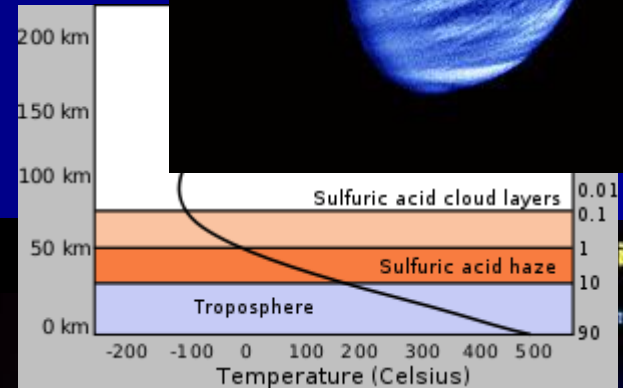
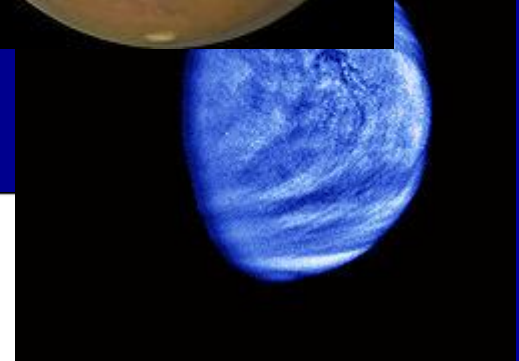
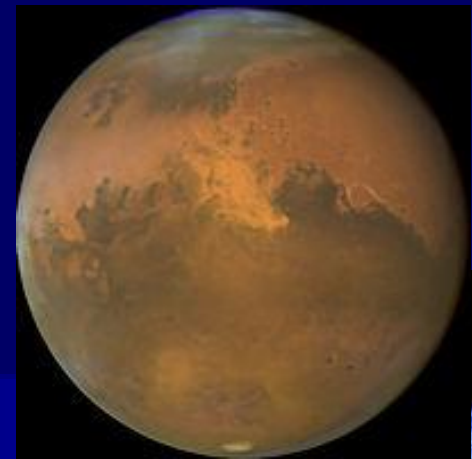
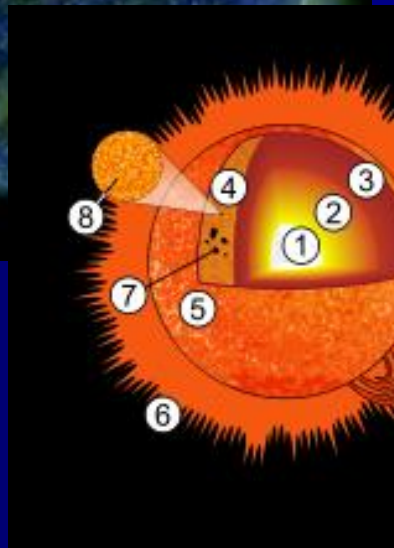
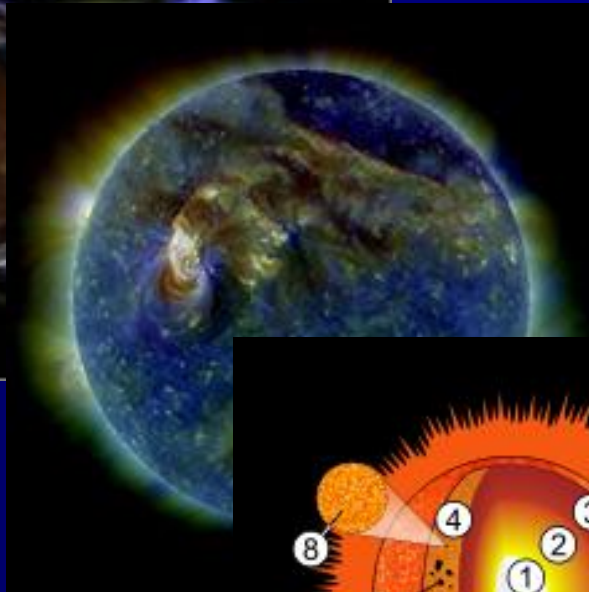
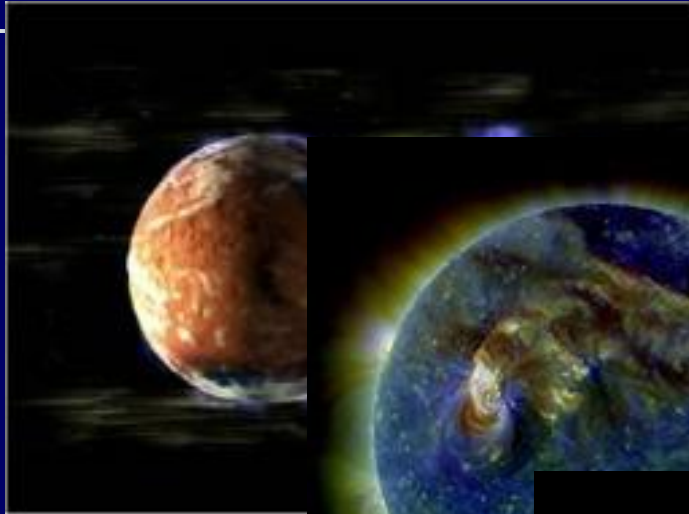


Space Physics

Space Physics



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

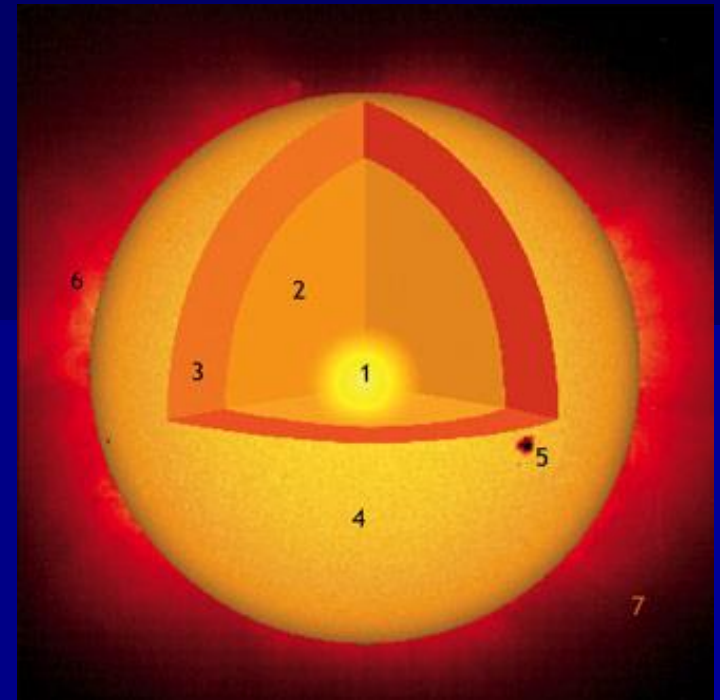
Faculae, Flares and Prominences

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 $M = 1.99 \times 10^{30}$ kg, radius $R = 6.96 \times 10^8$ m and effective temperature $T = 5750$ K. The total energy radiated by the Sun per second, i.e. its **luminosity** L is ,

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

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

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



Using Stephan's Law

$$E = \sigma T^4$$

Energy density per second

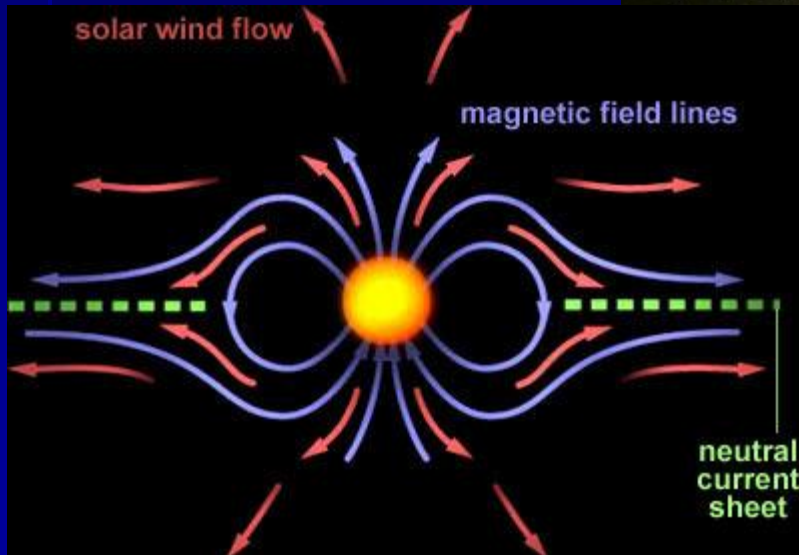
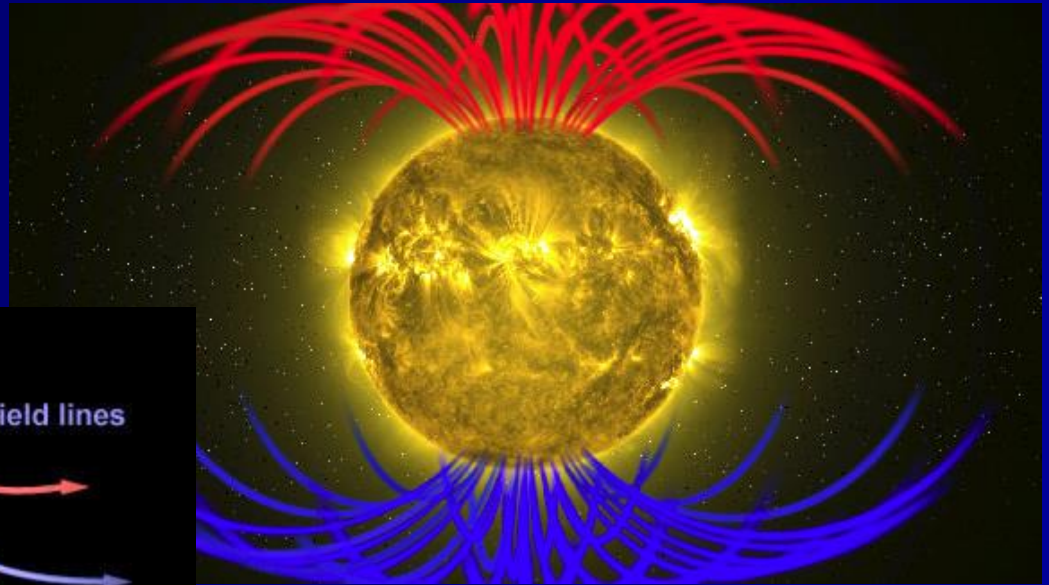
$$\rightarrow E = A \sigma T^4$$

