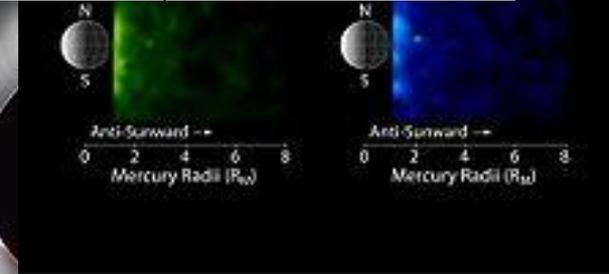
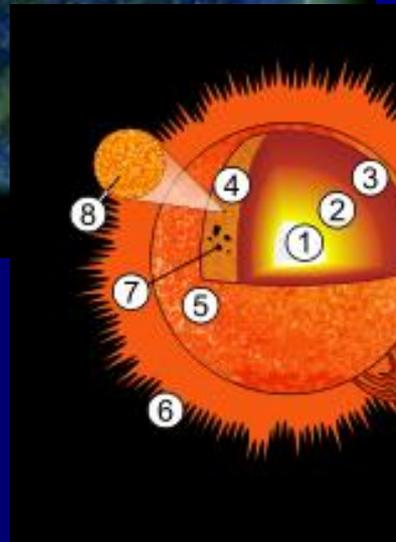
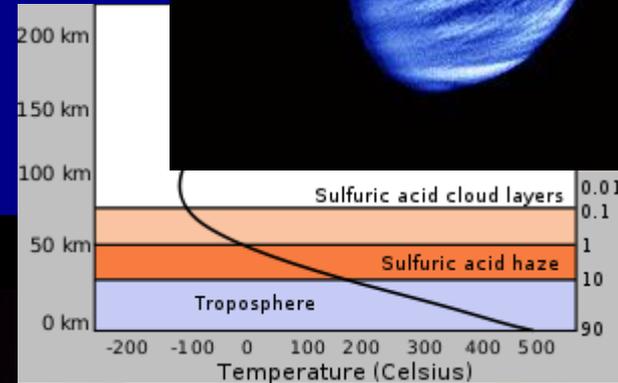
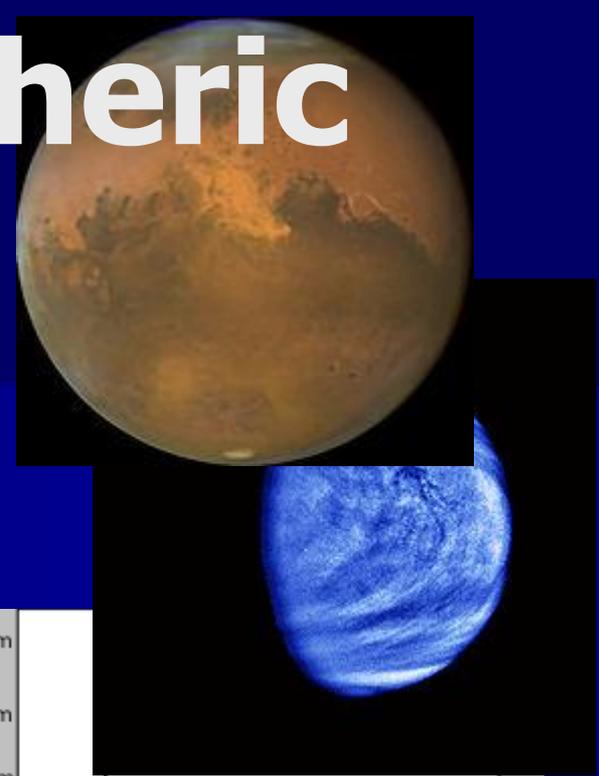
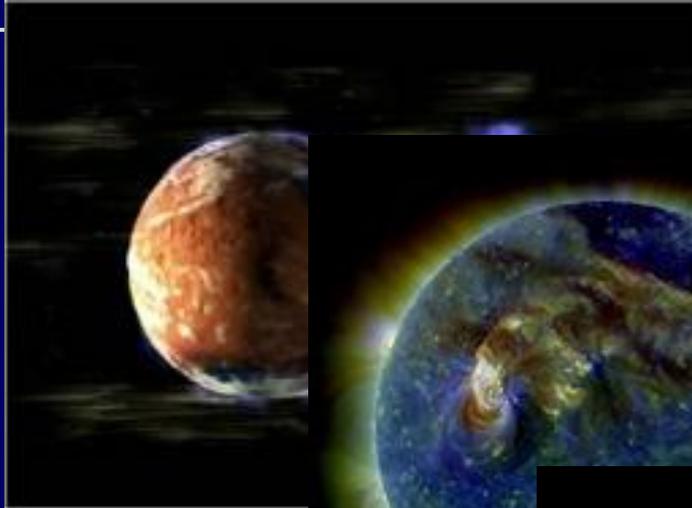


