We know a fair amount about the morphology of the sunspots' associated magnetic field. Often sunspots are "paired" with the field lines joining one to the other:

Other surface structure is seen either with no associated magnetic field, or organised along "open" field lines:

Some of the magnetically-bound structure can grow to form large "prominences"which are seen to stand well out from the solar surface. Sometimes these expand then contract back again, occasionally they lead to explosive events



There are regions, seen as dark in X-rays, called "Coronal Holes", where the magnetic field lines are "open" (i.e not curling back down and closing again in the Sun's surface). Here, the solar wind streams outwards from the solar surface. Violent explosive events known as Coronal Mass Ejections (CMEs) spew great clouds of high-energy material into space. When these clouds arrive at Earth they are often the cause of geomagnetic substorms, and active ionospheric and magnetospheric phenomena.

At the surface of the Sun the convective flows dominate the magnetic fields, b the magnetic fields, but higher in the solar atmosphere the magnetic fields dominate the plasma. In these latter regions the complete ionisation of the plasma mean that it has effectively infinite conductivity, and this "freezes in" the magnetic field so that it is trapped within the plasma and has to move with it.

The Sun's electromagnetic spectrum

The sun emits what is very close to a black body spectrum. The nearest black body equivalent would be the spectrum of 5900K, though if we look at the details there are some deviations from this:

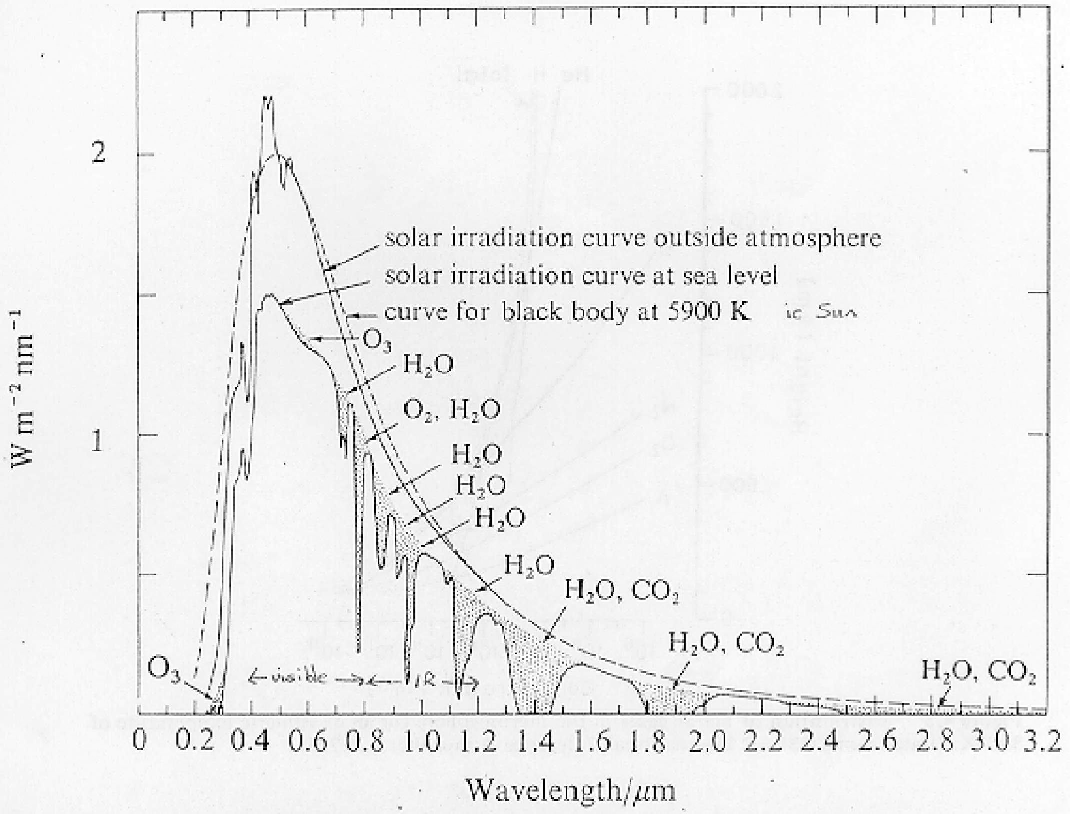


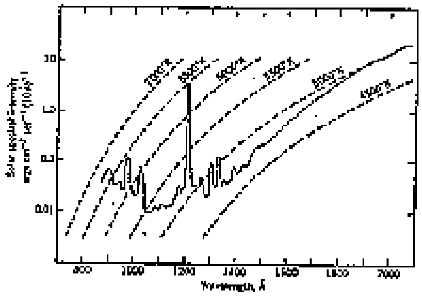
Fig. A8.1. Solar radiation curves. Shaded areas show absorption by vertical path of whole atmosphere by constituents shown (from Air Force Cambridge Research Laboratories, 1965).

"The Physics of Atmospheres" Houghton p.178

The outside curve is a black body radiator at 5900K. This is an especially good fit to the right-hand part of the sun's spectrum when seen from space. The left-hand side (shorter wavelengths than the peak) is better characterised by a slightly lower temperature - say around 5700. This is true down to around 300nm. Below that there is a fall-off which fit even cooler bodies, until we get to 140-200nm, when the energy rises well above the 5900K black-body level. We shall see this below.

In the diagram above we also see the effect of the Earth's atmosphere. The inner curve is what we see at ground level. You will notice that this cuts off some of the radiation at all wavelengths, but over the middle visible band - 400-800nm - most radiation gets through (fortunately for life at ground level!). There are big "vl!). There are big "valleys" of attenuation from 800-1300nm where water and Carbon Dioxide absorption have a large effect. Above 1300nm (1.3 microns) there are several frequency bands where the water and CO_2 absorption are so strong the radiation does not reach ground level at all. The radiation less than 200nm in wavelength (the EUV and XUV) is also stopped high in the atmosphere (again, fortunately for life on the ground!).

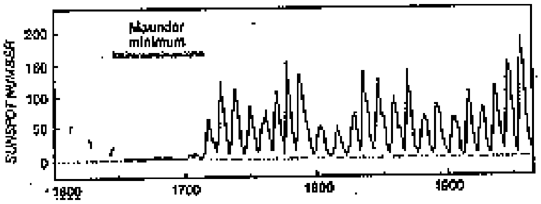
The solar spectrum (i.e above the atmosphere before attenuation) below 200nm is interesting for a number of reasons. We shall see later that this is important for the energy balance and composition of the upper atmosphere, but it is also intersting when it comes to the sun's solar cycle variations. A typical spectrum over the range 80-200nm wavelength is shown here:



Note that the energy is much enhanced over what is expected of a 5900K black body sun, and that there are distinct spikes at certain wavelengths where particular emissions are excited. The particularly strong line at 120nm is the Lyman-alpha line, which is important for ionising NO at D-region altitudes (80km).