Total Energy per second

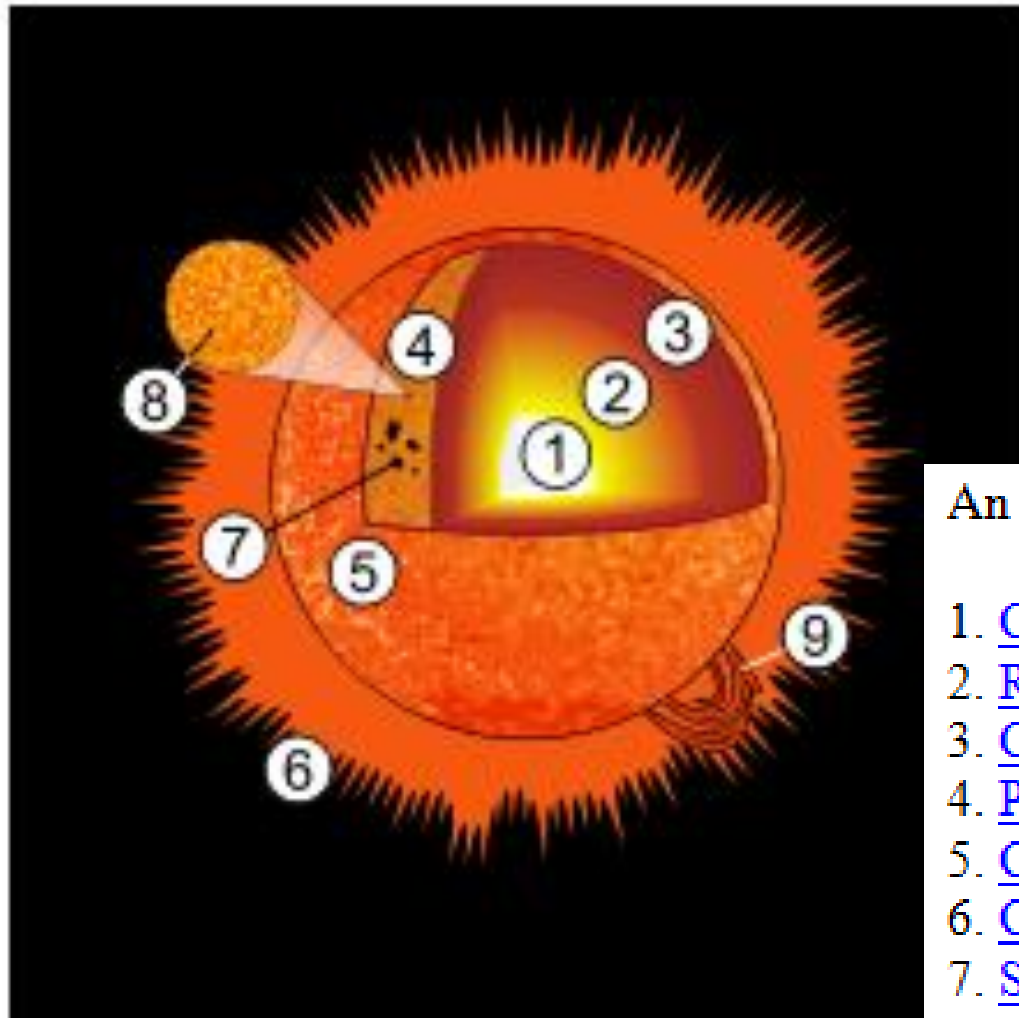
The Sun is a main sequence **G2 star** (A star is between super giant and bright giant), approximately **5 billion years old**. In many ways it is a very representative star and it is estimated that it will remain essentially in its **present state for at least another 5 billion years**.

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

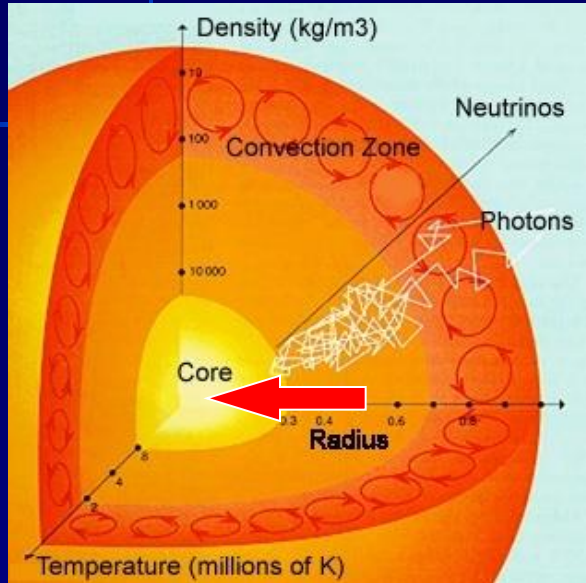


An illustration of the structure of the Sun:

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**.

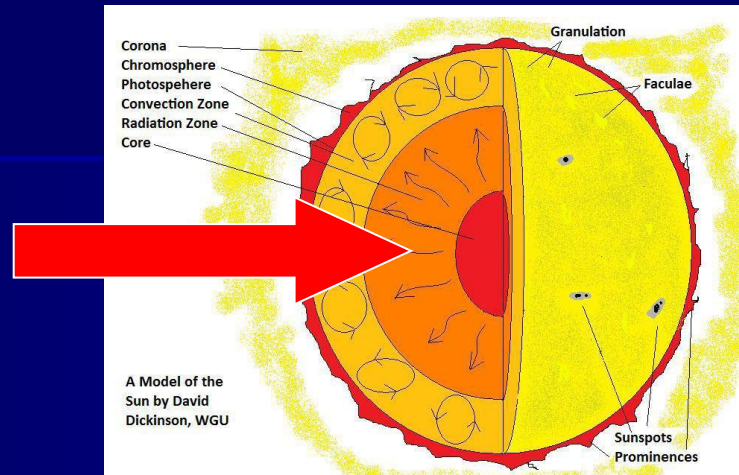
The core is the only region in the Sun that produces an appreciable amount of thermal energy through fusion; inside 24% of the Sun's radius, 99% of the power has been generated and by 30% of the radius, fusion has stopped nearly entirely.

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 9.2×10^{37} times each second in the core of the Sun.

The Structure of the Sun

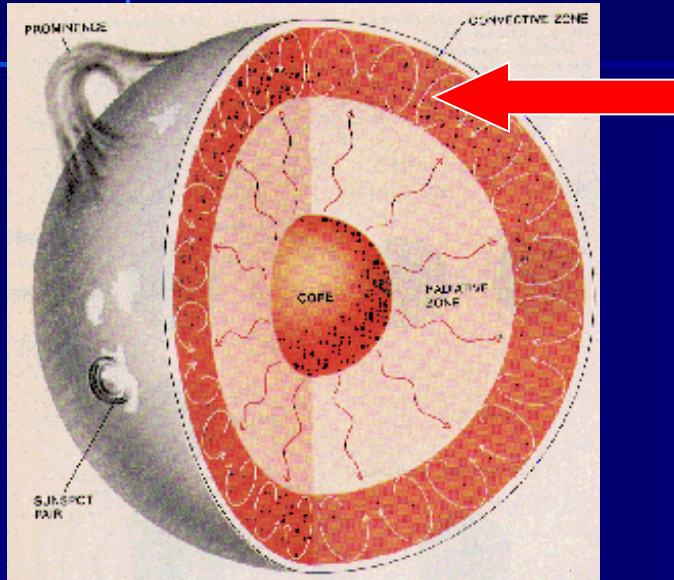
Radiative Zone



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 convection; 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 $20 \times 10^3 \text{ kgm}^{-3}$ to only $0.2 \times 10^3 \text{ kgm}^{-3}$ from the bottom to the top** of the radiative zone.