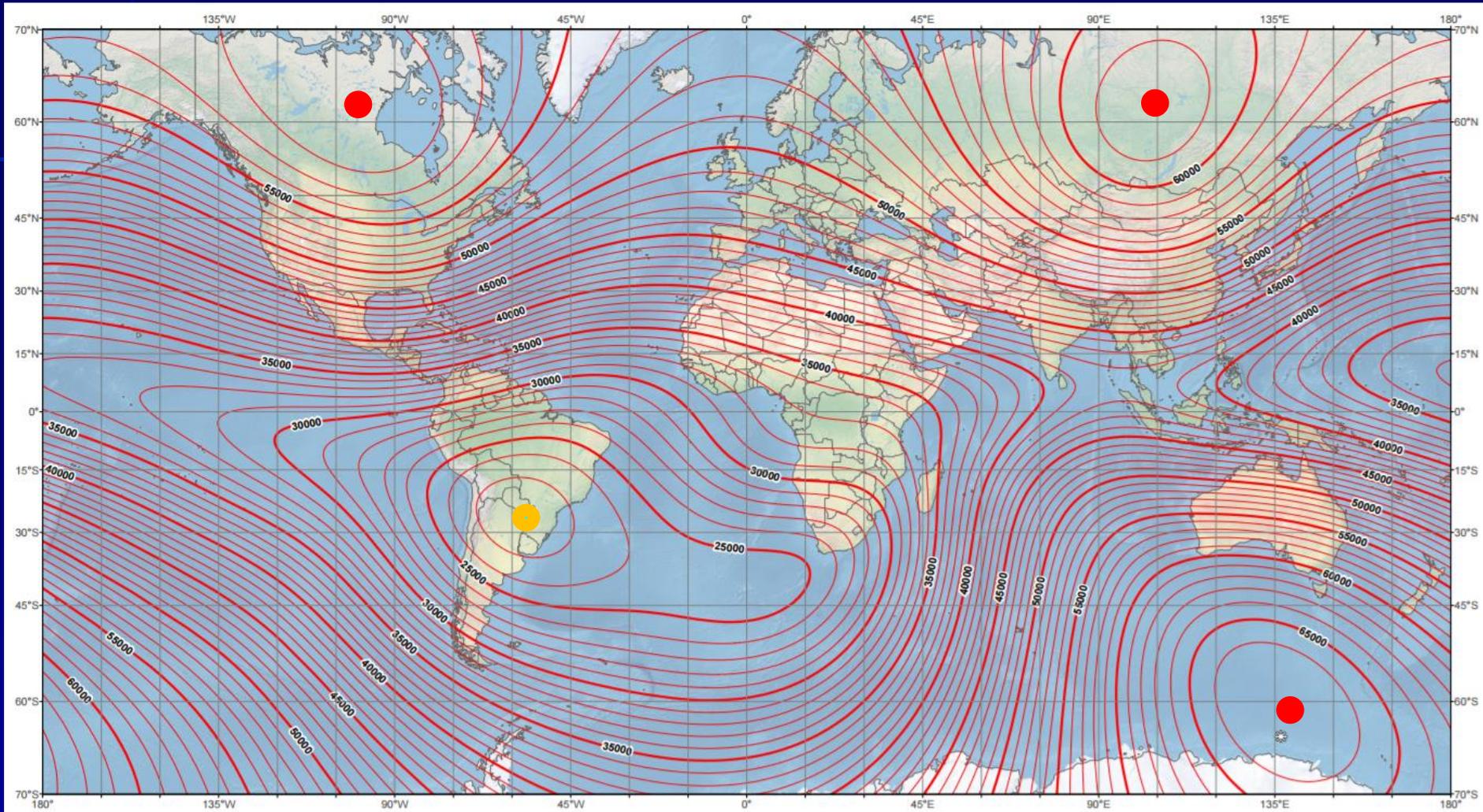
Space Physics

Space & Atmospheric Physics



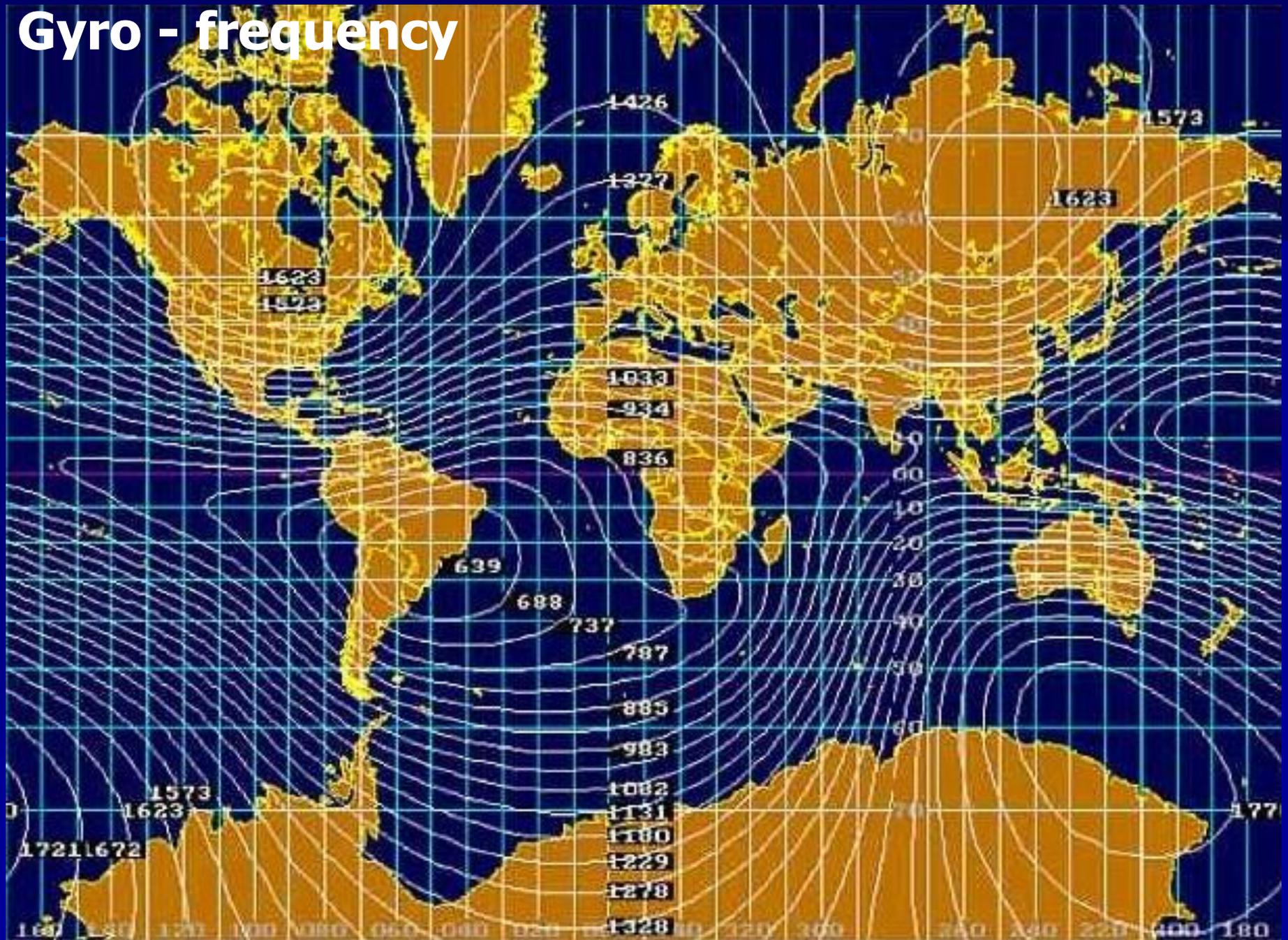
Lecture – 11 A

The Earth Magnetic Field



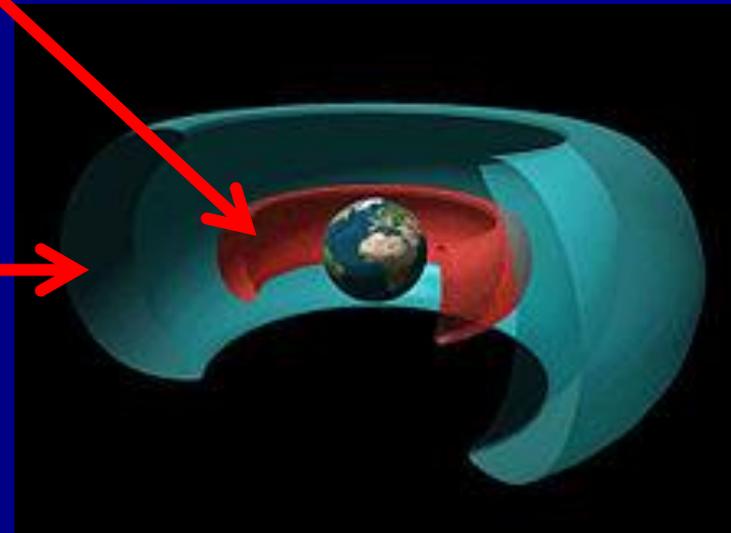
Min - ●
Max - ●

Gyro - frequency

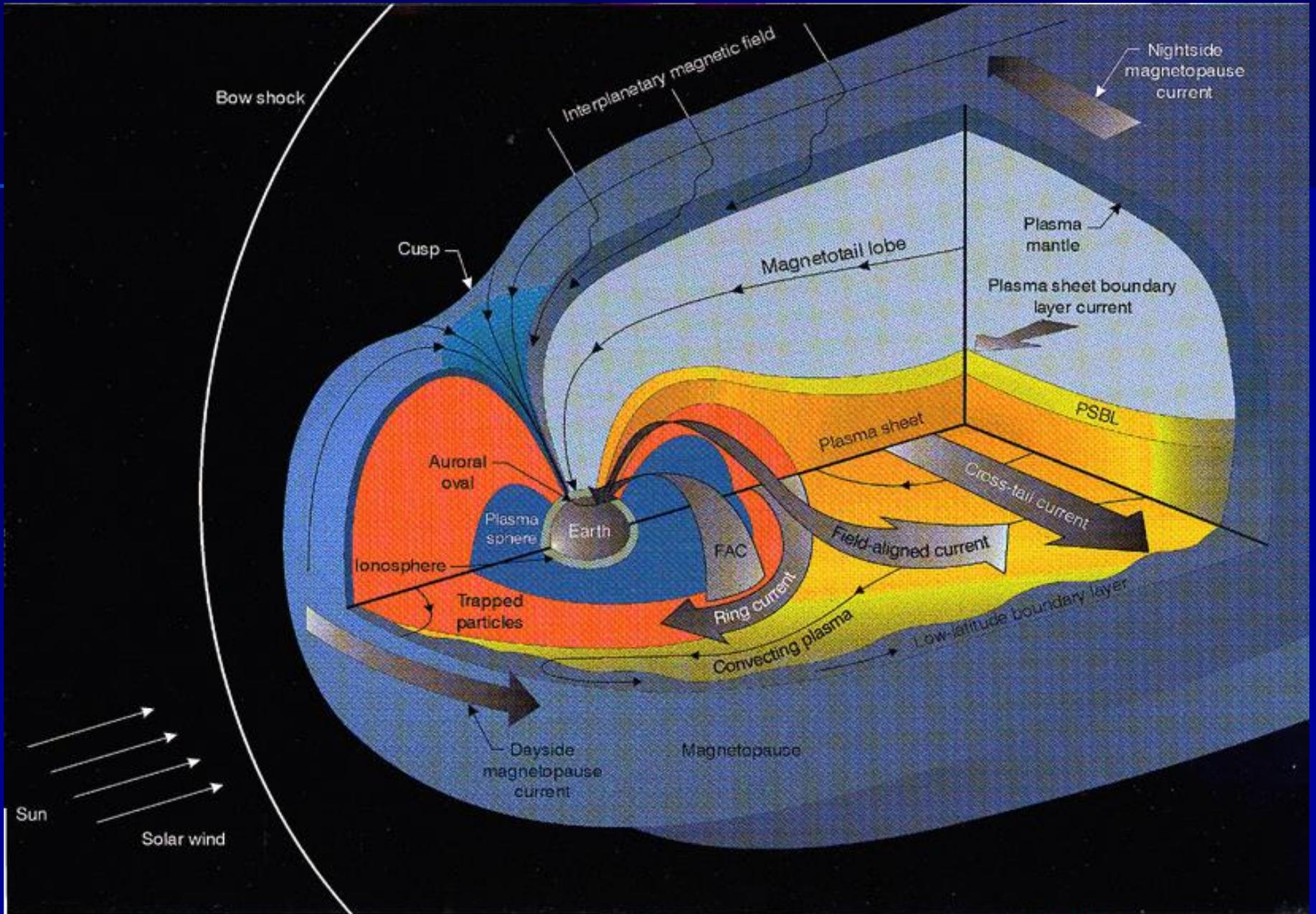


The Radiation Belts

- The first counters could not differentiate between **energetic protons** and **energetic electrons**.
- Today we know that the high counting rates of the **inner belt are produced by energetic protons** with energies in the 10 to 100 MeV range, while the high counting rates of the **outer belt are produced by high energetic electrons** with energies in the 1 MeV range and above.



The Boundary and the Tail of the Magnetosphere



The Active Sun

The Sun and Stars

Introduction of the Active Sun

The Photosphere

The Chromosphere and the Corona

Sunspots and the Solar Cycle

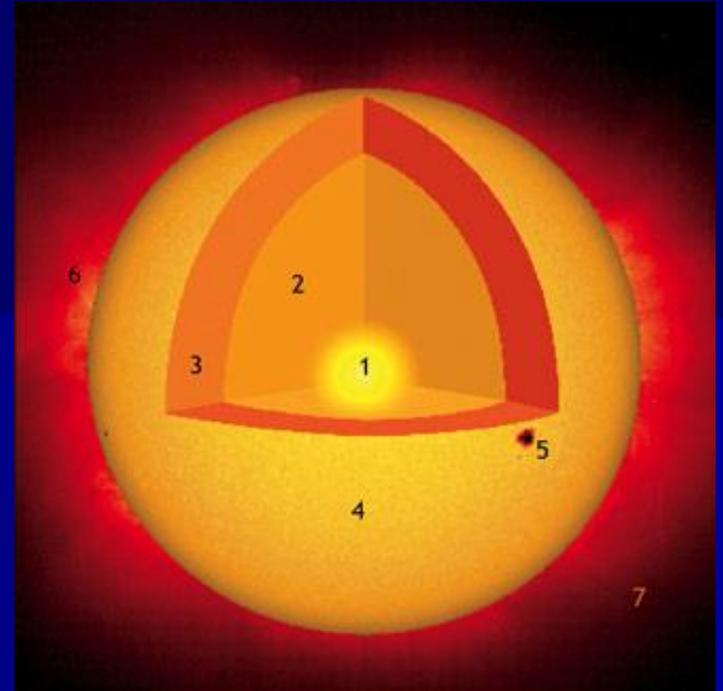
Faculae, Flares and Prominences

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 ,



Using Stephan's Law

$$E = \sigma T^4$$

Energy density per second

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

Total Energy per second

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

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

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

The Active Sun

Introduction



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 energy of the Sun is produced mostly **through the proton-proton nuclear reaction near its center** where the temperature is close to **10^7 K**. The **carbon nuclear cycle makes also a small contribution to the total energy produced**. In both of these processes the end result is that **4 Hydrogen atoms fuse together to form a Helium atom** with the release of approximately **25 MeV**. By comparing this number with the total luminosity of the Sun we see that nearly **10^{38} such fusions must place per second** which means that about **6.4×10^{11} kg of Hydrogen “burn” per second to Helium**. In this transmutation **0.7% of the mass becomes energy** ($E=mc^2$) and therefore about **4.5 million tons of solar matter are converted every second** into energy.

The Active Sun

The Sun is a **gaseous sphere** rotating with an average period of **27 days**. The word "average" is used because the **Sun possesses a differential rotation, i.e., its rotational period varies with latitude**. **The fastest rotation occurs at the equator** where the **sidereal** (with respect to the stars) **period** is very close to **25 days**. The rotation slows down with increasing latitude becoming longer than **30 days near the poles**.

