Space Physics

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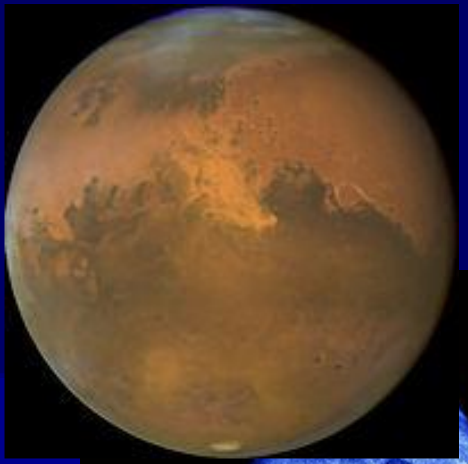
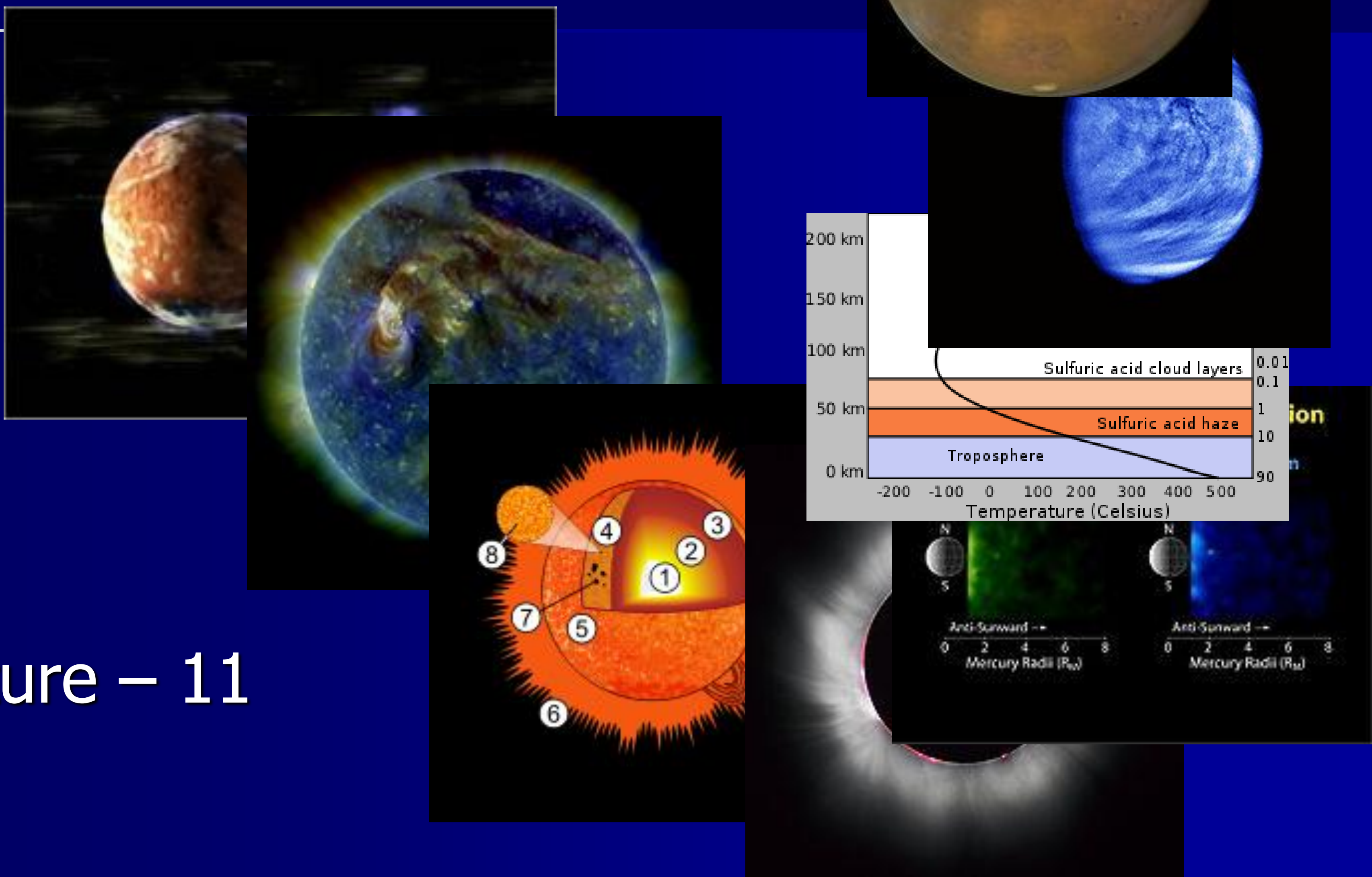
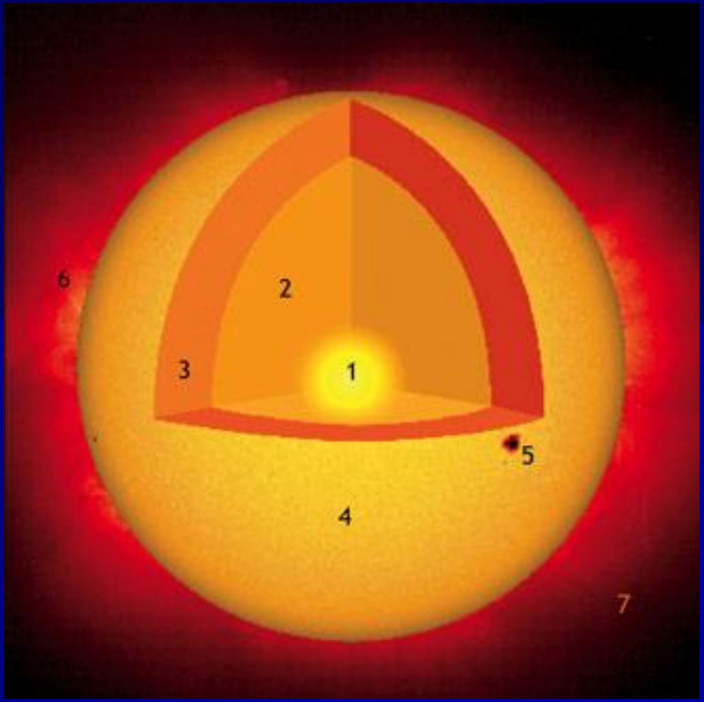




Lecture – 11

The Active Sun



The Sun and Stars
Introduction of the Active Sun
The Photosphere
The Chromosphere and the Corona
Sunspots and the Solar Cycle
Faculae, Flares and Prominences
Radio and X-ray Bursts from the Sun
The Development of an Active Region on the Sun
Effect of the Solar Cycle
Life Cycle of the Sun

The Active Sun

Introduction

The sun is a star of mass M = 1.99x10^{30} kg, radius R=6.96x10^{8} m and effective temperature T=5750K. The total energy radiated by the Sun per second, i.e. its luminosity L is ,

$$L = 4\pi R^2 . \sigma . T^4$$

$$L = 4\pi (6.96 \times 10^8)^2 . (5.67 \times 10^{-8}) . (5750)^4$$

$$L = 3.77 \times 10^{26} \, Js^{-1} (W)$$

Using Stephan's Law

$$E = \sigma T^4$$

Energy density per second

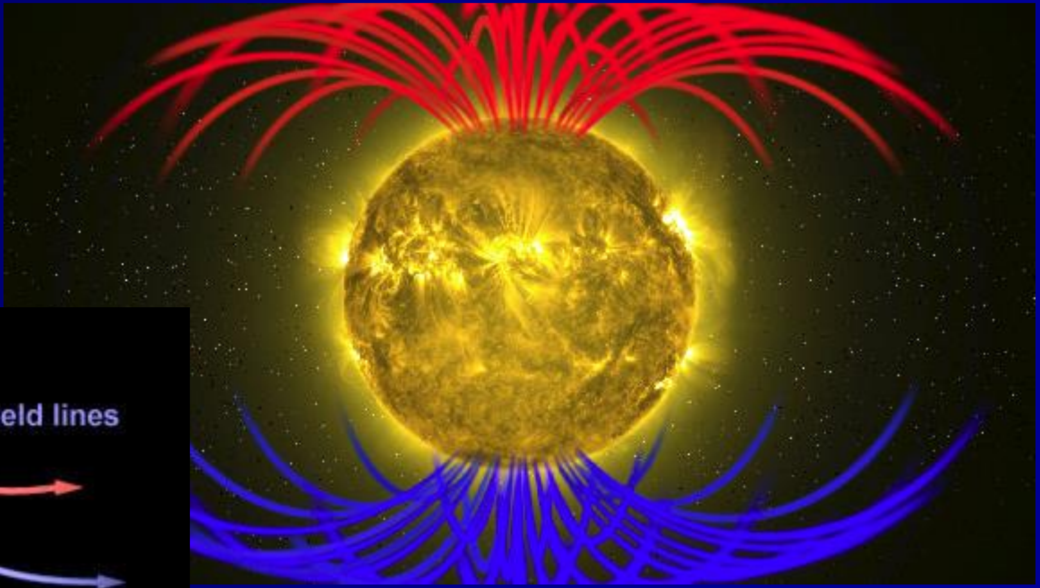
$$E = A \sigma T^4$$

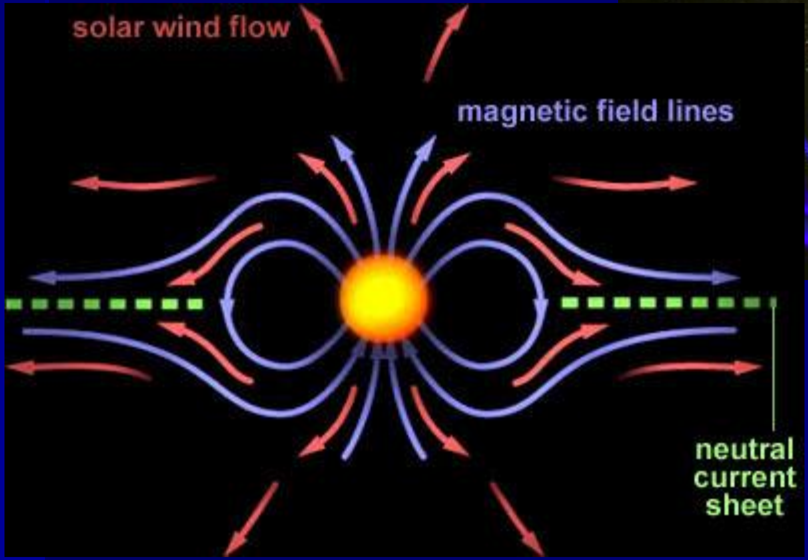
Total Energy per second

The Sun is a main sequence **G2 star** (A star is between super giant and bright giant), approximately **5 billion years old**. In many ways it is a very representative star and it is estimated that it will remain essentially in its present state for at least another 5 billion years.