The Structure of the Sun

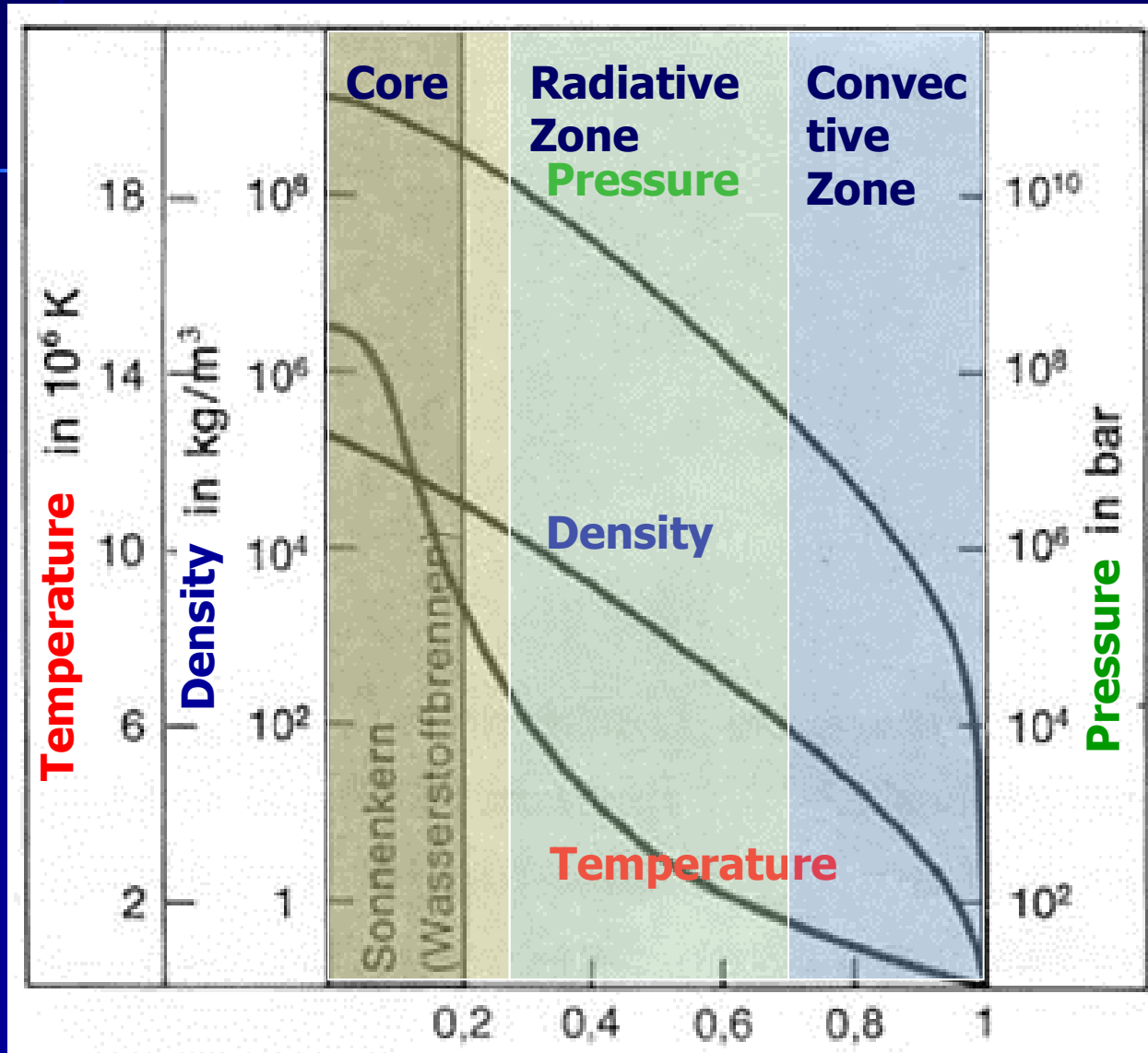
Convective Zone



In the Sun's 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/m³**.

Pressure, Density & Temperature Inside the Sun



Center to ~20-25% R_{\odot}

→ Core

~25% to ~70% R_{\odot}

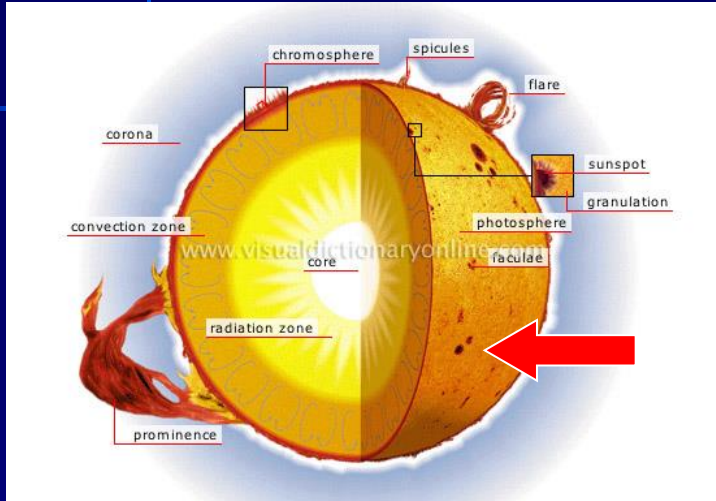
→ Radiative Zone

~70% to 100% R_{\odot}

→ 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

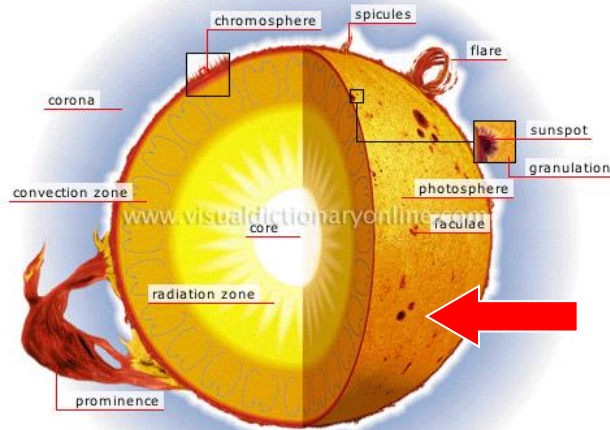
The energy emitted by the photosphere is produced in the core of the Sun through the conversion of hydrogen to helium and is transferred to the bottom of the photosphere by convection.