The Active Sun

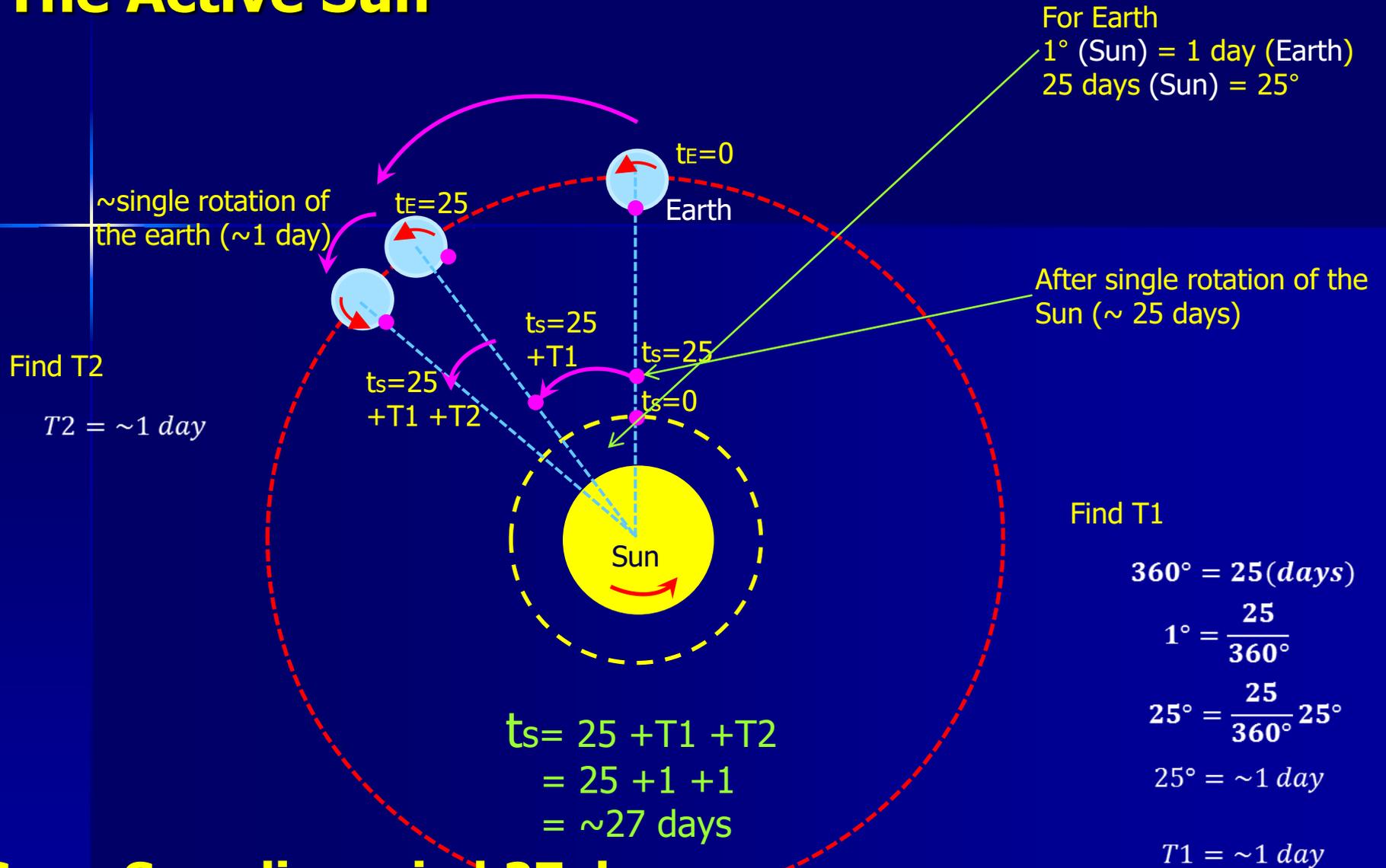
An expression which gives to a good approximation the **daily sidereal rotation**, in degrees, for different solar latitudes, λ is,

The daily sidereal rotation $\phi = 14.4^\circ - 2.8^\circ \sin^2 \lambda$ Solar latitudes

Rotation period at latitude $\lambda = \frac{360^\circ}{\phi}$ (days)

It should be mentioned that for a terrestrial observer the Sun appears to rotate with a longer period, called the **synodic period** (moon month) which for the equatorial regions, is close to **27 days**. The reason of course is that the Earth advances by approximately **1 degree per day** in its orbit around the Sun and after 25 days a point near the equator of the Sun needs roughly two more days to reach the new angle of the Earth.

The Active Sun

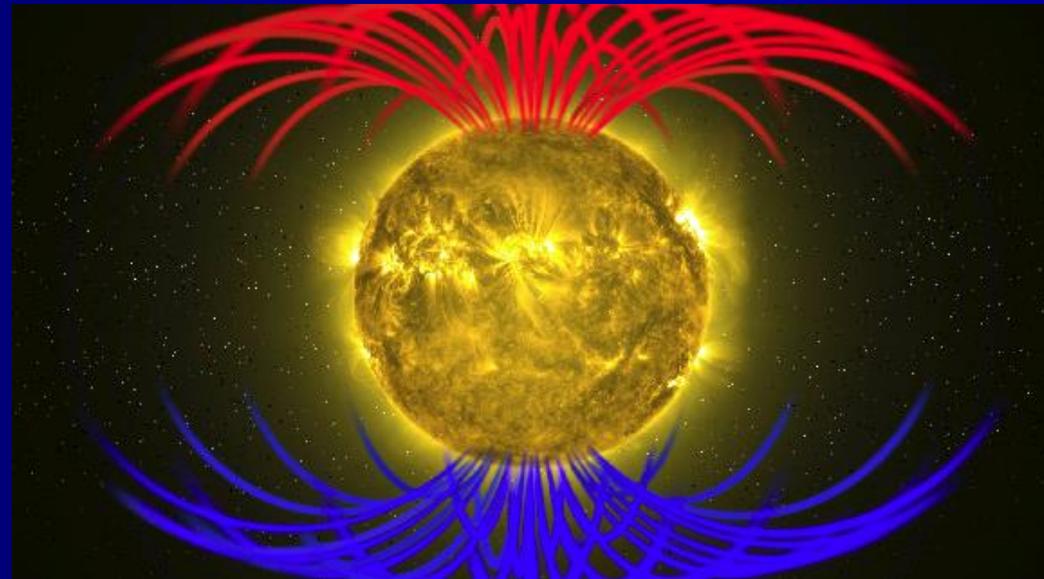
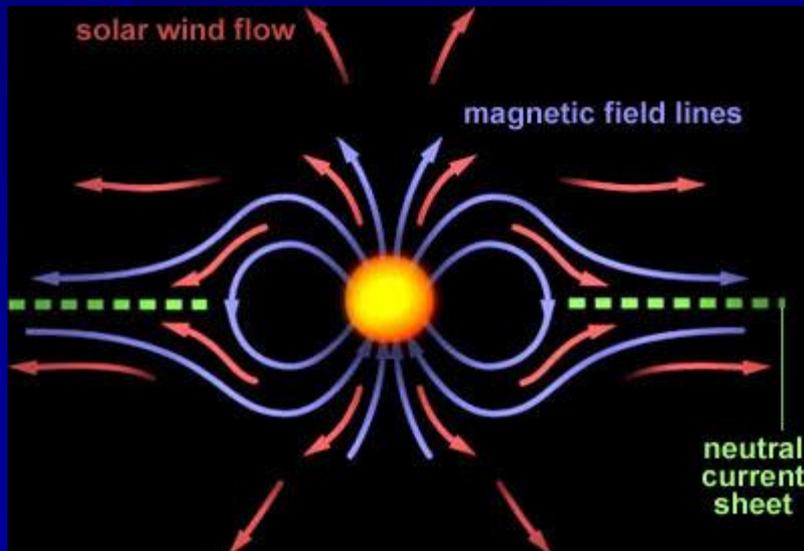


Sun - Synodic period 27 days.

The reason of course is that the Earth advances by approximately **1 degree per day** in its orbit around the Sun and after 25 days a **point near the equator of the Sun needs roughly two more days** to reach the new angle of the Earth.

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**.