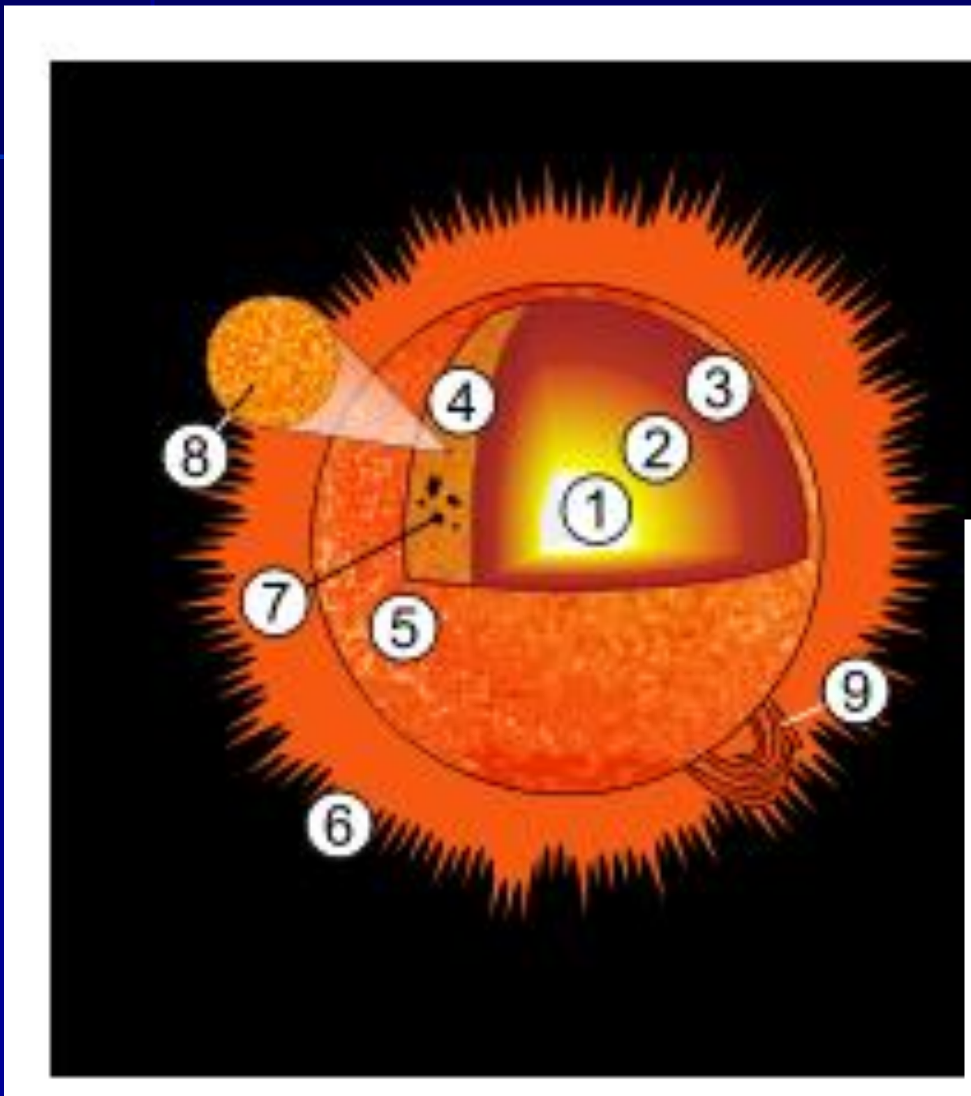
The Active Sun

The Sun possesses (with around) a rather **weak magnetic field** which reaches a typical value of a **few Gauss** on the surface on the Sun. Occasionally, the solar magnetic field displays transient (changeable) local enhancement where field intensities can reach values as high as several thousand Gauss.





Structure of the Sun

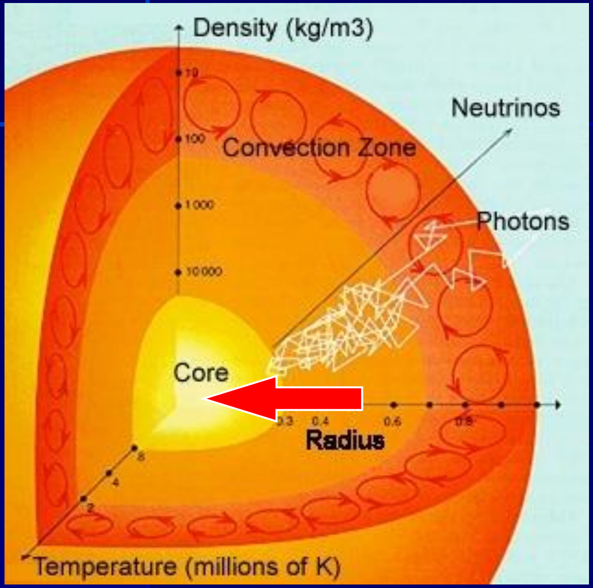


An illustration of the structure of the Sun:

1. Core
2. Radiative zone
3. Convective zone
4. Photosphere
5. Chromosphere
6. Corona
7. Sunspot
8. Granules
9. Prominence

The Structure of the Sun

Core



The core of the Sun is considered to extend from the center to about 20-25% of the solar radius. It has a **density** of up to **150,000 kgm^{-3}** and a **temperature** of close to **13.6 million Kelvin**.

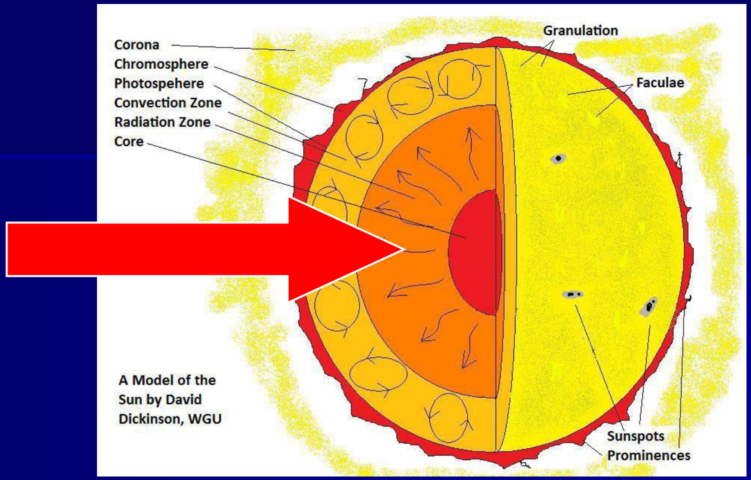
The core is the only region in the Sun that produces an appreciable amount of thermal energy through fusion; inside 24% of the Sun's radius, 99% of the power has been generated and by 30% of the radius, fusion has stopped nearly entirely.

The rest of the star is heated by energy that is transferred outward from the core and the layers just outside.

The proton-proton chain occurs around 9.2 x 10^{37} times each second in the core of the Sun.

The Structure of the Sun

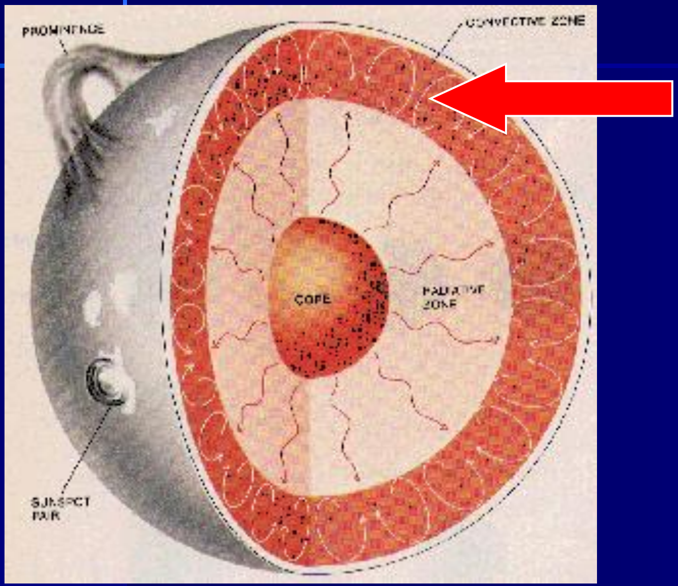
Radiative Zone



From about 0.25 to about 0.7 solar radii, **solar material is hot and dense enough that thermal radiation** is sufficient to transfer the intense heat of the core outward. This zone is free of thermal convention; while the material gets cooler from **7** to about **2 million Kelvin** with the increasing altitude, this temperature gradient is less than the value of the adiabatic lapse rate and hence can not drive convection. Energy is transferred by **radiation-ions** of **hydrogen** and **helium** emit photons, which travel only a brief distance before being reabsorbed by other ions. The **density drops from 20 x 10^3 kgm^{-3} to only 0.2 x 10^3 kgm^{-3} from the bottom to the top** of the radiative zone.