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**,

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

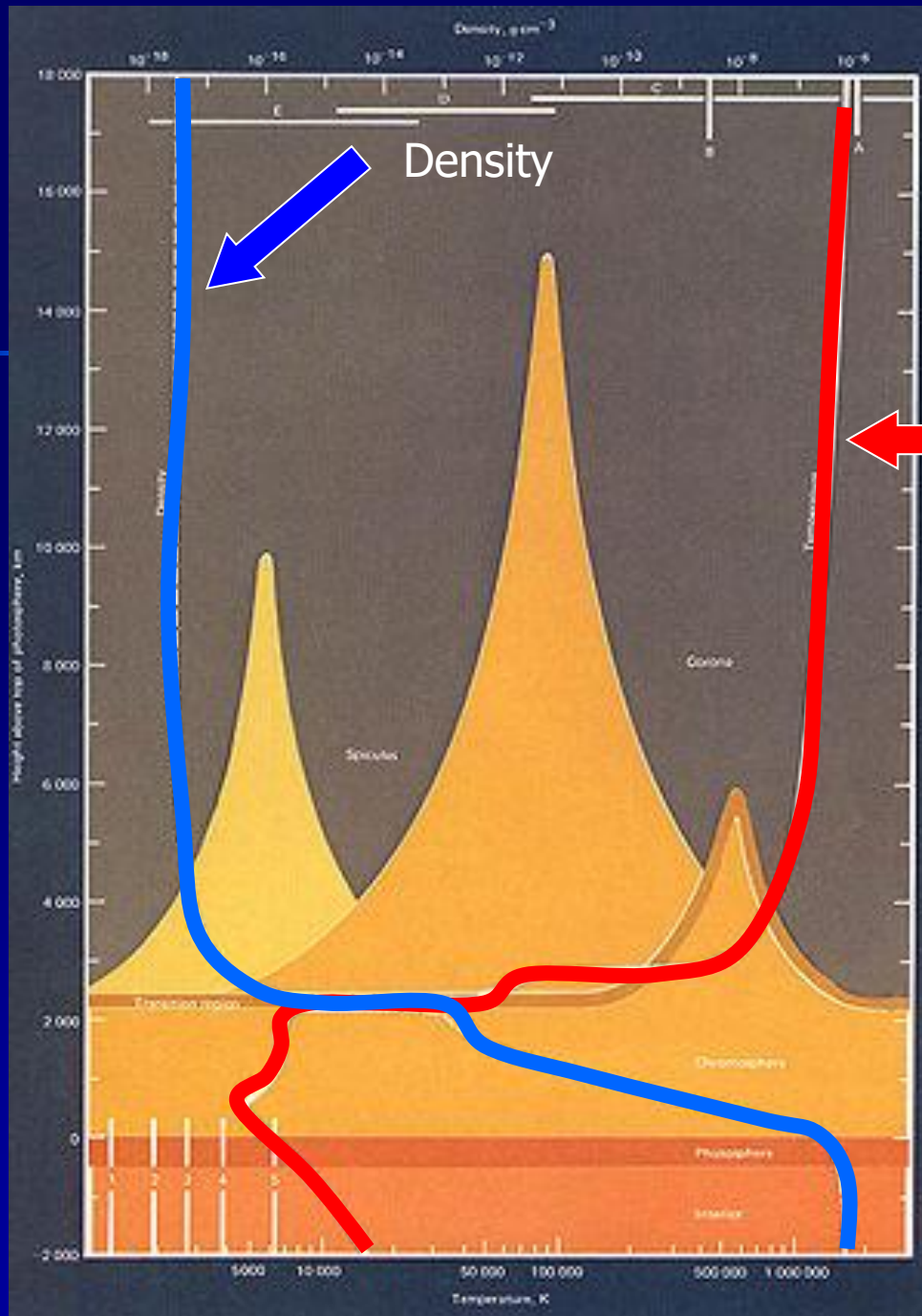
Photospheric composition

(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



Temperature

Structure of the Sun : Chromosphere & Corona



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 one 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 1.5×10^6 K which is the nearly constant temperature of the **solar corona**.



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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

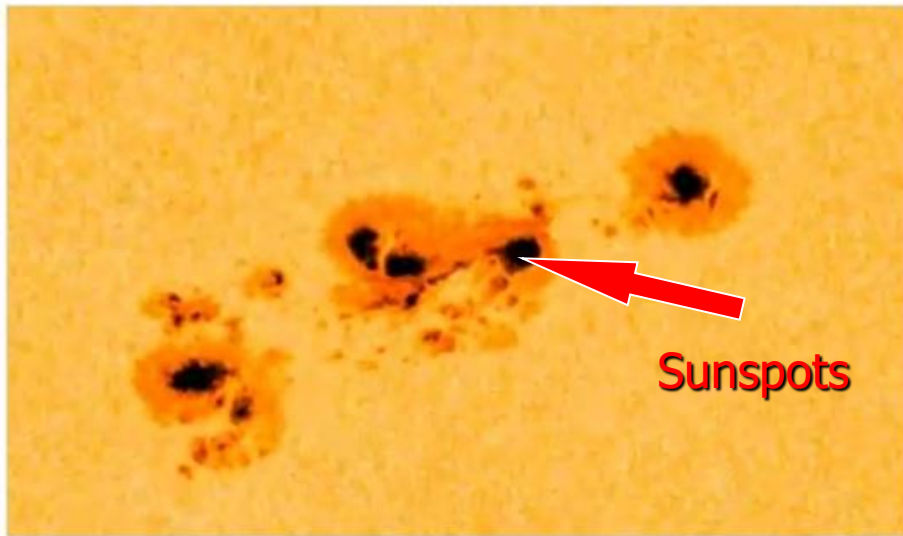
The Chromosphere and the Corona

The first 1000 km of the chromosphere are a fairly uniform layer, but above this height the chromosphere becomes a very in-homogeneous region because it consists 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 spicules continuously rise and fall and their average life time is close to 5 minutes.**

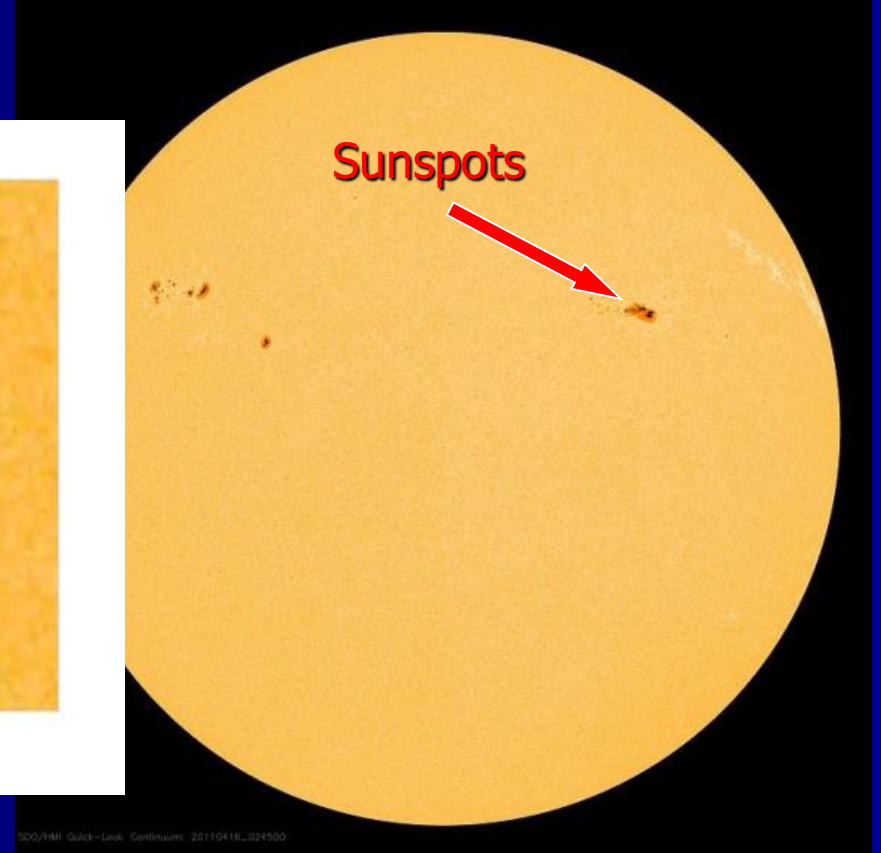
The solar corona begins essentially in the region between the spicules and extends outwards merging ultimately with the interplanetary medium. The **temperature of the corona** is approximately **1.5×10^6 K** and changes very slowly with the distance from the Sun. The **coronal gas at this high temperature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

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

Relative Sunspot Number → R

k ← *Calibration Factor*

g ← *Number of sunspot groups on the disk of the Sun*

f ← *Number of individual sunspots 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

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

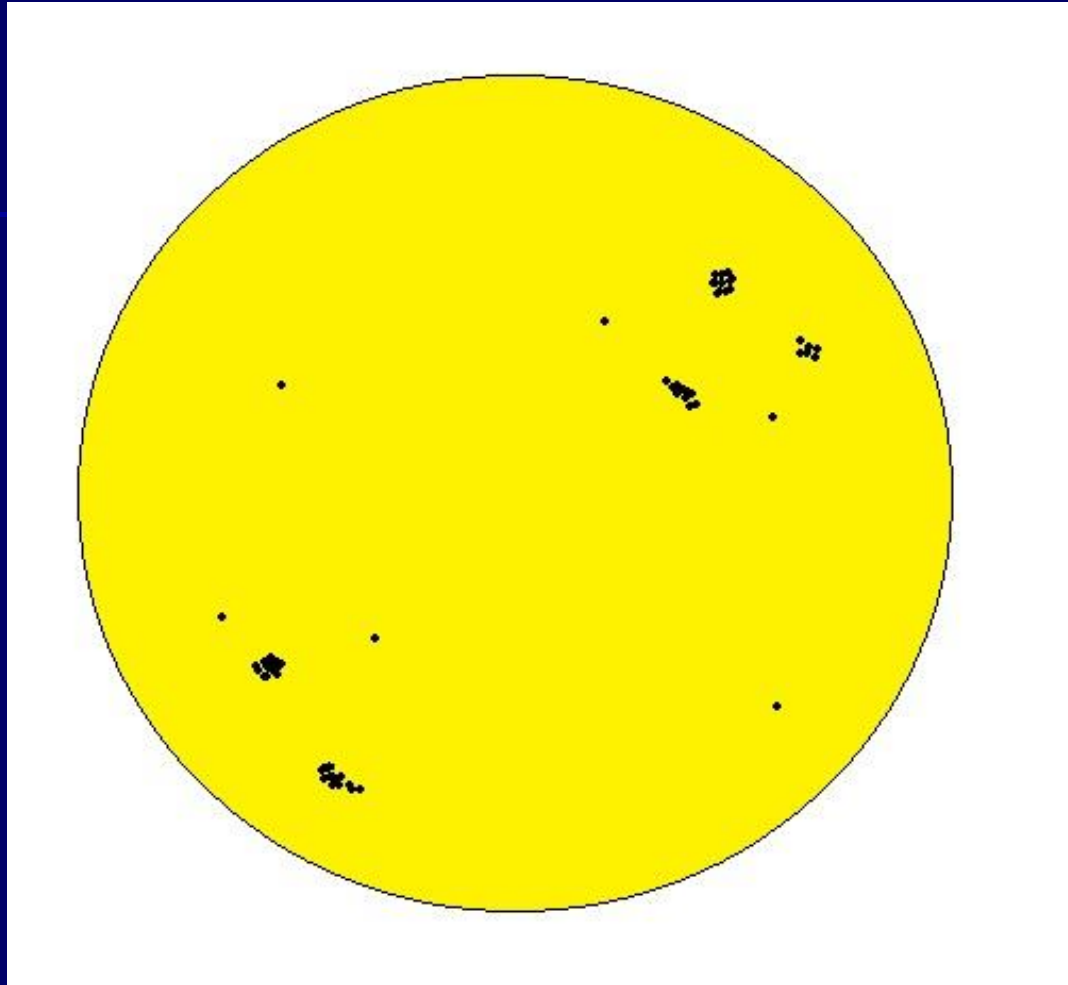
In 1855 Wolf became the **director** of the **new Zurich Observatory** and established there a **Long Tradition of Solar Observations**. For this reason **R** is also called **Wolf sunspot number** or **Zurich sunspot number**.