The Active Sun

The Sun and Stars

Introduction of the Active Sun

The Photosphere

The Chromosphere and the Corona

Sunspots and the Solar Cycle

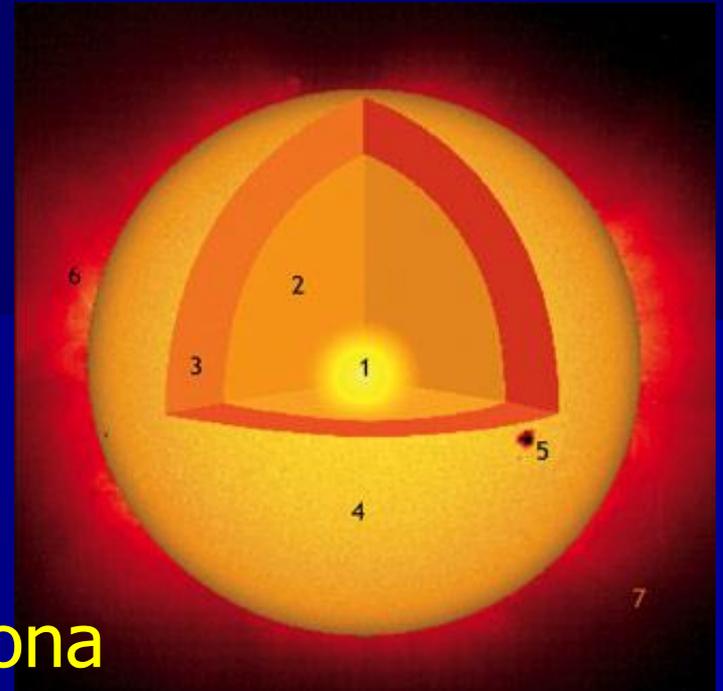
Faculae, Flares and Prominences

Radio and X-ray Bursts from the Sun

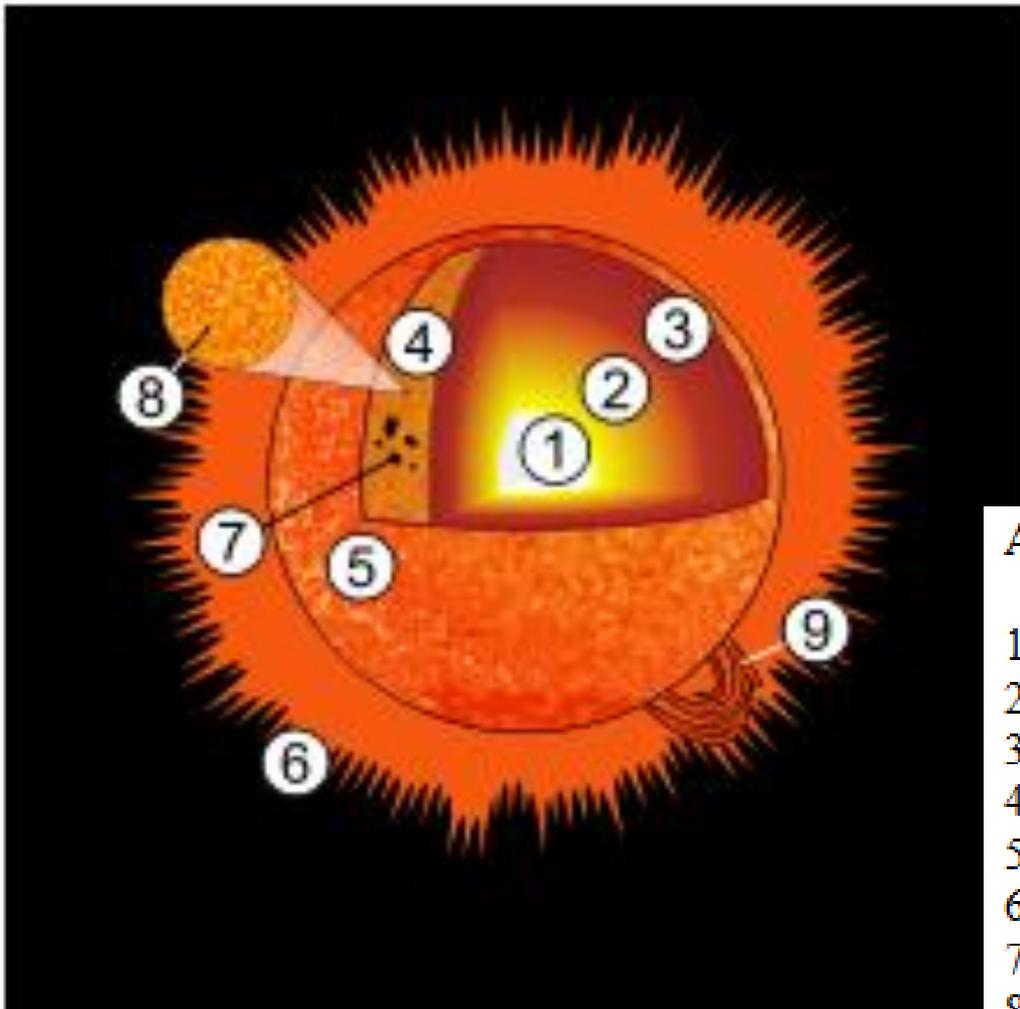
The Development of an Active Region on the Sun

Effect of the Solar Cycle

Life Cycle of the Sun



The Structure of the Sun

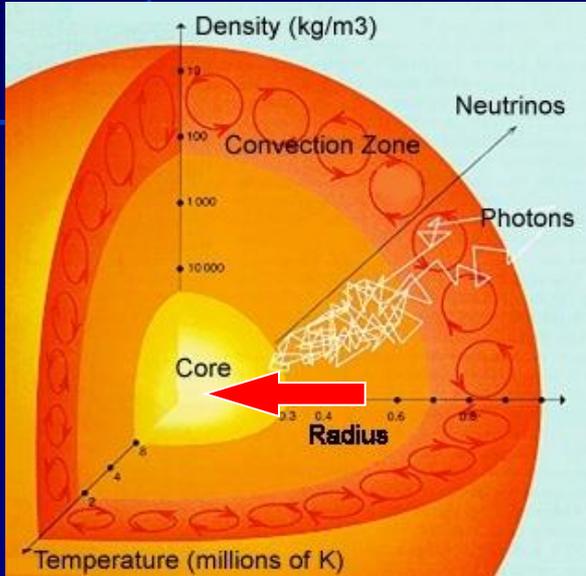


An illustration of the structure of the Sun:

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

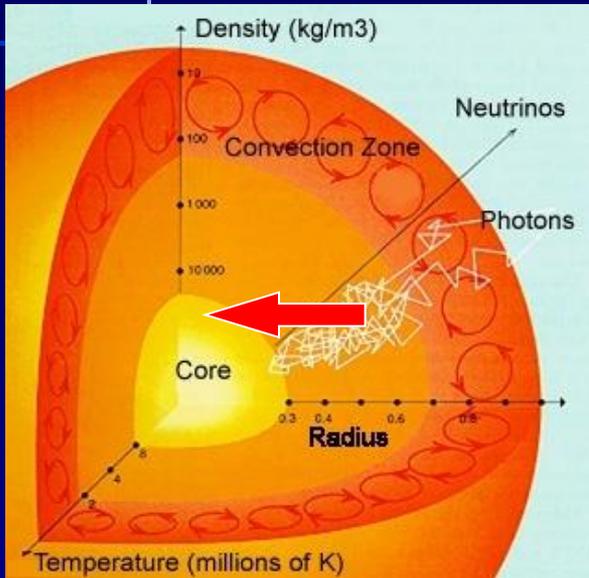


The core of the Sun is considered to extend from the center to about 20-25% of the solar radius. It has a **density** of up to **150,000 kgm⁻³** and a **temperature** of close to **13.6 million Kelvin**.