The Structure of the Sun

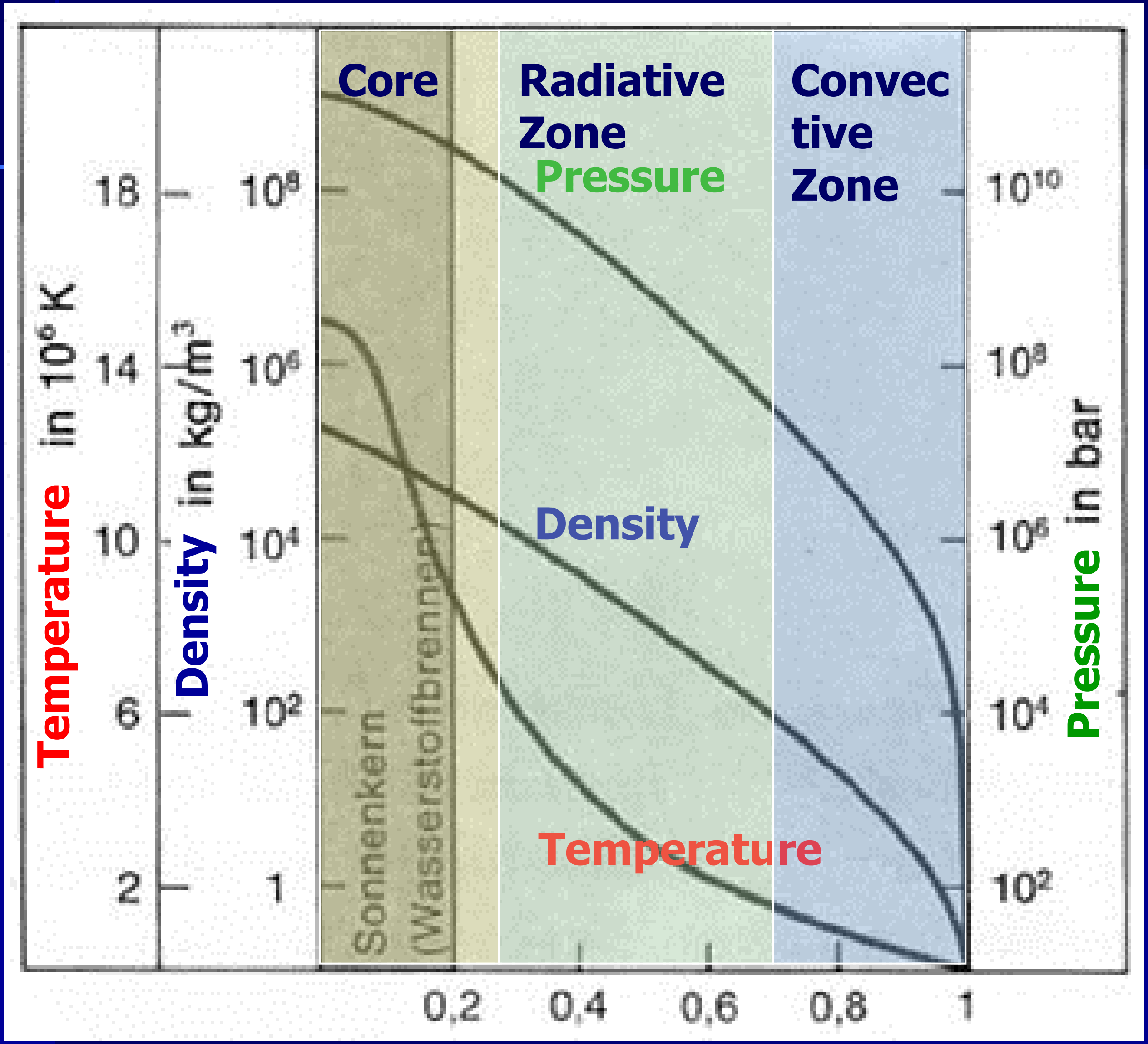
Convective Zone



In the Suns 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 thermal energy of the interior outward through radiation; in other words its 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 (suddenly sink) **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 **5750 K** and the density to only **0.2 g/m^3**.

Pressure, Density & Temperature Inside the Sun



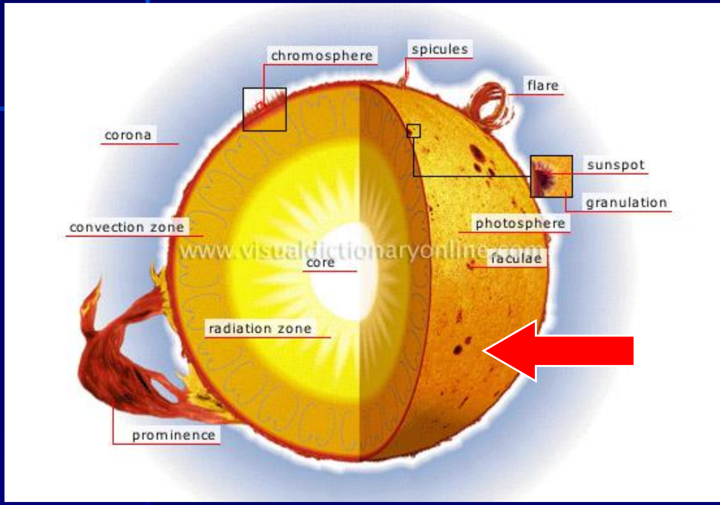
Center to ~20-25% R_o → Core

~25% to ~70% R_o → Radiative Zone

~70% to 100% R_o → Convective Zone

The Structure of the Sun

The photosphere



The photosphere is the layer of the Sun from which we receive practically all of the **optical emission**. One can think of it as a luminous shell at a glowing temperature of nearly 6000 K. The width of the solar photosphere is determined not by any physical boundaries, but by the degree to which each layer of the solar atmosphere is transparent or opaque to the optical rays.

The region above the photosphere is practically transparent to the optical rays which originate in the photosphere. **On the contrary** (against) **the layers below the photosphere are opaque and therefore not accessible to optical observations**.

The thickness of the solar photosphere in white light is only of the **order of several hundred kilometers**, i.e. less than 0.1% of the radius of the Sun. Hence the photosphere, which emits practically **all of the visible solar radiation**, is an **extremely thin layer of the Sun**.

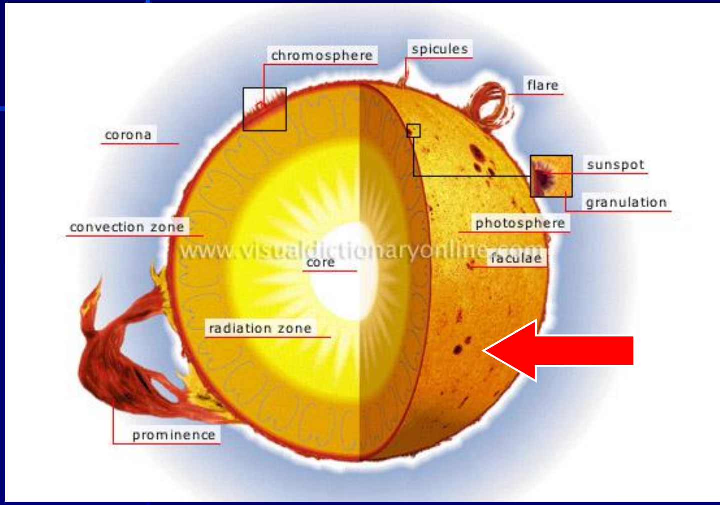
The Structure of the Sun

The photosphere

The energy emitted by the photosphere is produced in the core of the Sun through the conversion of hydrogen to helium and is transferred to the bottom of the photosphere by convection.

The relation, which describes this entire process is called the **equation of radioactive transfer**. In the solar photosphere, most of energy absorbed in the optical domain is used for freeing electrons which are attached to neutral hydrogen atoms. This is called **negative ion absorption**,