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!

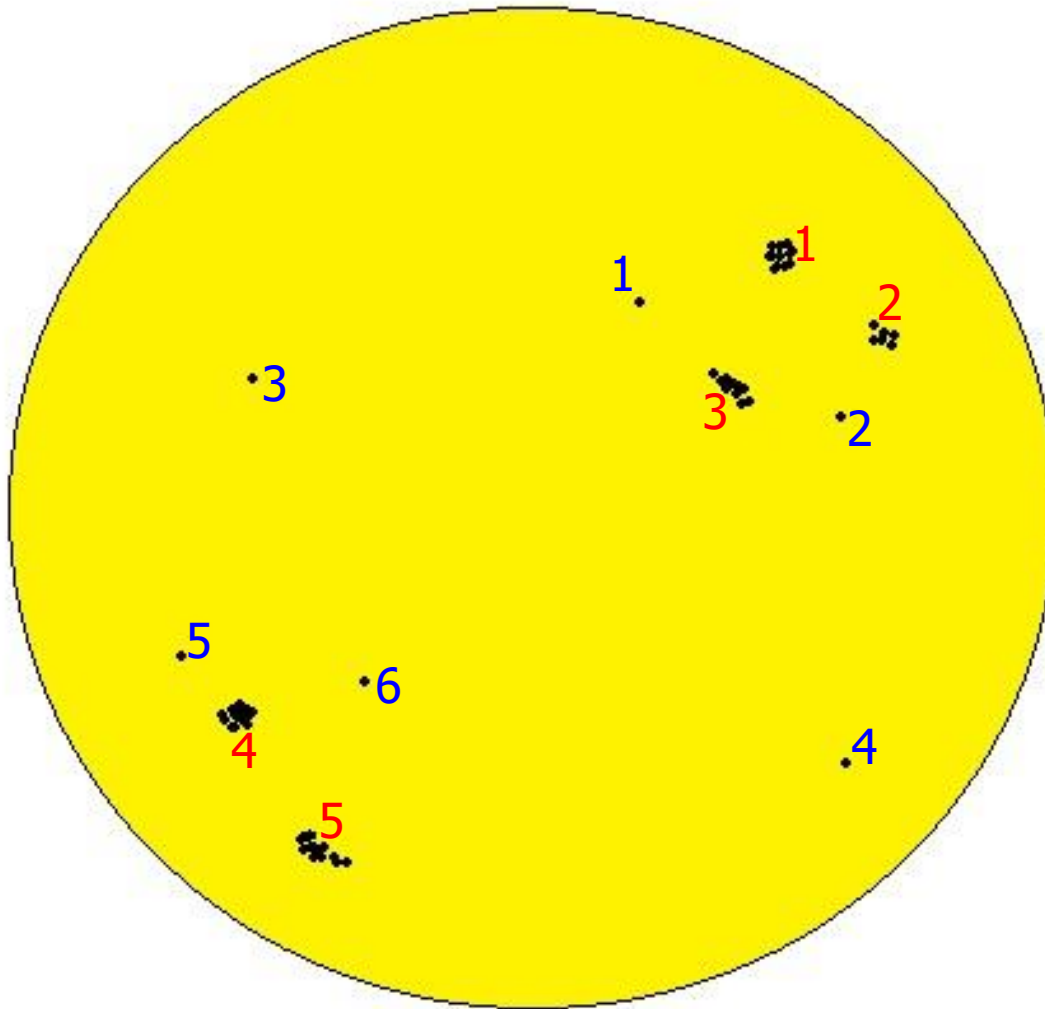


Sunspots & the Solar Cycle



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,

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

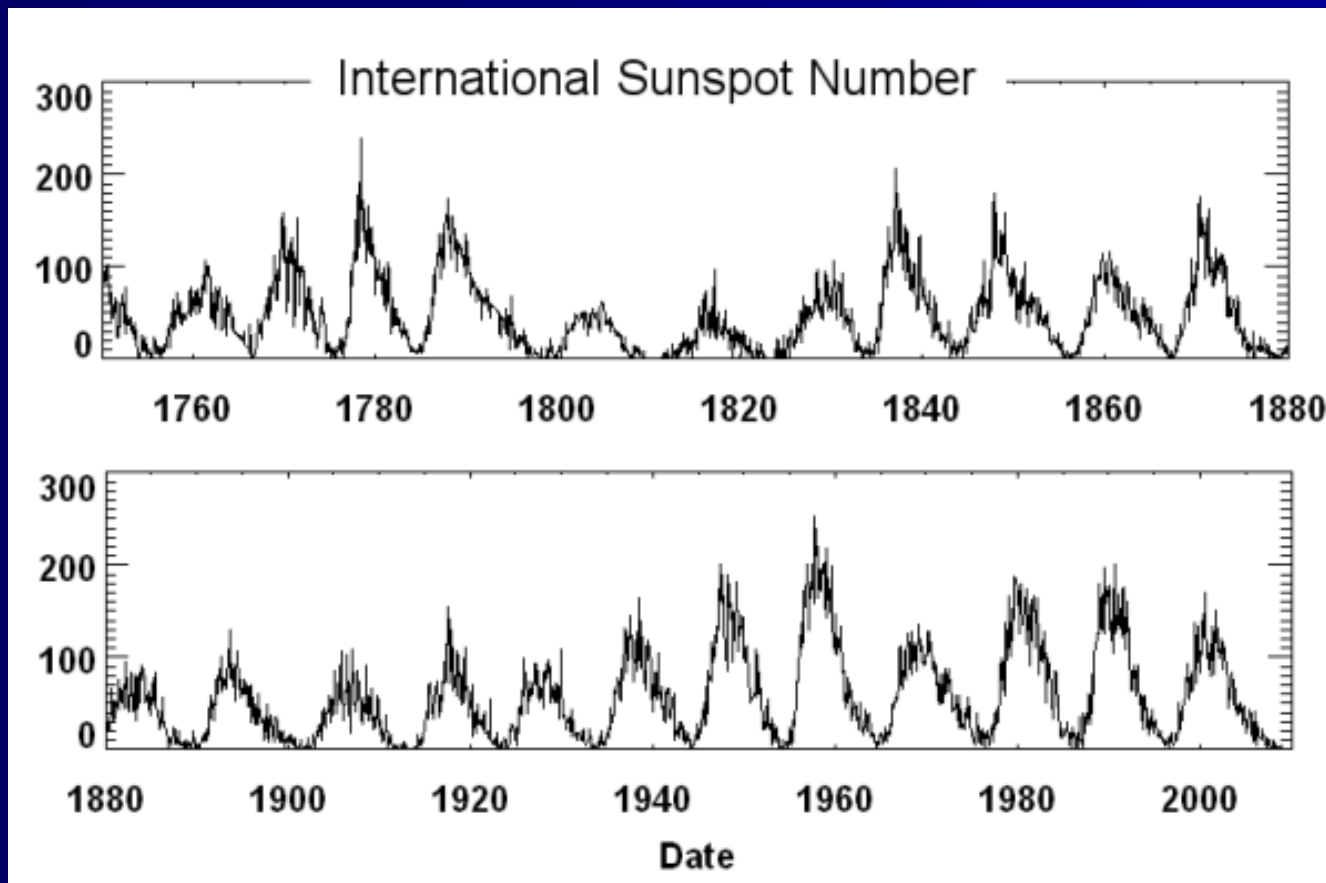
$$R = k[10 \times 5 + 6]$$

If $k = 0.45$

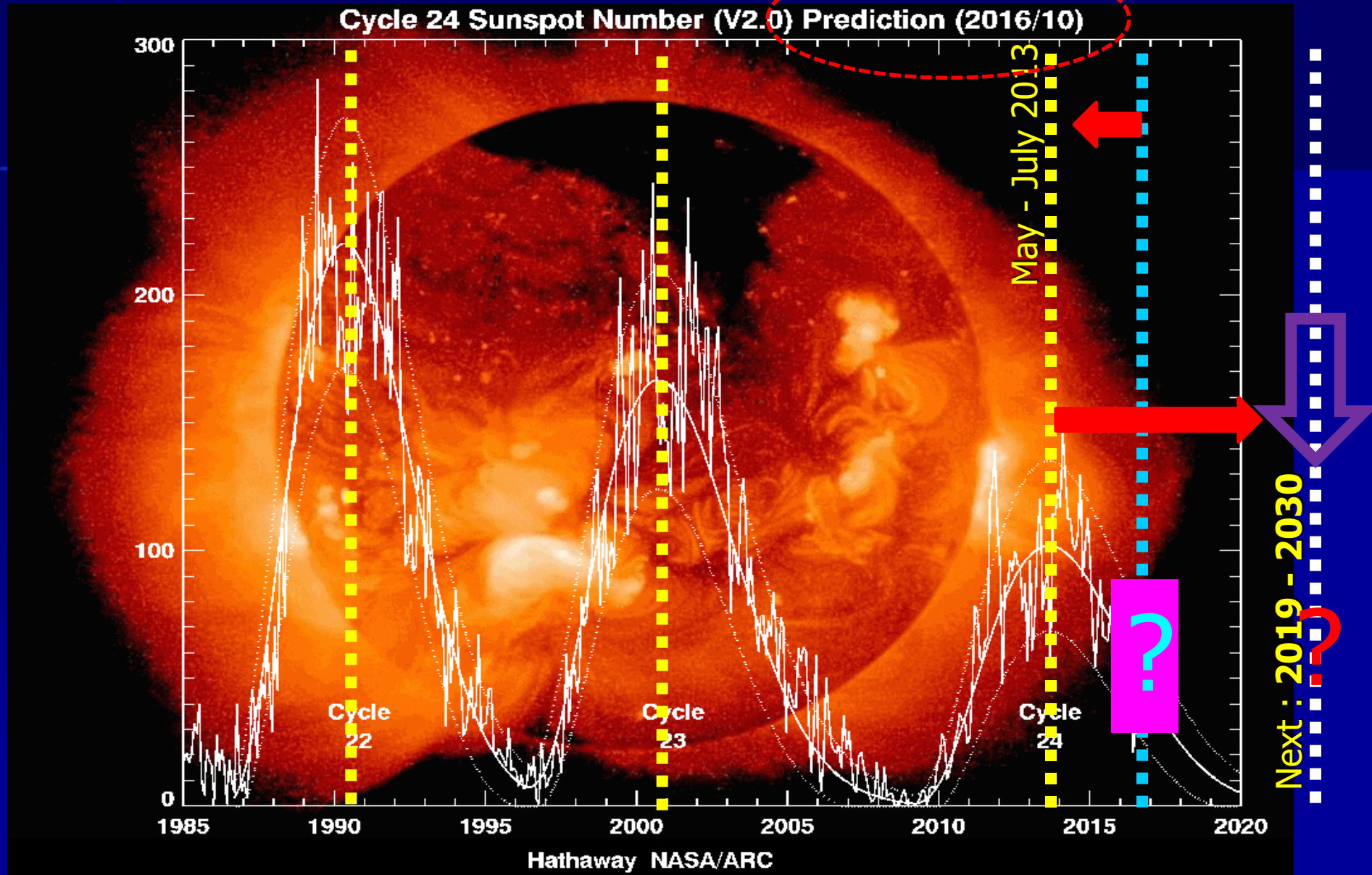
$$R = 25.2$$

International sunspot numbers from 1745 to the present