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 Structure of the Sun

Core

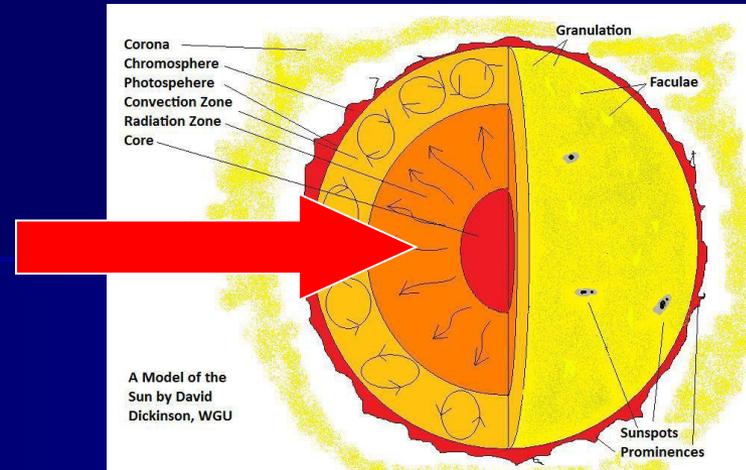


The rest of the star is heated by energy that is transferred outward from the core and the layers just outside. The energy produced by fusion in the core must then travel through many successive layers to the solar photosphere before it escapes into space as Sunlight or kinetic energy of particles.

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

The Structure of the Sun

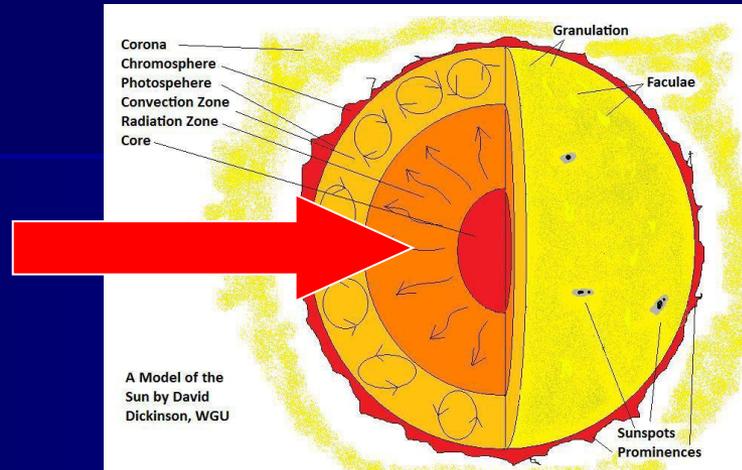
Radiative Zone



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.

The Structure of the Sun

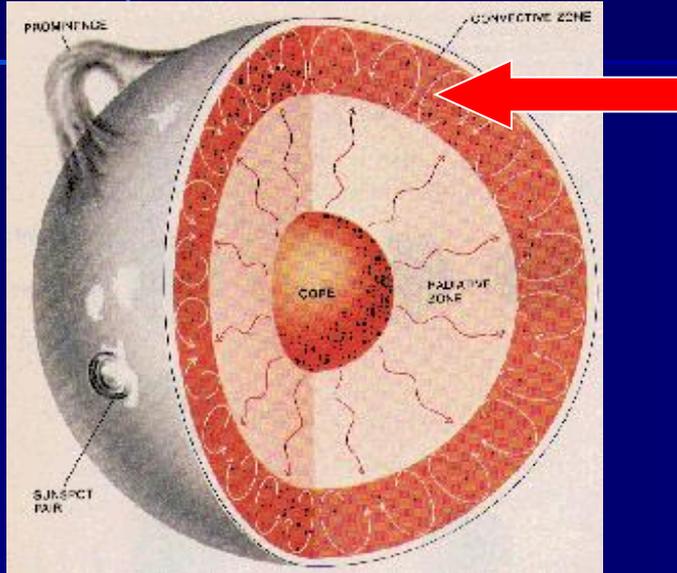
Radiative Zone



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

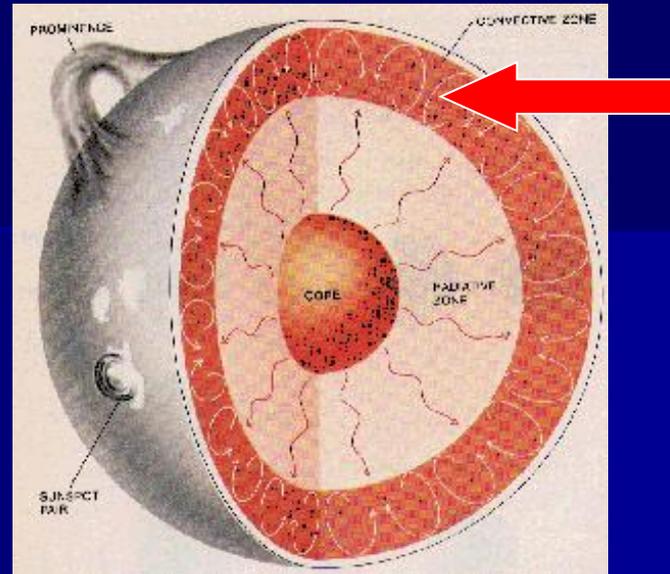
Convective Zone



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 **it's opaque enough**. As a result, thermal convection occurs as **thermal columns** carry hot material to the surface (photosphere) of the Sun.