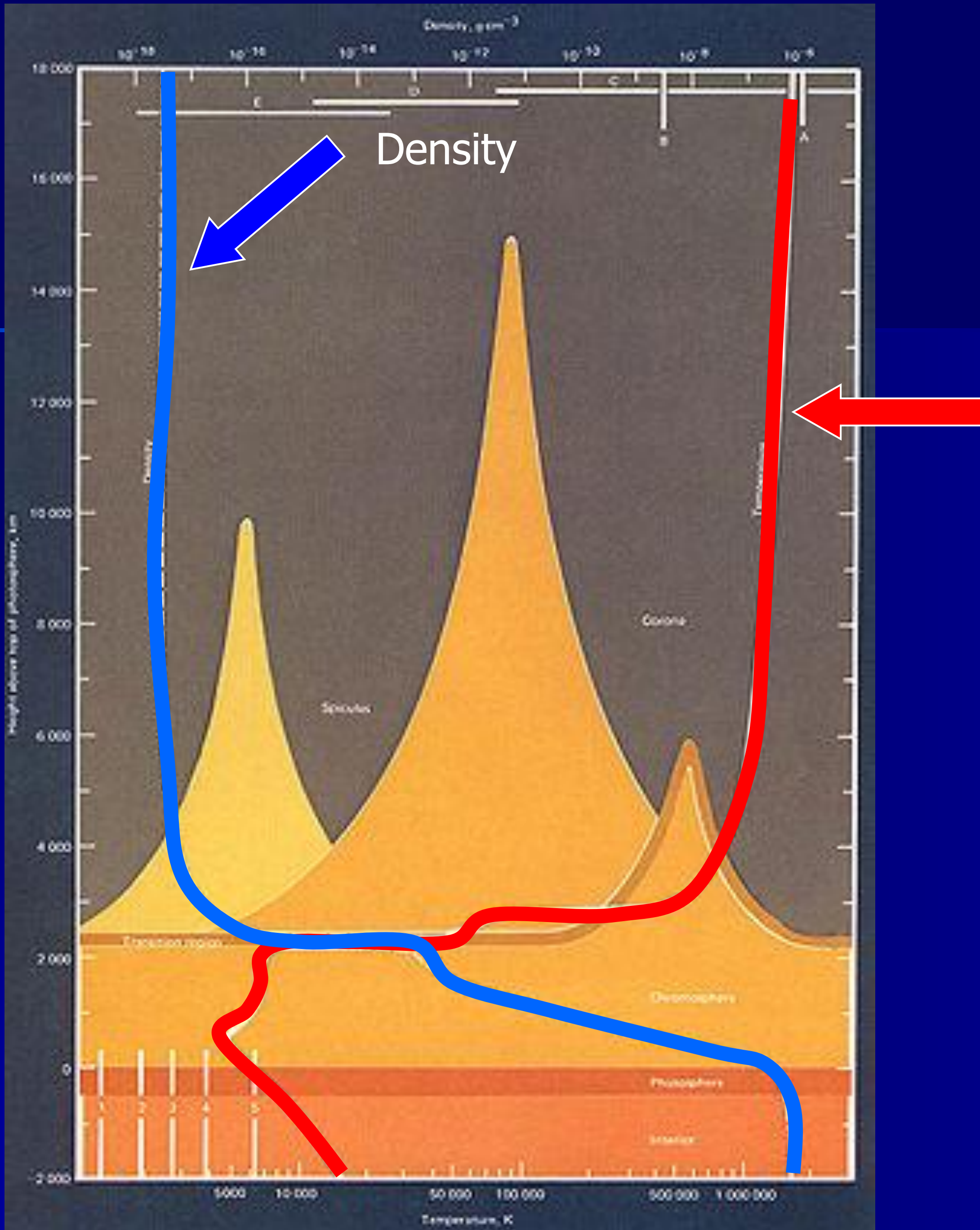
$$H^{-} + hf = H + e^{-}$$



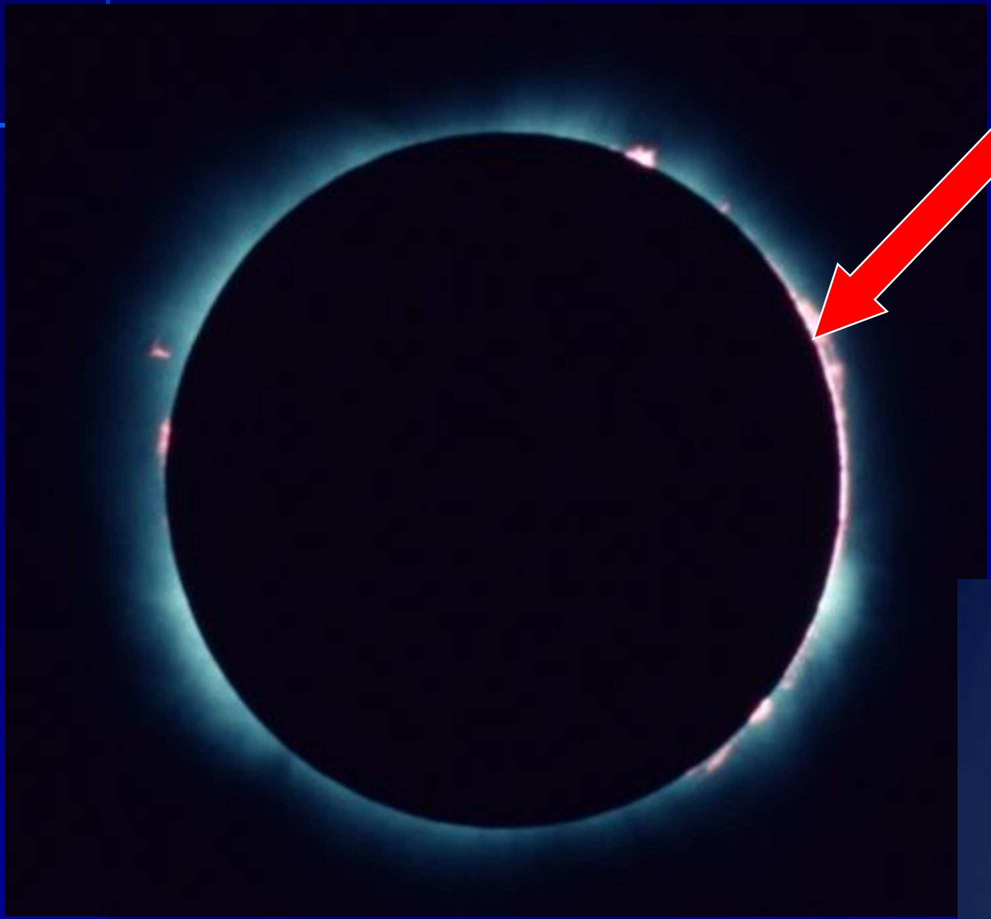
Photospheric composition (by mass)

Hydrogen	73.46%
Helium	24.85%
Oxygen	0.77%
Carbon	0.29%
Iron	0.16%
Sulfur	0.12%
Neon	0.12%
Nitrogen	0.09%
Silicon	0.07%
Magnesium	0.05%

Temperature and density of the Sun's atmosphere

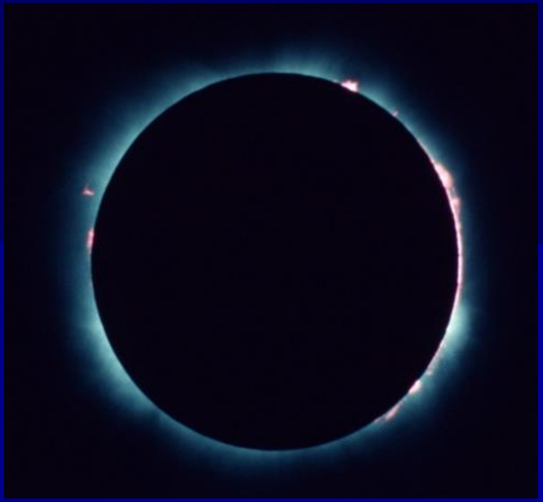


Structure of the Sun : Chromosphere & Corona



The Structure of the Sun

The Chromosphere and the Corona



The region above the photosphere is called the chromosphere, which in Greek means the "**color-sphere**". This name comes from the **Red color** of the chromosphere which is due to the predominance (sight strongly) of **H–alpha line of hydrogen** (The first Balmer line at 6563 Å). The chromosphere is approximately 10000 km thick and **becomes visible only a few moments before totality during a total eclipse of the Sun**. As we have seen, the **effective temperature of the Sun (5750 K) approximately 100km below the surface of the photosphere**. At the top of the photosphere, the temperature drops to about 5000 K and continues to decrease to about 4500 K in the first few hundred kilometers of the chromosphere.

The Structure of the Sun

The Chromosphere and the Corona

Beyond this minimum the temperature begins to increase, slowly at first and then more rapidly. It reaches values in the 10,000 K to 50,000 K to range in the first few thousand kilometers and then the transition zone occurs, where the temperature rises steeply (more sloping) from 50,000 K to 500,000 K in probably less than a thousand kilometers. This sharp increase in temperature represents on of the most complex and most intriguing (fantastic) problems of **solar physics**.

Above this region the temperature continues to increase but at a much slower rate reaching finally at an altitude of 10,000 to 20,000 km a temperature of about 1.5 x 10^6 K which is the nearly constant temperature of the **solar corona**.

During a total Solar eclipse, the solar corona can be seen with the naked eye during the brief period of totality.

The Structure of the Sun

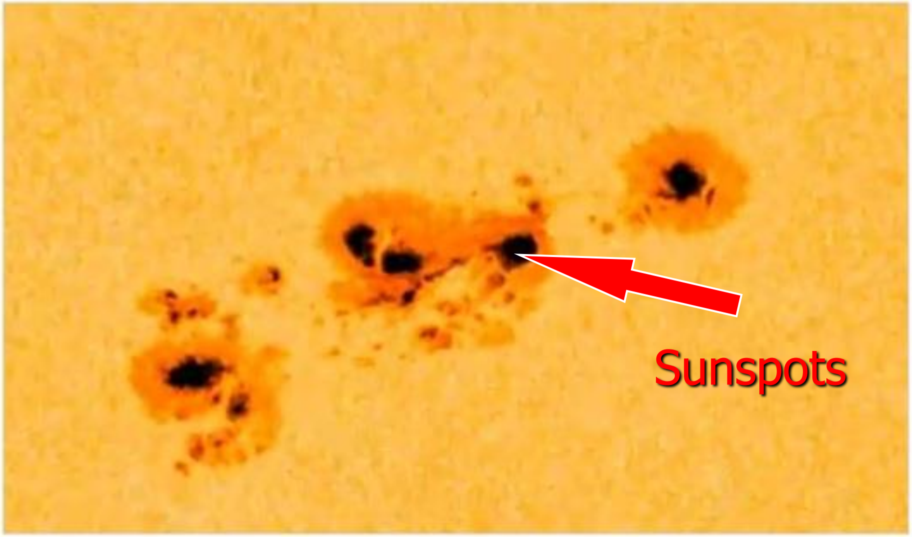
The Chromosphere and the Corona

The first 1000 km of the chromosphere are a fairly uniform layer, but above this height the chromosphere become a very in-homogeneous region because it consist of many small jets shooting out into the corona. These projections are called "**spicules"** and in general have the shape of a rather long **cylindrical cone** approximately **1000 km thick** and about **5000 km tall**. **The specules continuously rise and fall and their average life time is close to 5 minutes**.