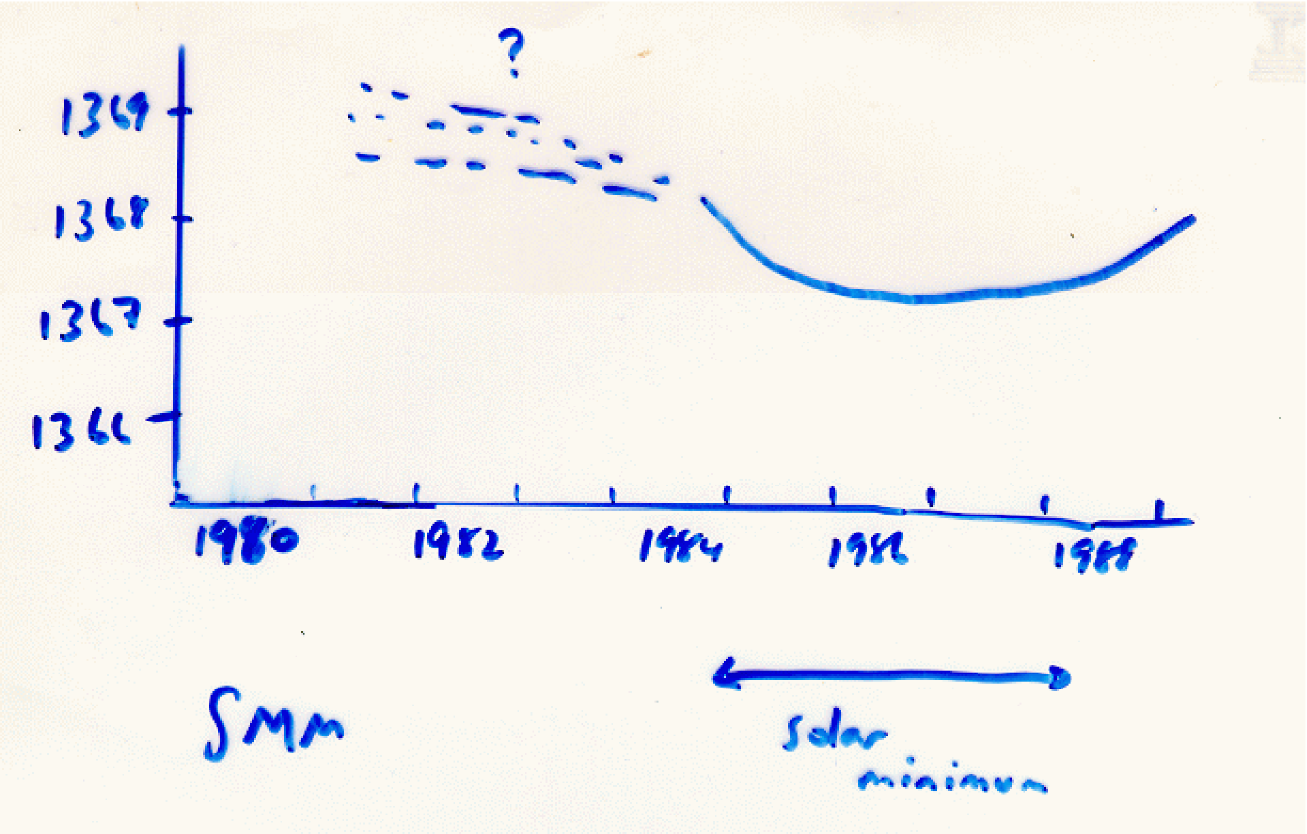
Solar Cycle variations

We know that sun-spots come and go in an 11-year cycle called the solar cycle.



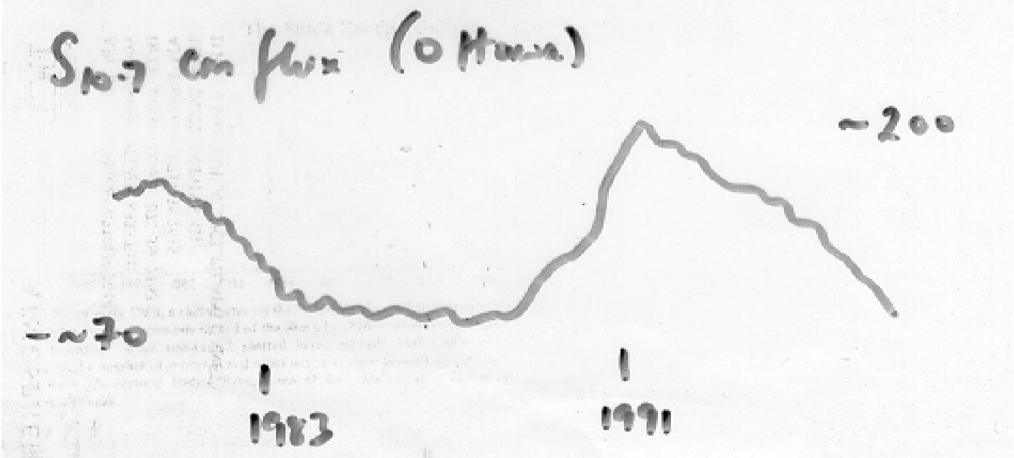
This graph shows that these variations have been seen with varying intensity since 1700. (This is a plot oThis is a plot of sunspot number with time from 1600 to date.) Notice that the peak intensity varies. Notice also the virtual non-existence of sun-spots from 1650 to 1700. This period - the Maunder minimum - corresponded to the "Little Ice Age" in Europe - a period of intensely cold winters (when, for instance, ice fairs used to be held on the frozen Thames). The suns spot record goes back beyond this with Chinese and Korean observations, and more indirect methods can be used to infer solar activity back beyond this, so we are fairly sure that the solar cycle has been discernible for many hundreds of years. There was another minimum, the Sporer minimum, befor ethe Maunder minimum, which also seems to have been accompanied by climate changes.. Does this mean, then that the solar sunspot cycle is correlated with variations in total energy output from the sun? Well, apparently not, as this following graph of the solar constant variation with time shows:

Solar cycle variation of the "solar constant" (corrected for varying distance of the Sun from the Earth):



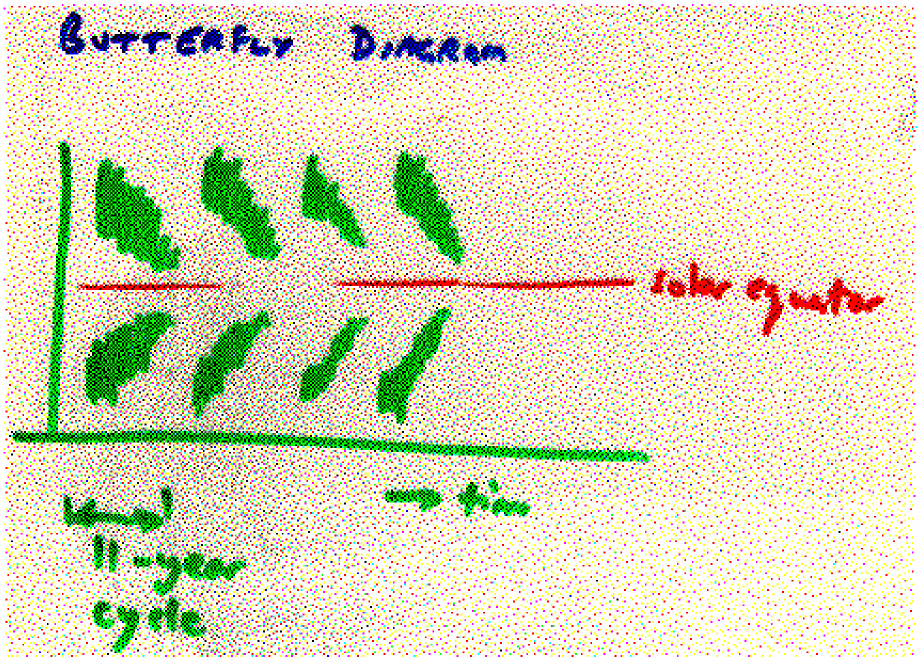
This is from SMM (Solar Maximum Mission) data. The first part of this had a large spread - hence the question mark over 1982-4. However, the later data is well determined, and one can see that there is only a very small solar cycle variation - only 1 or 2 parts in 1400 (<0.1 %). [The solar constant solar constant is the integrated power per square metre received from the sun at the earth.]