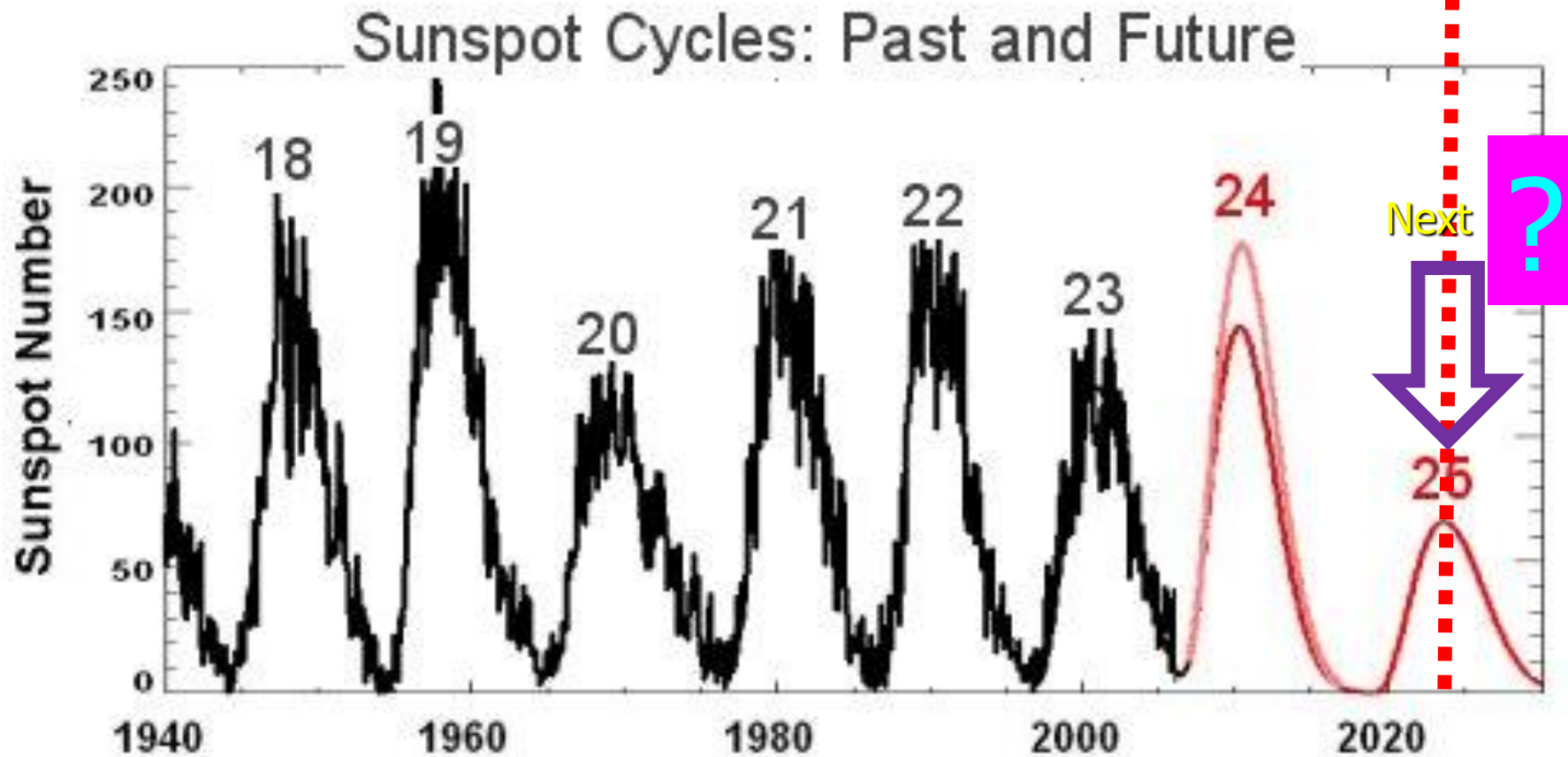
The following figure shows the variation of the yearly average of the sunspot number since 1745 to the present. Data for the first hundred years were reconstructed from old records by **Wolf**.



Future Sunspot Predictions



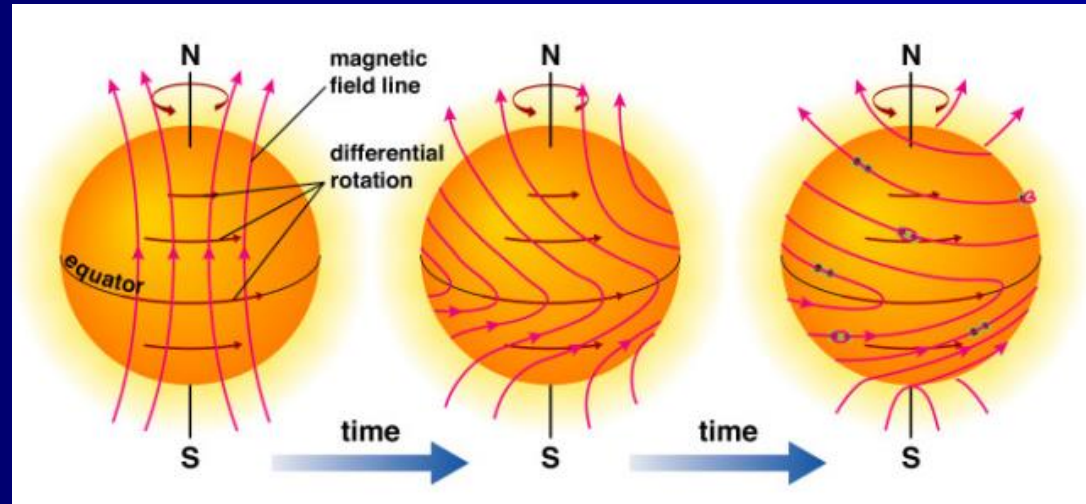
Future Sunspot Predictions :



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 !