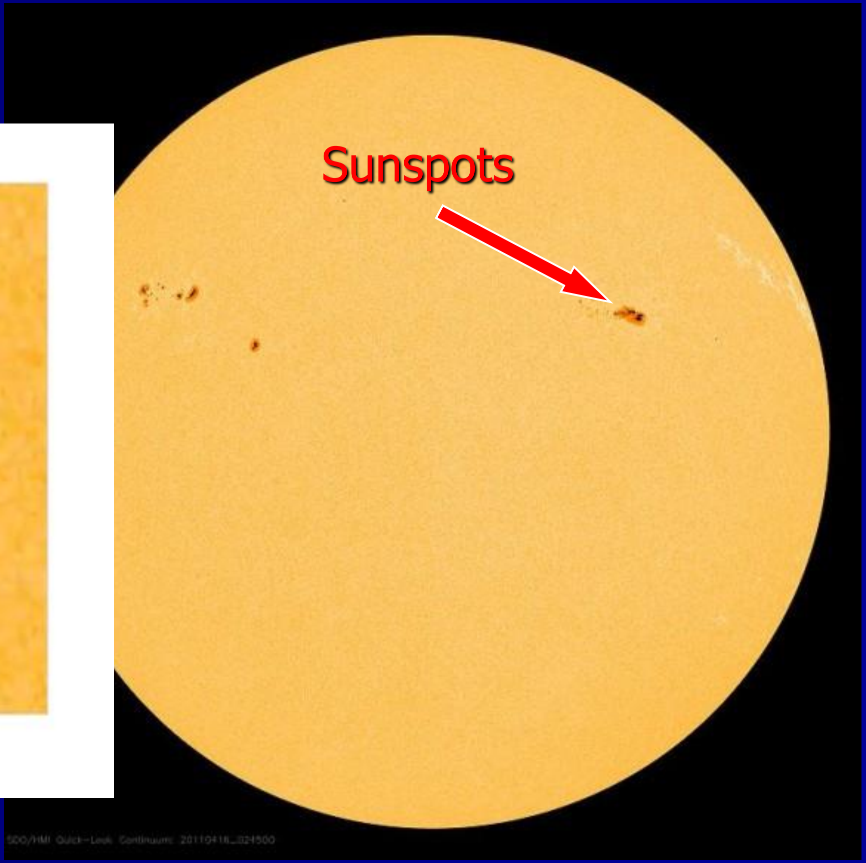
The solar corona begins essentially in the region between the spicules and extends outwards merging ultimately with the the interplanetary medium. The temperature of the corona is approximately **1.5×10^6 K** and changes very slowly with the distance from the Sun. The **coronal gas at this high temperature is fully ionized** and consists essentially of **electrons** and **protons**.

Sunspots & the Solar Cycle

Sunspots are small, dark, transient (changeable) spots on the surface of the Sun. They can easily be seen with naked eye by projecting the image of the Sun on a white surface. It is believed that Theophrastus of Athens, a pupil of Aristotle, was the first one to observe the Sunspots around 300 BC. The Chinese complied many naked-eye records of sunspots from the 1st to 17th century.



Sunspots *NASA/SDO*



Sunspots & the Solar Cycle

It was not until 1843 that **Heinrich Schwabe** announced in Germany that his long sunspot observations had shown that the average number of sunspots on the Sun varies with a **period of approximately 10 years**.

Further studies in past records by **Rudolf Wolf** confirmed the existence of an **11 year sunspot cycle** and in 1851, Wolf introduced his relative sunspot number R which is given in the relation,

Calibration Factor

Relative Sunspot Number

$$R = k\left[10\,g + f\right]$$

Number of individual sunspots on the disk of the Sun

Number of sunspot groups on the disk of the Sun

Where, **k** is a coefficient assigned to each observing station to assure uniformity in the R numbers obtained by the different stations. This k is called "**Calibration Factor**" of the equation.

Relative Sunspot Number, R

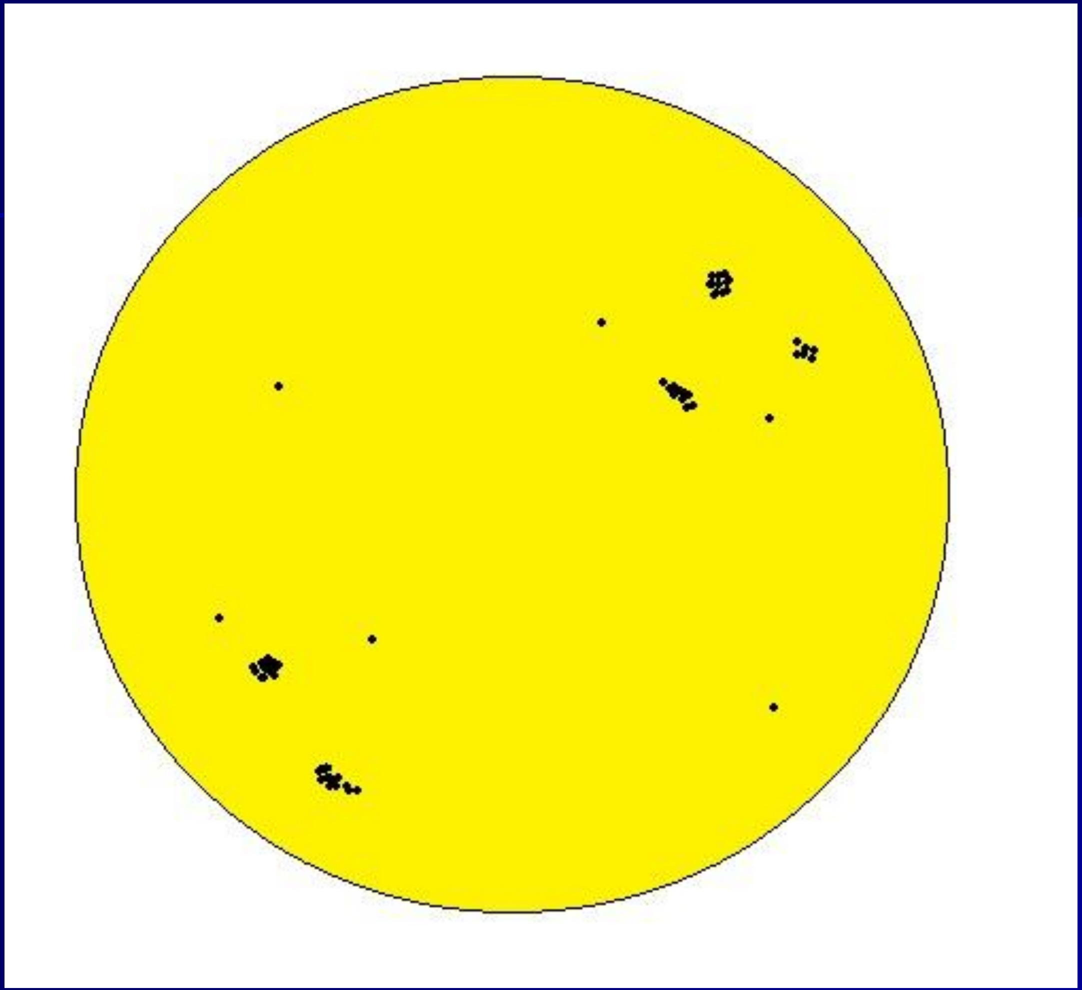
$$R = k\left[10\,g + f\right]$$

In 1855 Wolf become the director of the new Zurich Observatory and established there a Long Tradition of Solar Observations. For this reason **R** is also called **Wolf sunspot number** or **Zurich sunspot number**.

Coefficient k :

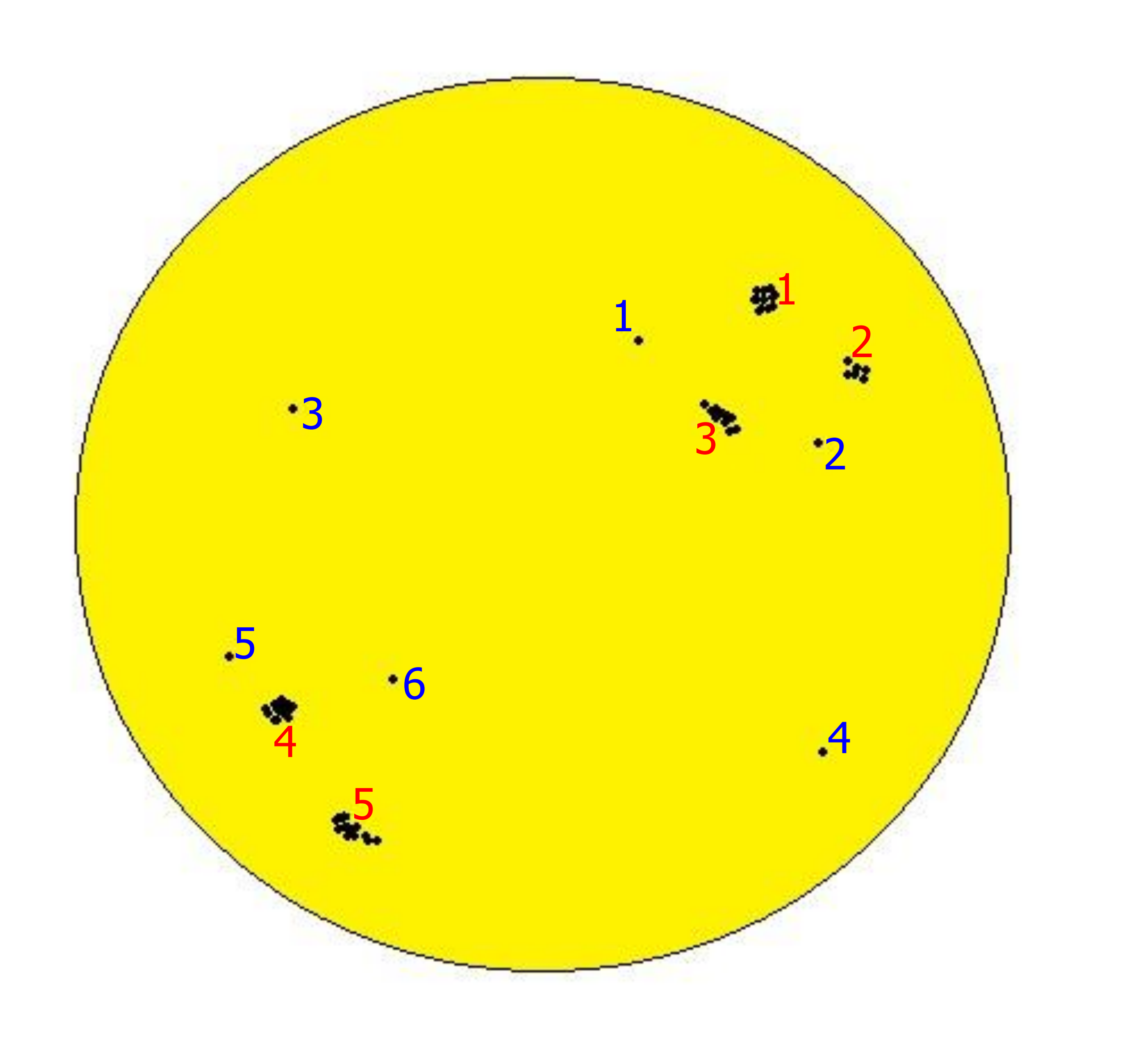
This k is **variable scaling factor** (Usually $k < 1$) **that accounts for observing conditions** and **the type of telescope** (binoculars, Space Telescope, …). Scientists combine data from lots of observations – each with its own k factor to arrive at a daily value!