However, that small part of the solar spectrum in the EUV and XUV regions shows a much larger variation with solar cycle. The UV varies by 20% with solar cycle, and the XUV by factors up to 3 - the higher energy on the whole the larger the variation. A good proxy for the EUV variation is provided by the 10.7cm flux. This has been recorded for many years and is a standard measure of solar activity used in atmospheric and solar research:

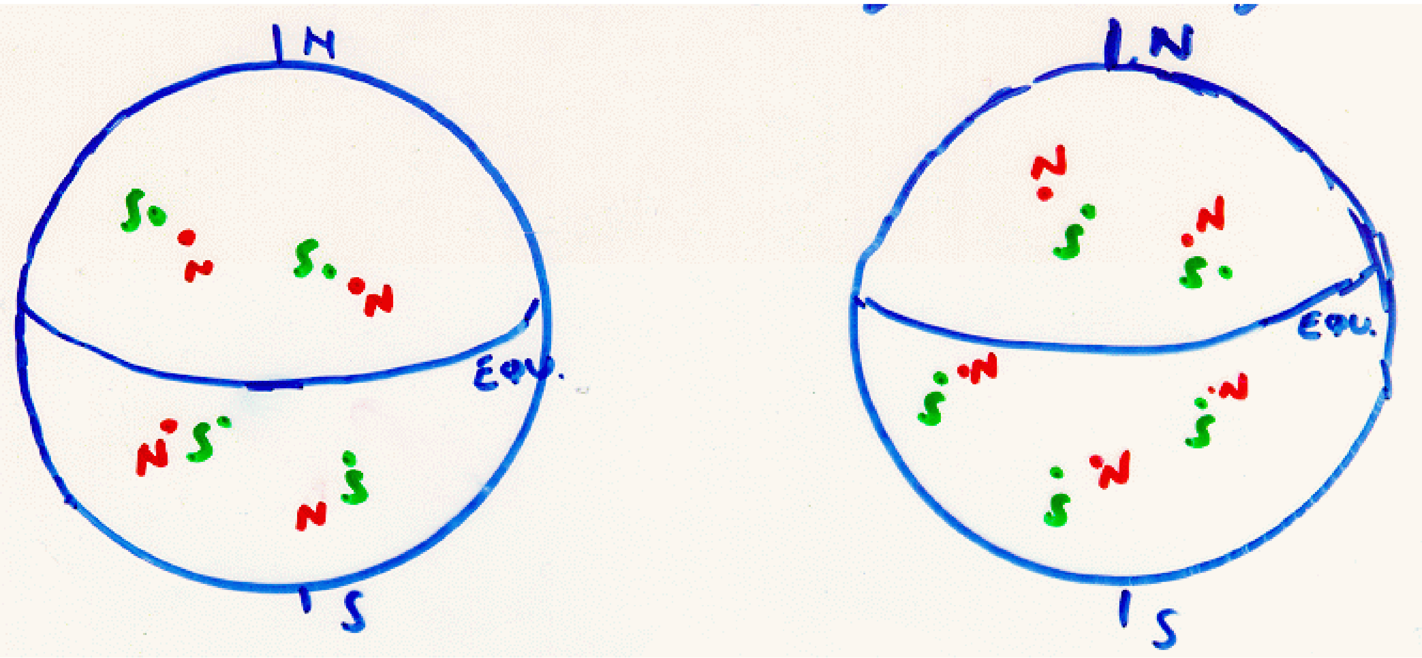


Variations in sunspot position:

Besides variations in numbers sunspots are seen also to vary in a number of other ways. When a solar cycle starts, after a minimum, they usually are seen at higher latitudes than later in the cycle. They then increase in number and appear nearer the equator. The result is that pattern of appearance is that of the well-known "butterfly diagram" shown here:



When studied in detail the sunspots are seen to each have a magnetic polarity and to tend to occur in pairs of opposite polarity. It seems that the magnetic field exits from one and curves over and disappears into the other (i.e the sunspots represent the ends of a magnetic loop coming from the sun's surface). When the polarities of the sunspots is studies (we can measure the magnetic fieldhe magnetic fields remotely because of the Zeeman effect - the magnetic splitting of emission lines) we find that in one hemisphere all the "leading" spots of a pair tend to have the same polarity. What is more, the "leading" spots in the other hemisphere (ie the other side of the equator) tend to have the opposite polarity. In the following solar cycle, the polarities swap round. That is we have a situation like this:



where the left hand diagram represents the situation in one solar cycle and the right hand diagram the situation in the next. Thus we can, in some senses talk of a solar cycle being 22 years rather than 11, since it takes that long for the