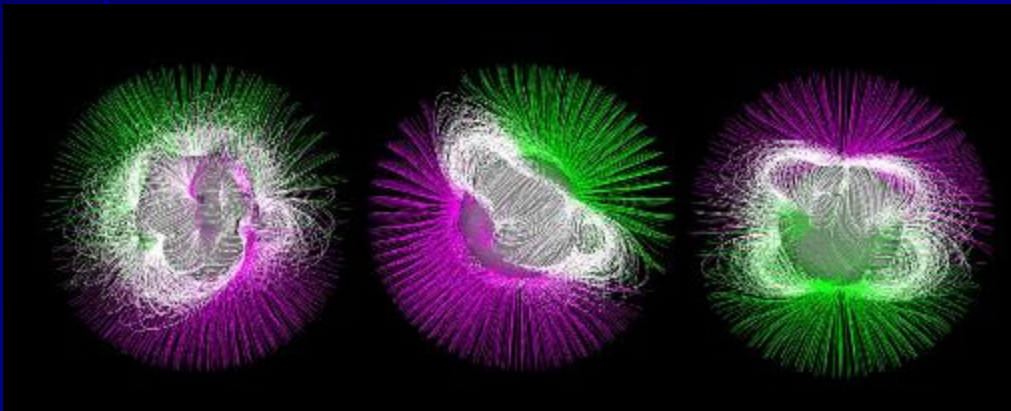
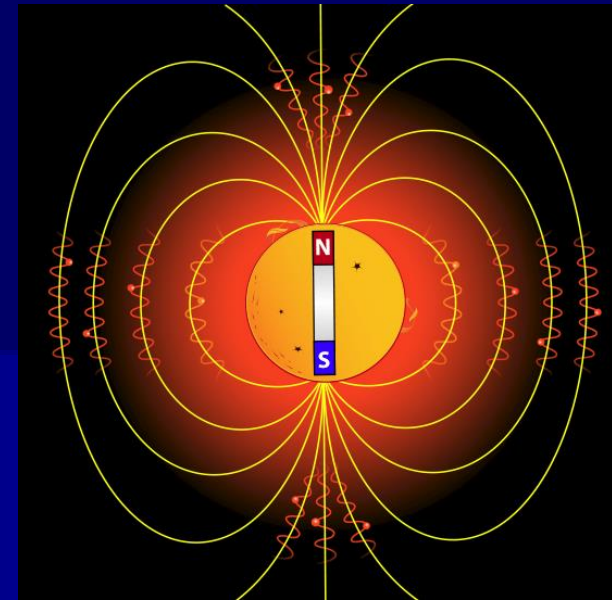
In 1908 **George Ellery Hale**'s observations revealed that the Solar Cycle is a **magnetic cycle with an average duration of 22 years**. However, because very nearly all manifestations of the solar cycle are insensitive to magnetic polarity, it remains common usage to speak of the "**11 years solar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



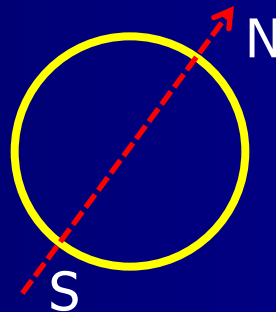
The Solar Cycle

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	

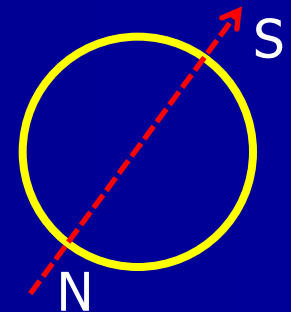
Half a century later, Harold Babcock and Horace Babcock (father and son) showed that the **solar surface is magnetized** even outside of the sunspots; that this **weaker magnetic field** is to **first order a dipole**; and that **this dipole also undergoes polarity reversals with the same period (22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



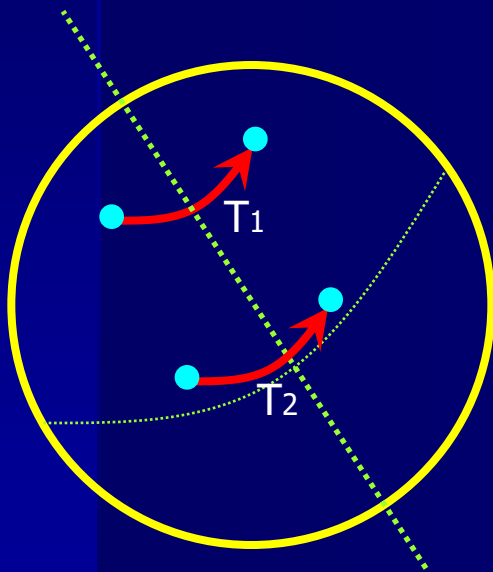
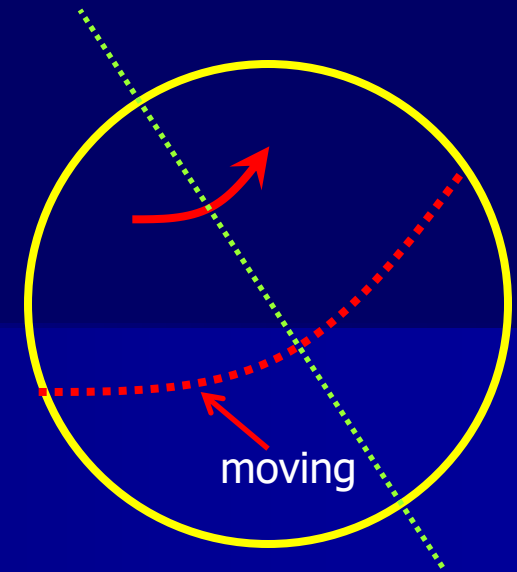
Sun's Magnetic Field



After 22 years



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.

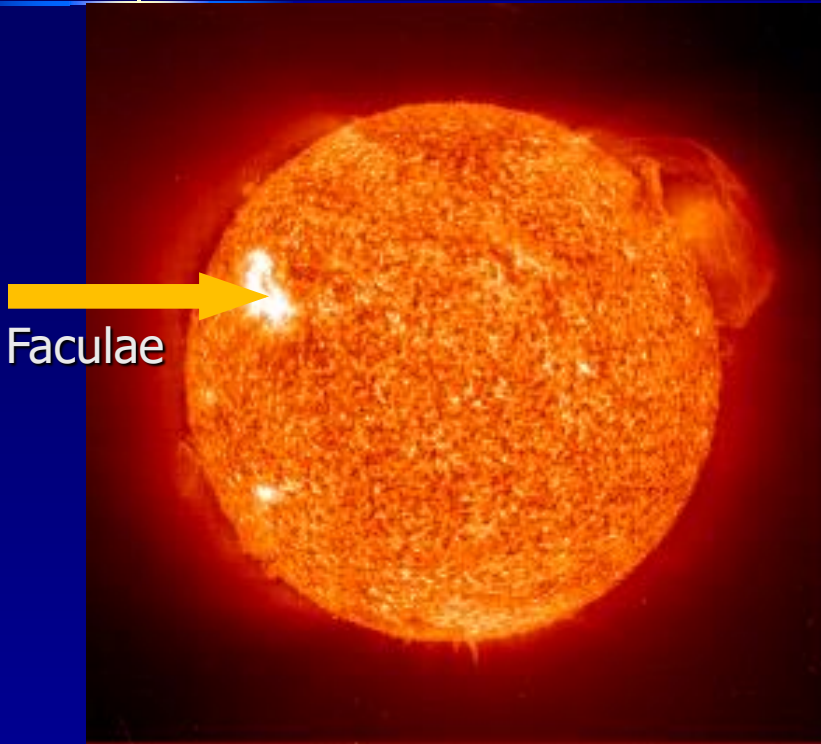


$$T_1 \neq T_2$$

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

In this section we will discuss the different **optical manifestations of the active Sun**.



The first sign of solar activity is the appearance of a bright area which, when near the limb of the Sun, is brighter than the photosphere even in white light. These bright areas are called "**Faculae**", or more precisely "**Photospheric Faculae**".

Faculae usually engulf (swallow) a sunspot group, but they become noticeable before the appearance of the **sunspots and often survive them by a month or two**.