Sunspots & the Solar Cycle



Eg: The above figure shows the telescopic image of the Sun and the value of the variable scaling factor based on the telescope 0.45. Find the value of the sunspot number.

Sunspots & the Solar Cycle



Number of sunspot groups on the disk of the Sun

g = 5

Number of individual sunspots on the disk of the Sun

f = 6

Relative Sunspot Number,

$$R = k\,[10\,g + f\,]$$

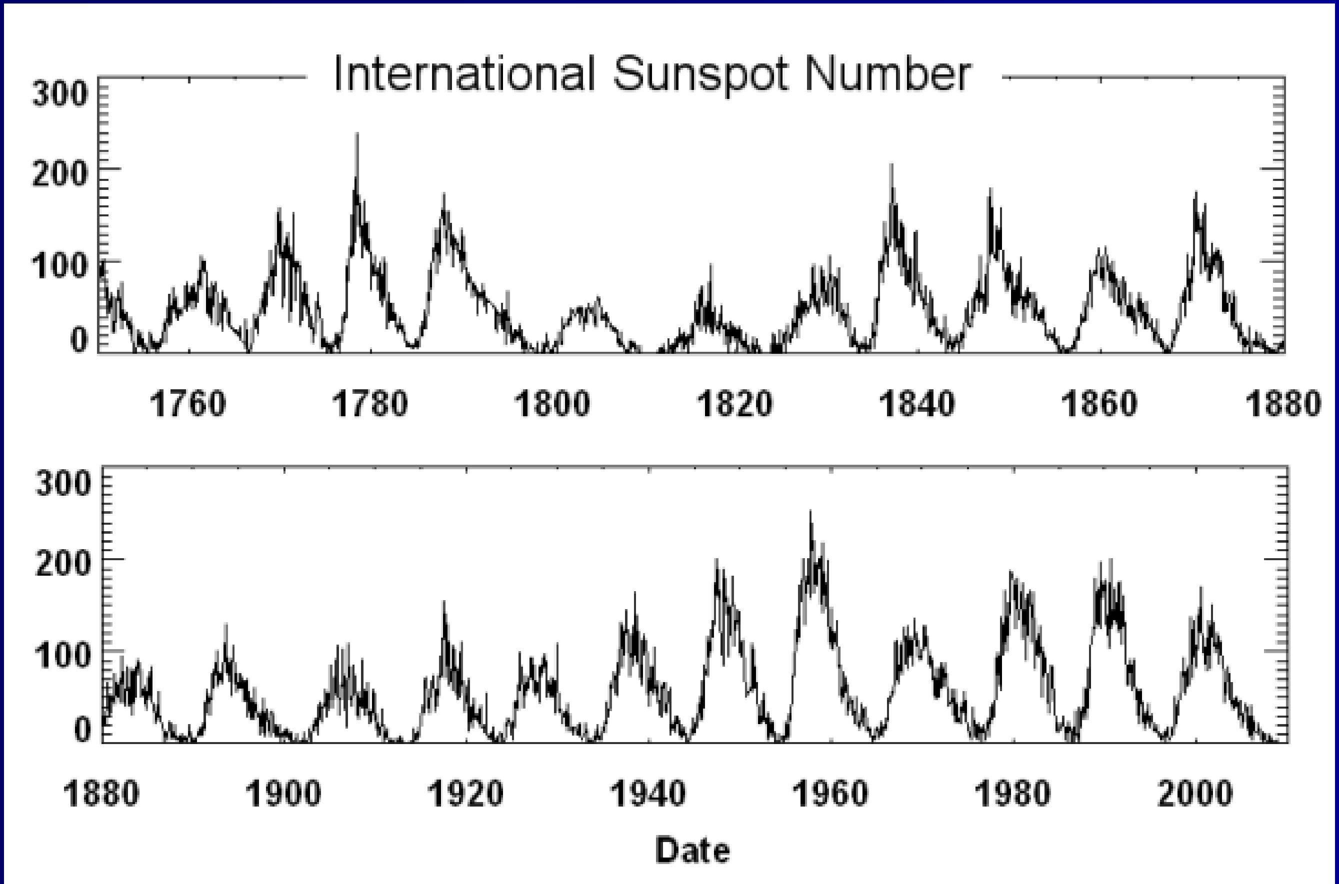
$$R = k[10 \times 5 + 6]$$

If $k = 0.45$

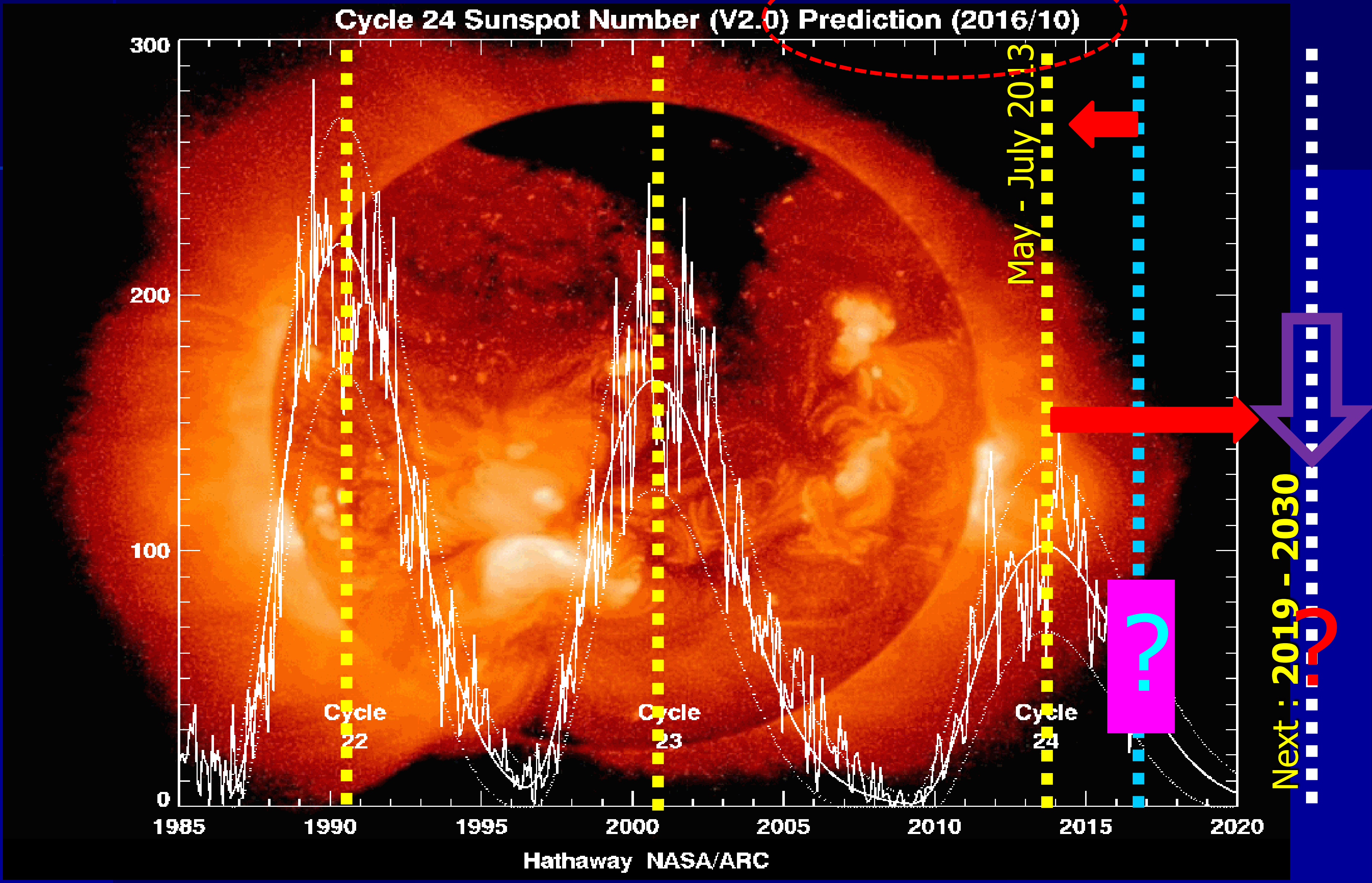
$$R = 25.2$$

International sunspot numbers from 1745 to the present

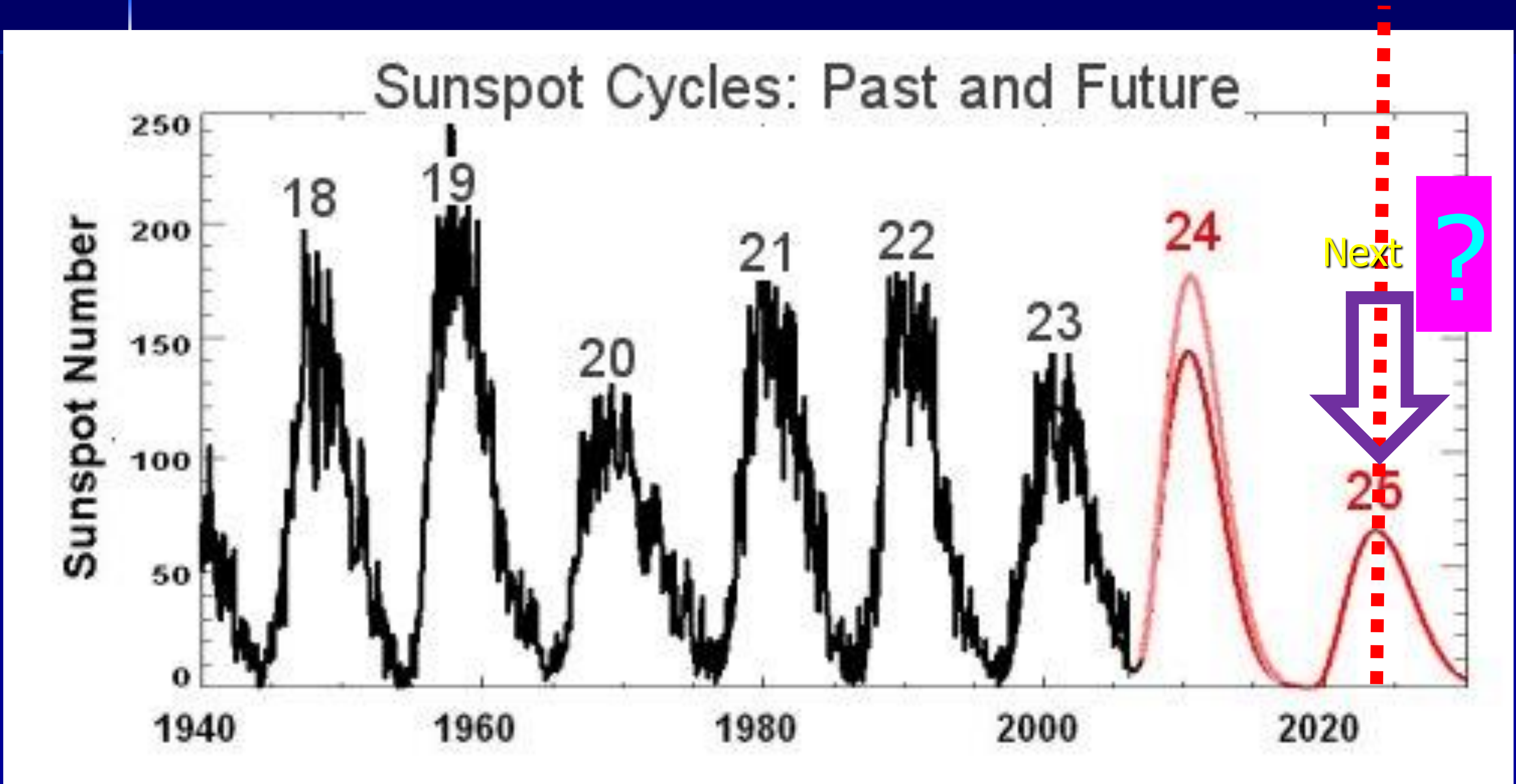
The following figure shows the variation of the yearly average of the sunspot number since 1745 to the present. Data for the first hundred years were reconstructed from old records by **Wolf**.