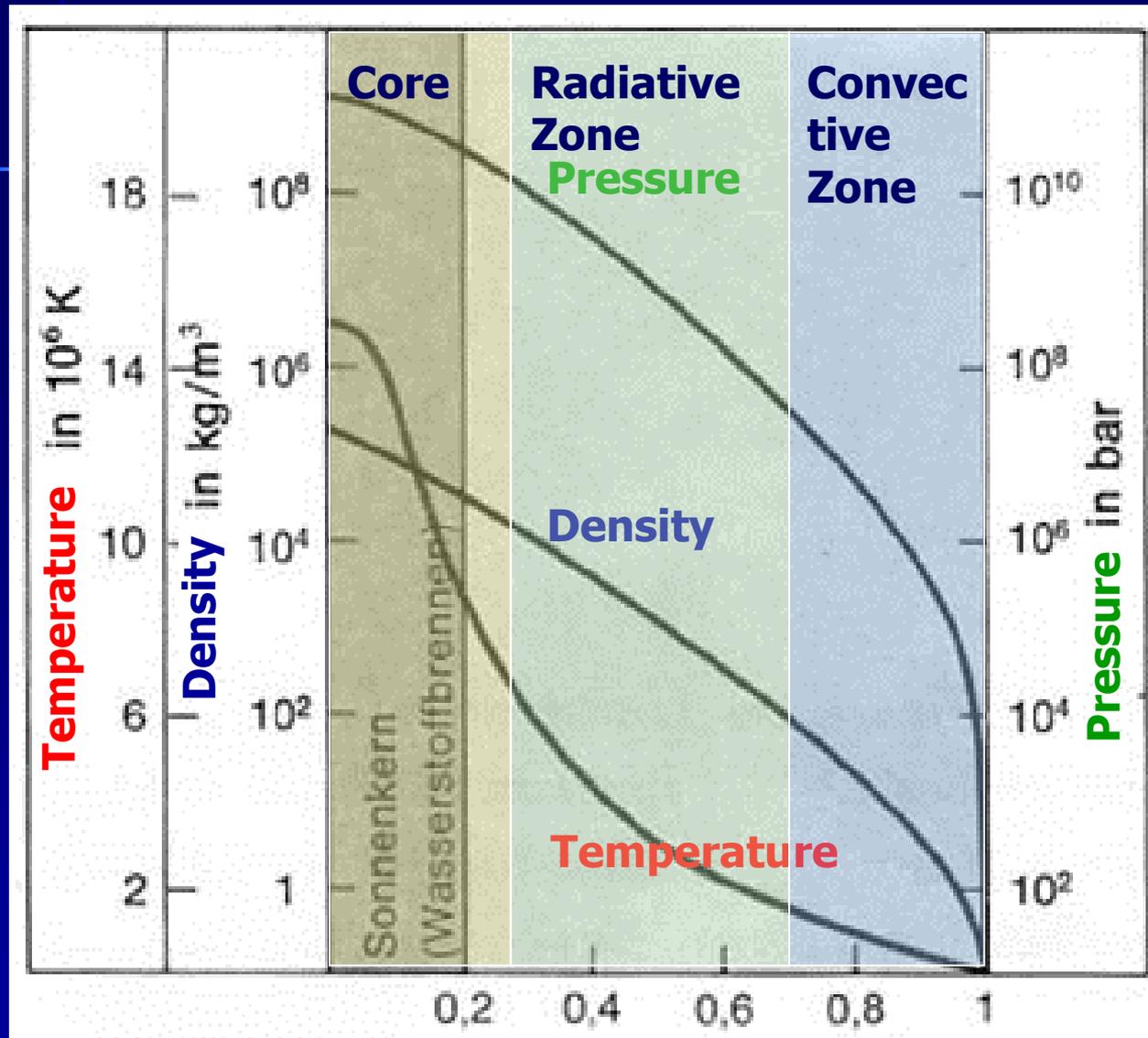
The Structure of the Sun

Convective Zone



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}

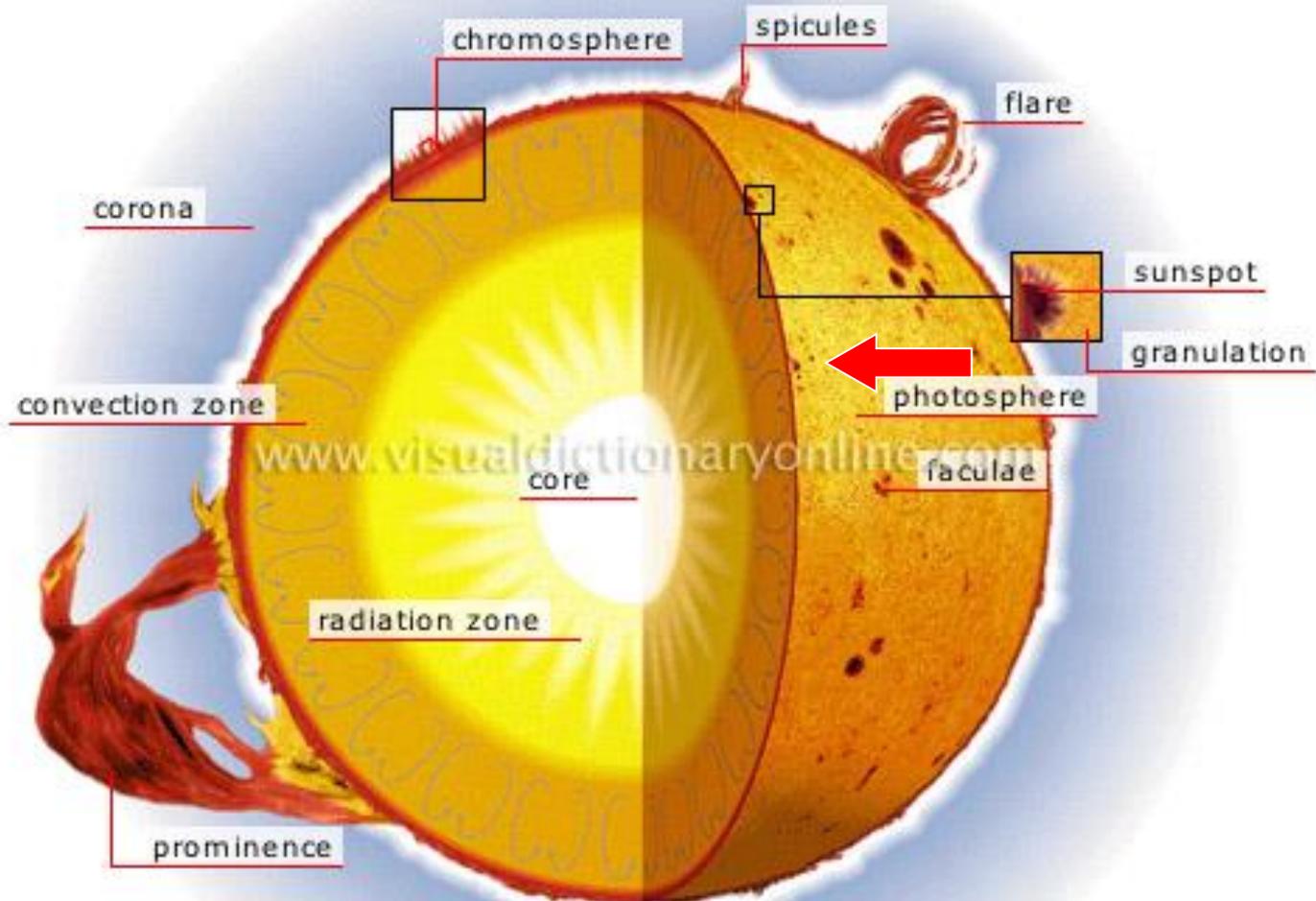
→ Radiative
Zone

~70% to
100% R_{\odot}

→ Convective
Zone

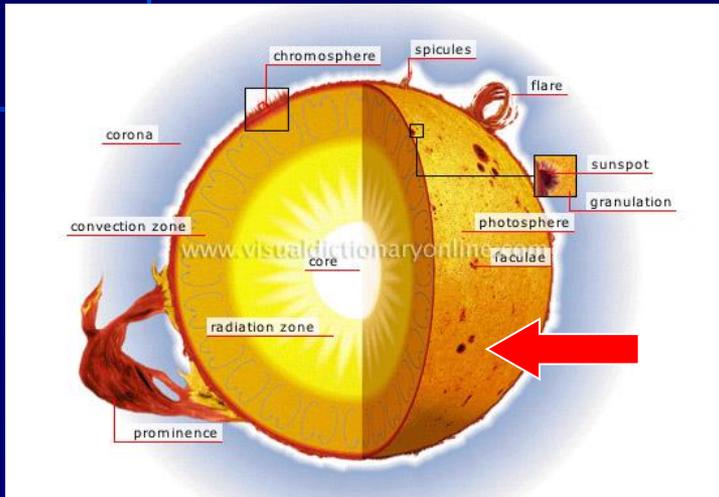
The Structure of the Sun

The photosphere



The 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 Structure of the Sun

The photosphere

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. Inside the photosphere, the energy passes from layer to layer in the form of radiation (**radiative transfer**) which at the temperature and density of the photosphere is a much more effective process than convective transfer.

The relation, which describes this entire process is called the **equation of radiative 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**,

The Structure of the Sun

The photosphere

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

and the corresponding absorption coefficient χf varies by less than a factor of 2 over the entire optical region of the spectrum where most of the solar radiation is emitted.