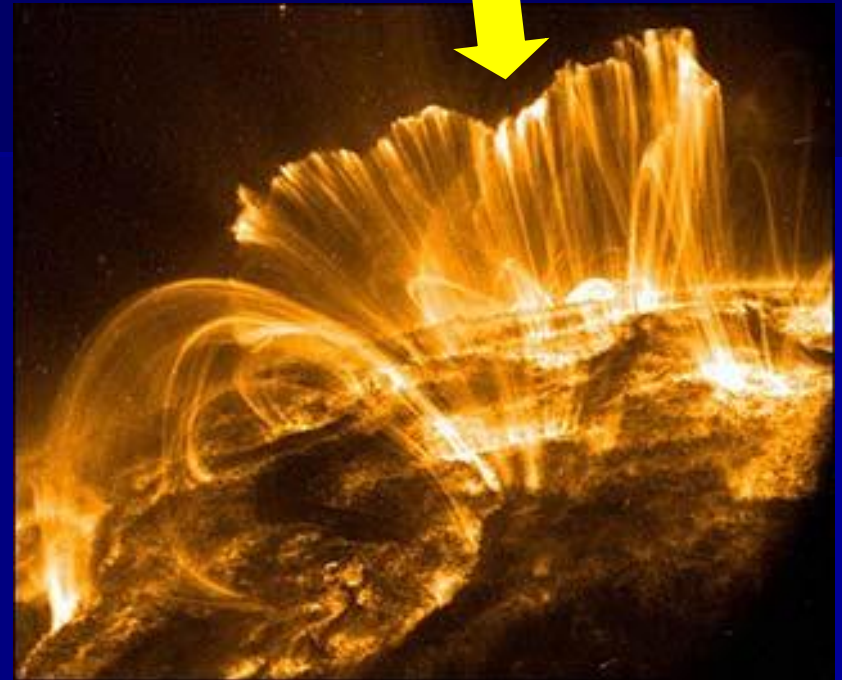
Faculae , **Flares** & Prominences

A **flare** is a sudden local increase in the brightness of the solar surface which lasts for nearly one hour.

Flares appear in an active region, i.e.; a pelage (birth) area with sunspots the eruption (very fast explosion) of a **Solar Flare** is the culmination (get a peak) of the activity that has been mounting up in the sunspot region.

A flare is the optical effect produced by the sudden release of tremendous (very large) amount of energy (6×10^{25} J/s) in the upper chromosphere or the lower corona. This explosion, which probably takes place above the layers where the optical flare appears, produces also a **strong outburst** (blast to the outside) of **X-ray** and **Radio Emission** which we will discuss in the next section.

Flares



Solar Activity & Solar Flares

The incidence of solar flares is another measure of solar activity and is related to the sunspot number by,

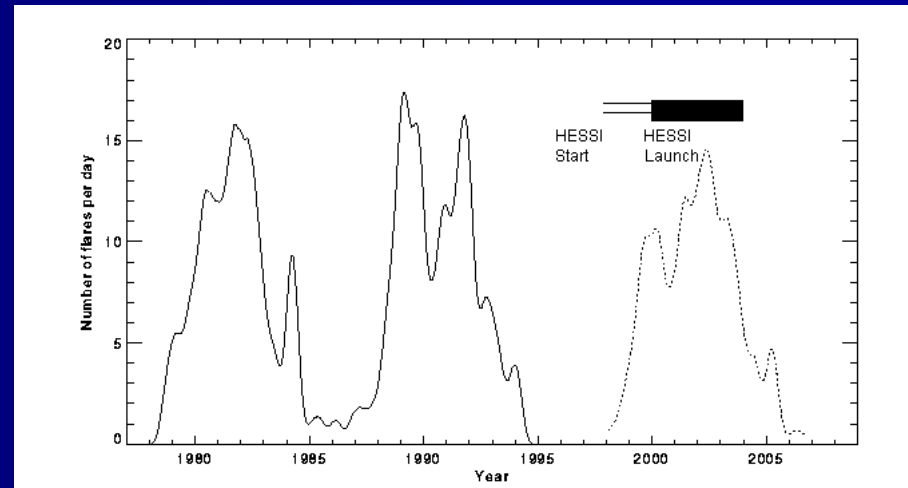
*Number of Solar
Flares observed*

*Mean Sunspot
Number*

$$N_t = \alpha [\bar{R} - 10]$$

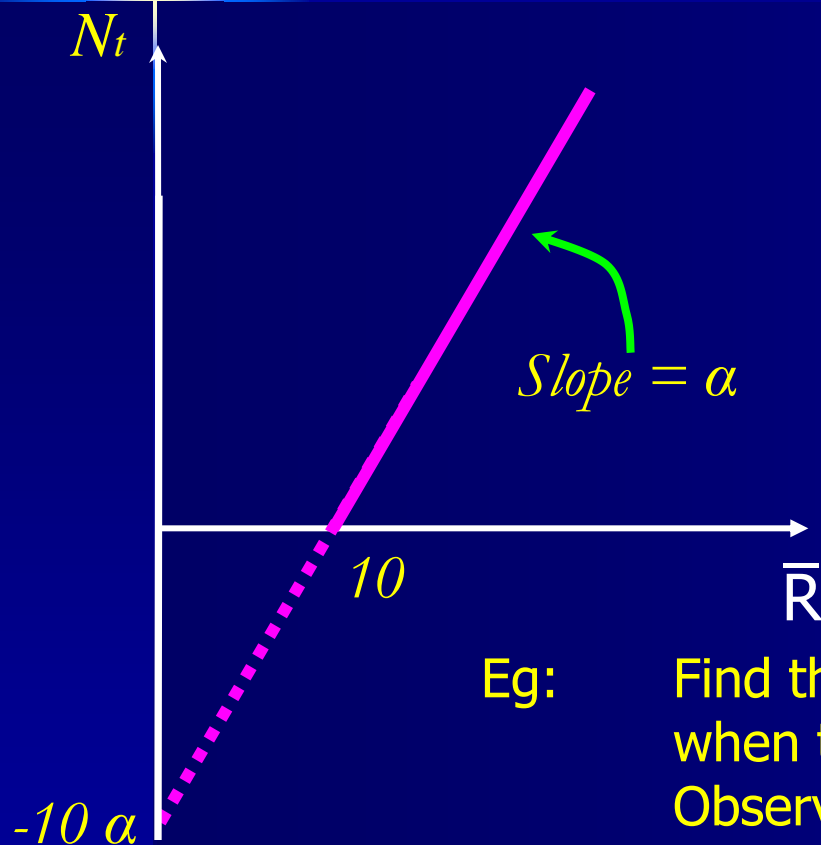
Observatory Constant
 $\sim 1.5 - 2.0$

Where, N_t is **Number of Solar Flares observed during one solar rotation**, \bar{R} is the **Mean Sunspot Number** and α (alpha) is an **Observatory Constant** of value between $\sim 1.5 - 2.0$.



Solar Activity & Solar Flares

The graph of Number of solar flares observed per solar rotation verse mean sunspot number :



Eg:

Find the number of solar flares per solar rotation when the mean sunspot number is 25 and Observatory Constant 1.6.

$$N_t = \alpha [\bar{R} - 10]$$

$$N_t = \alpha \bar{R} - 10 \alpha$$

↓ ↓ ↓ ↓
y m x - c

$$\text{If, } N_t = 0 \rightarrow \bar{R} = 10$$

$$\text{If, } \bar{R} = 0 \rightarrow N_t = -10 \alpha$$

$$N_t = \alpha [\bar{R} - 10]$$

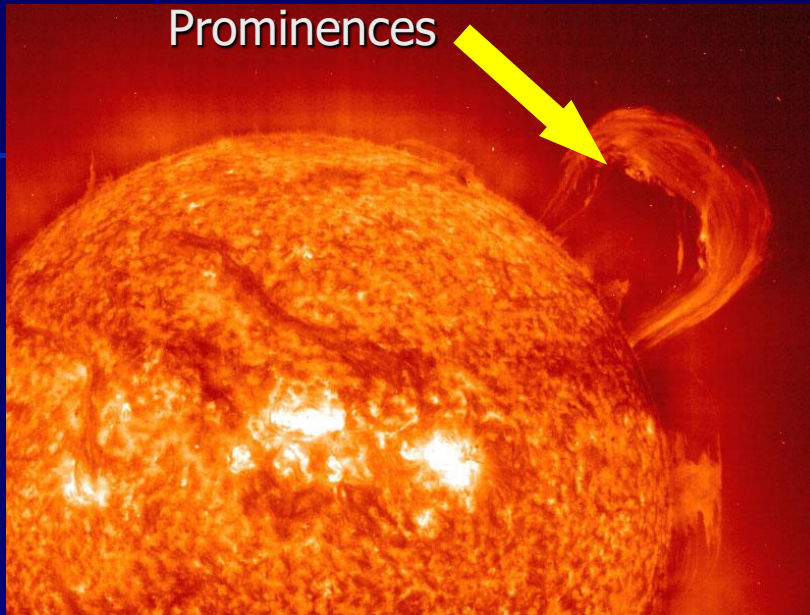


$$N_t = 1.6 [25 - 10]$$



$$N_t = 24$$

Faculae , Flares & Prominences (නෙරුම)



Solar **prominence** (**more gases emitted place**) have been recorded in same very impressive sequences with time-lapse photography. When seen at the limb of the Sun, **prominence appear as luminous arch-like structures with continuous internal motion**. These arches are about 200,000 km long but only a few thousand kilometers thick.

When they are projected on the luminous disk of the Sun they simply appear as **long dark filaments**.

The **active prominences** which appear over a sunspot group and for this reason they are called **sunspot prominences**, and the **quiescent** (**very calm**) **prominences** which are associated with peculiar (**own**) regions without sunspots or with sunspot groups in their decaying stage.

Thank You !