Future Sunspot Predictions



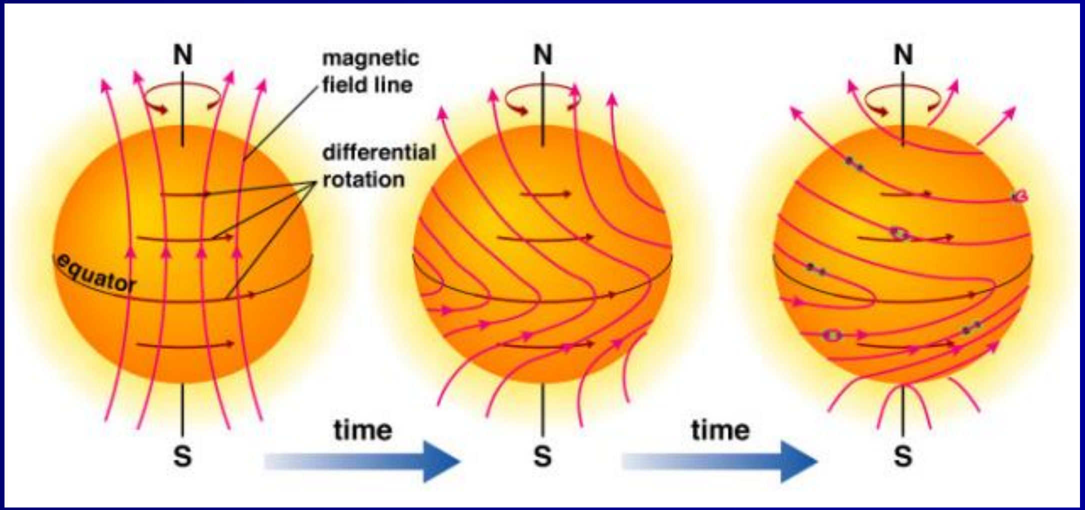
Future Sunspot Predictions :



In more recent years it has been found that all other manifestations of solar activity follow essentially the same **11 year cycle**. It should be mentioned that the cycle of the various indices show considerable differences over the 11 year cycle and their maxima might differ by a year or more.

It is probably more accurate to speak of a 22 years solar cycle which includes two 11 years sub cycle !

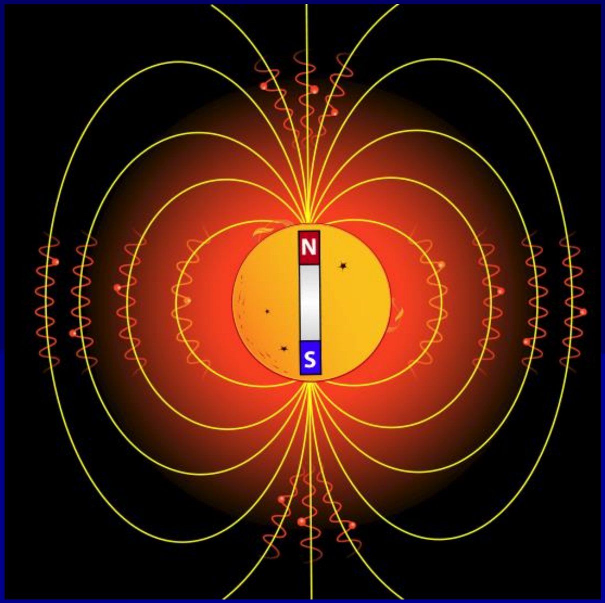
In 1908 **George Ellery Hale**'s observations revealed that the Solar Cycle is a **magnetic cycle with an average duration of 22 years**. However, because very nearly all manifestations of the solar cycle are insensitive to magnetic polarity, it remains common usage to speak of the " **11 years solar cycle** ".

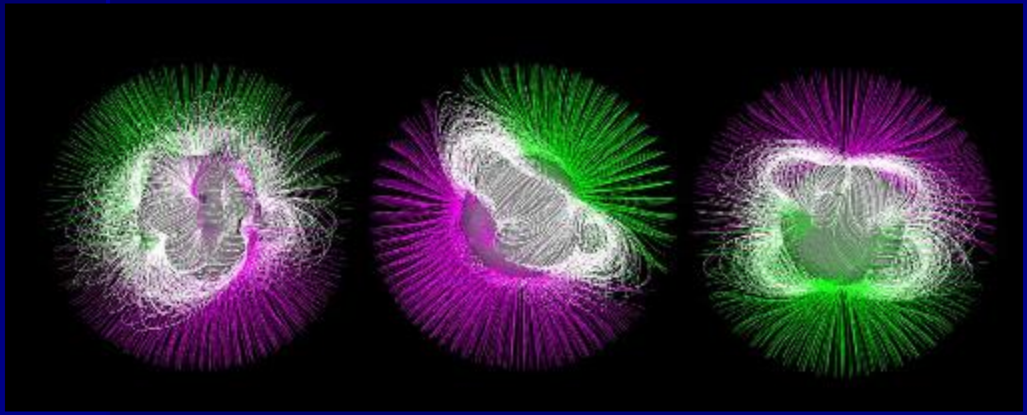


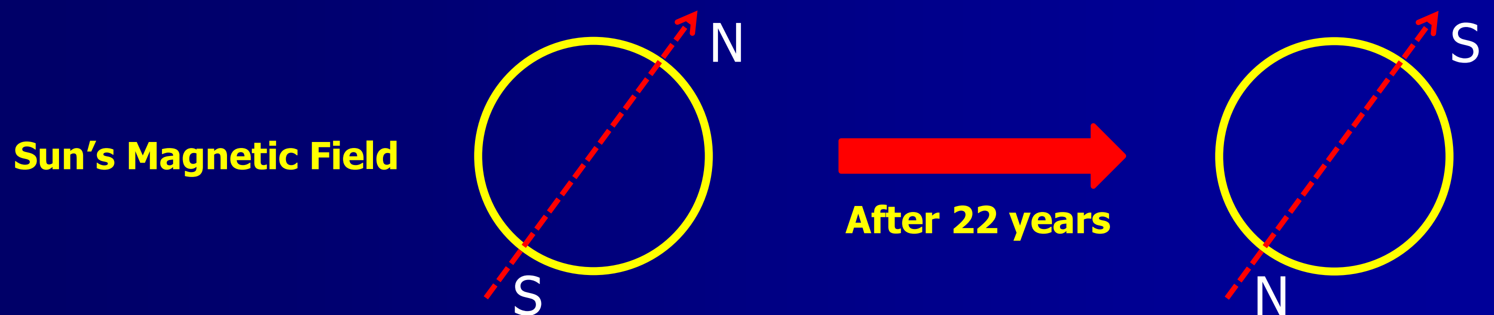
The Solar Cycle

Solar Cycles						
Cycle	Started	Finished	Duration (years)	Maximum (monthly SSN (Smoothed Sunspot Number))[4]	Minimum (monthly SSN; end of cycle)[5][6]	Spotless Days (end of cycle)[7][8][9]
Solar cycle 1	March 1755	June 1766	11.3	86.5	11.2	
Solar cycle 2	June 1766	June 1775	9.0	115.8	7.2	
Solar cycle 3	June 1775	September 1784	9.3	158.5	9.5	
Solar cycle 4	September 1784	May 1798	13.7	141.1	3.2	
Solar cycle 5	May 1798	December 1810	12.6	49.2	0.0	
Solar cycle 6	December 1810	May 1823	12.4	48.7	0.1	
Solar cycle 7	May 1823	November 1833	10.5	71.5	7.3	
Solar cycle 8	November 1833	July 1843	9.8	146.9	10.6	
Solar cycle 9	July 1843	December 1855	12.4	131.9	3.2	~654
Solar cycle 10	December 1855	March 1867	11.3	97.3	5.2	~406
Solar cycle 11	March 1867	December 1878	11.8	140.3	2.2	~1028
Solar cycle 12	December 1878	March 1890	11.3	74.6	5.0	~736
Solar cycle 13	March 1890	February 1902	11.9	87.9 (Jan 1894)	2.7	~938
Solar cycle 14	February 1902	August 1913	11.5	64.2 (Feb 1906)	1.5	~1019
Solar cycle 15	August 1913	August 1923	10.0	105.4 (Aug 1917)	5.6	534
Solar cycle 16	August 1923	September 1933	10.1	78.1 (Apr 1928)	3.5	568
Solar cycle 17	September 1933	February 1944	10.4	119.2 (Apr 1937)	7.7	269
Solar cycle 18	February 1944	April 1954	10.2	151.8 (May 1947)	3.4	446
Solar cycle 19	April 1954	October 1964	10.5	201.3 (Mar 1958)	9.6	227
Solar cycle 20	October 1964	June 1976	11.7	110.6 (Nov 1968)	12.2	272
Solar cycle 21	June 1976	September 1986	10.3	164.5 (Dec 1979)	12.3	273
Solar cycle 22	September 1986	May 1996	9.7	158.5 (Jul 1989)	8.0	309
Solar cycle 23	May 1996	December 2008 [10]	12.6	120.8 (Mar 2000)	1.7	820 (through Jan 15, 2011) [11]
Solar cycle 24	December 2008 [10]					
Mean			11.1	114.1	5.8	

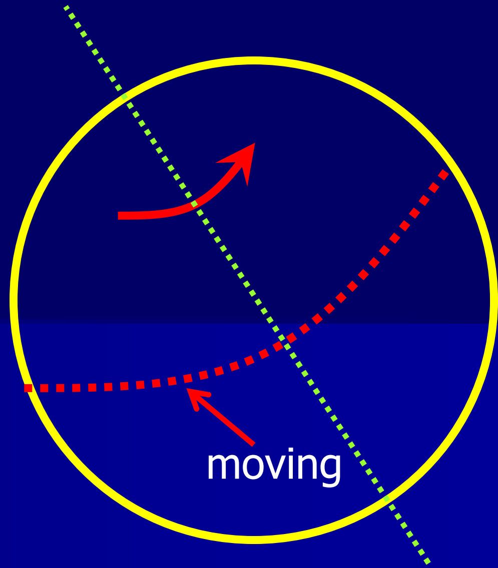
Half a century later, Harold Babcock and Horace Babcock (father and son) showed that the solar surface is magnetized even outside of the sunspots; that this **weaker magnetic field** is to first order a dipole; and that this dipole also undergoes polarity reversals with the same period (22 years) as the sunspot cycle.

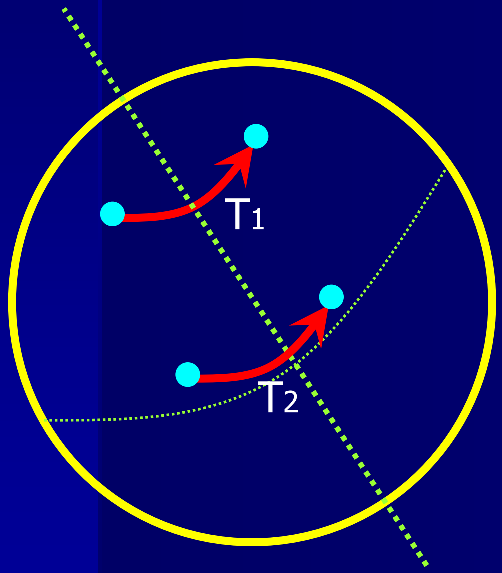






If the Sun is rotating, the sunspots are also rotating. If we analyzed the two sunspots, the gap between those two sunspots are changing due to the Sun's rotating. Because the surface of the Sun is not a solid sphere.



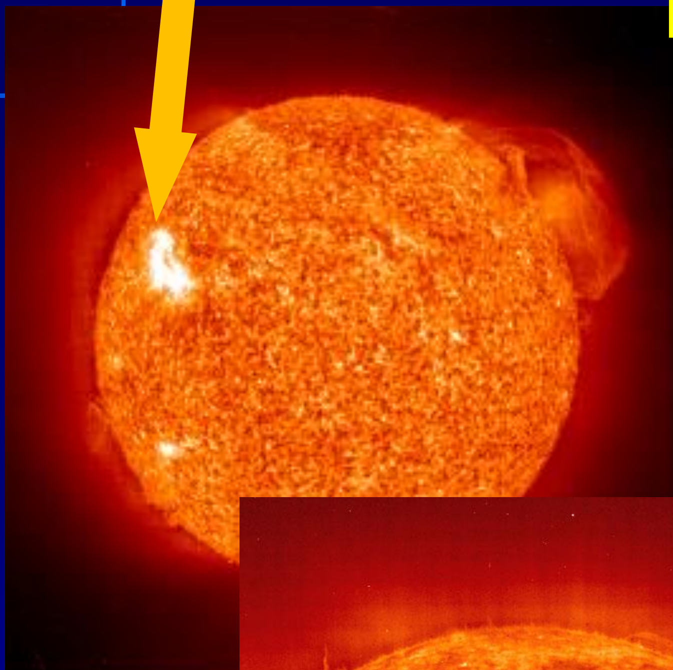


$T_1 \neq T_2$

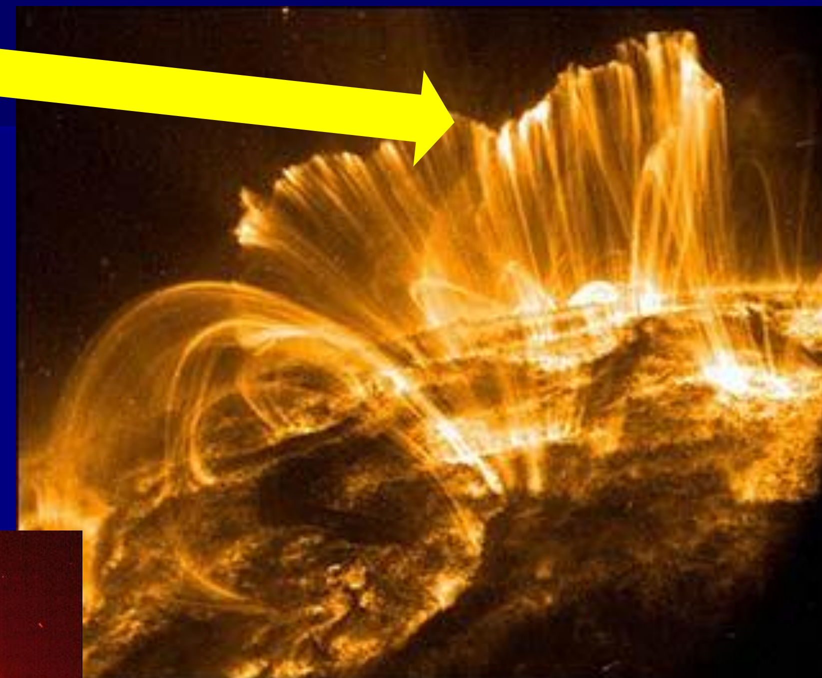
Also the other thing is the velocities of two sunspots, one on the equator and the other one near the poles are not the same values. That means rotating velocities of the Sun's equator and the poles are different to each other.

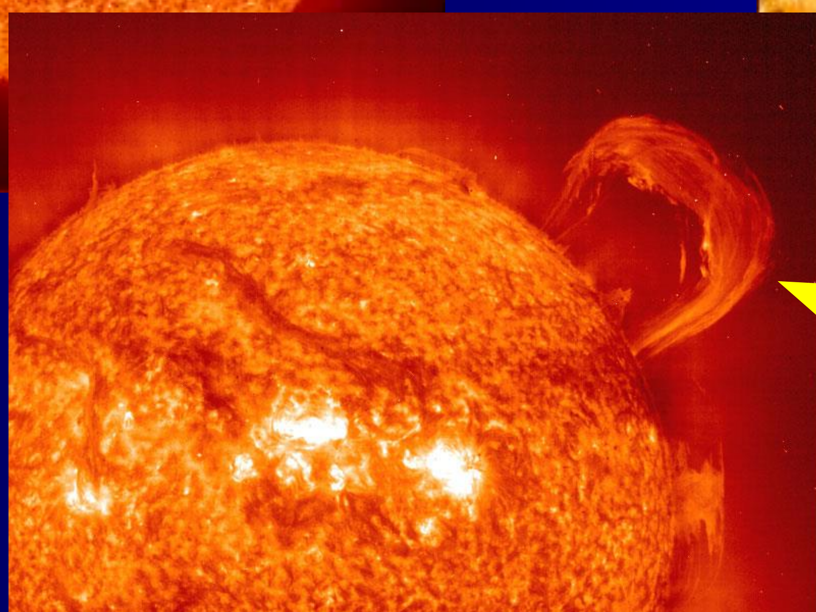
Faculae , Flares & Prominences (නෙරුම)

Faculae (දීදුල)



Flares





Prominences (නෙරුම)

Thank You !