It is also justified to assume that the solar photosphere is in both **local thermodynamic equilibrium** and **radiative equilibrium** so that the solution of the equation of radiative transfer is given by the **Eddington approximation**,

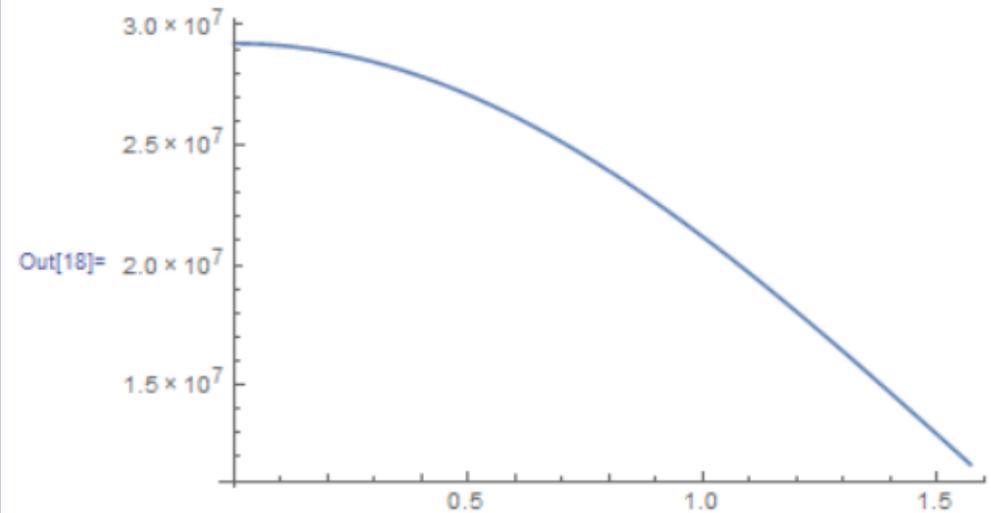
$$I(\theta, 0) = \frac{\sigma T_e^4}{2\pi} \left(1 + \frac{3}{2} \cos \theta \right)$$

Where $I(\theta, 0)$ is the intensity of the solar radiation emitted from the top of the photosphere ($r=0$) at an angle θ to the verticle. T_e is the effective temperature of the Sun. **Above equation shows that $I(\theta, 0)$ will decrease as θ varies from 0° to 90° .** (Because $\cos \theta$ is decreasing when θ is increasing from 0° to 90°)

The Structure of the Sun

```
In[15]:= sig = 5.6704 × 10-8 ;  
te = 6000 ;  
it = ((sig * (te) ^ 4) / (2 * Pi)) * (1 + (3 / 2) * Cos[t])  
Plot[it, {t, 0, Pi / 2}]
```

```
Out[17]= 1.1696 × 107  $\left( 1 + \frac{3 \cos[t]}{2} \right)$ 
```



The relative magnitude of $I(\theta, 0)$ with respect to the intensity at the center of the Solar disk $I(0, 0)$ is given by,

$$\frac{I(\theta, 0)}{I(0, 0)} = \frac{\frac{\sigma T_e^4}{2\pi} \left(1 + \frac{3}{2} \cos \theta \right)}{\frac{\sigma T_e^4}{2\pi} \left(1 + \frac{3}{2} \cos 0 \right)}$$

The Structure of the Sun

The photosphere

The relative magnitude of $I(\theta,0)$ with respect to the intensity at the center of the Solar disk $I(0,0)$ is given by,

$$\frac{I(\theta,0)}{I(0,0)} = \frac{\frac{\sigma T_e^4}{2\pi} \left(1 + \frac{3}{2} \cos \theta\right)}{\frac{\sigma T_e^4}{2\pi} \left(1 + \frac{3}{2} \cos 0\right)}$$



$$\frac{I(\theta,0)}{I(0,0)} = \frac{2}{5} + \frac{3}{5} \cos \theta$$



$$\frac{I(\theta,0)}{I(0,0)} = 1 - \frac{3}{5} + \frac{3}{5} \cos \theta$$

$$\frac{I(\theta,0)}{I(0,0)} = 1 - u + u \cos \theta$$



$$u = \frac{3}{5} = 0.6$$

If $\theta = 0$, then $\frac{I(\theta,0)}{I(0,0)} = 1 - u + u \cos 0$

$$\frac{I(\theta,0)}{I(0,0)} = 1$$

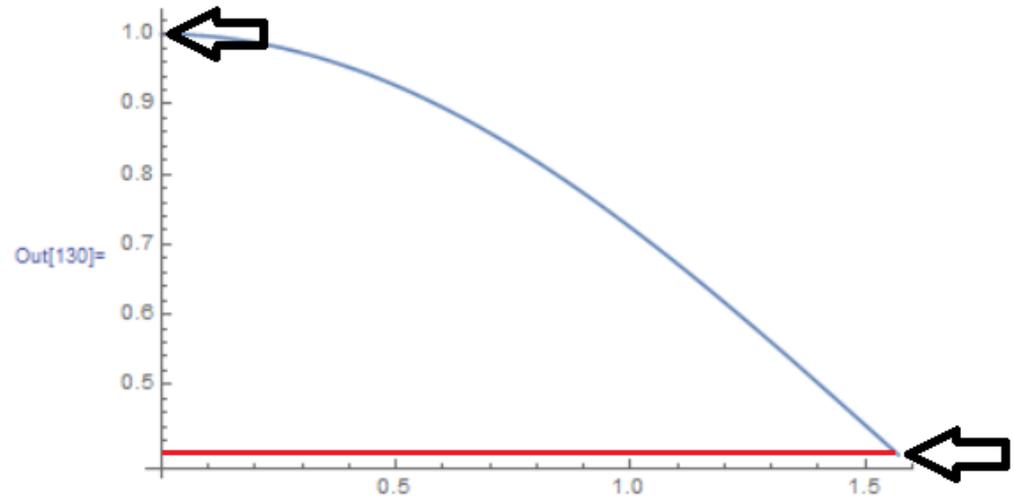
If $\theta = 90^\circ$, then $\frac{I(\theta,0)}{I(0,0)} = 1 - u + u \cos 90^\circ$

$$\frac{I(\theta,0)}{I(0,0)} = 1 - u = 0.4$$

The Structure of the Sun

```
In[127]:= sig = 5.6704 × 10-8;  
te = 6000;  
it2 = (1 + (3/2) * Cos[t]) / (1 + (3/2))  
Plot[it2, {t, 0 Degree, 90 Degree}]
```

Out[129]=
$$\frac{2}{5} \left(1 + \frac{3 \cos[t]}{2} \right)$$

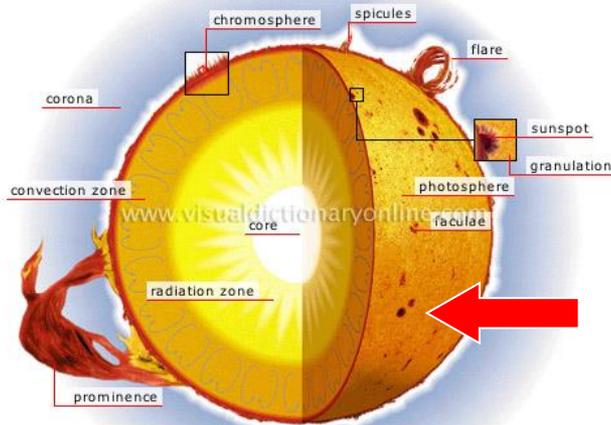


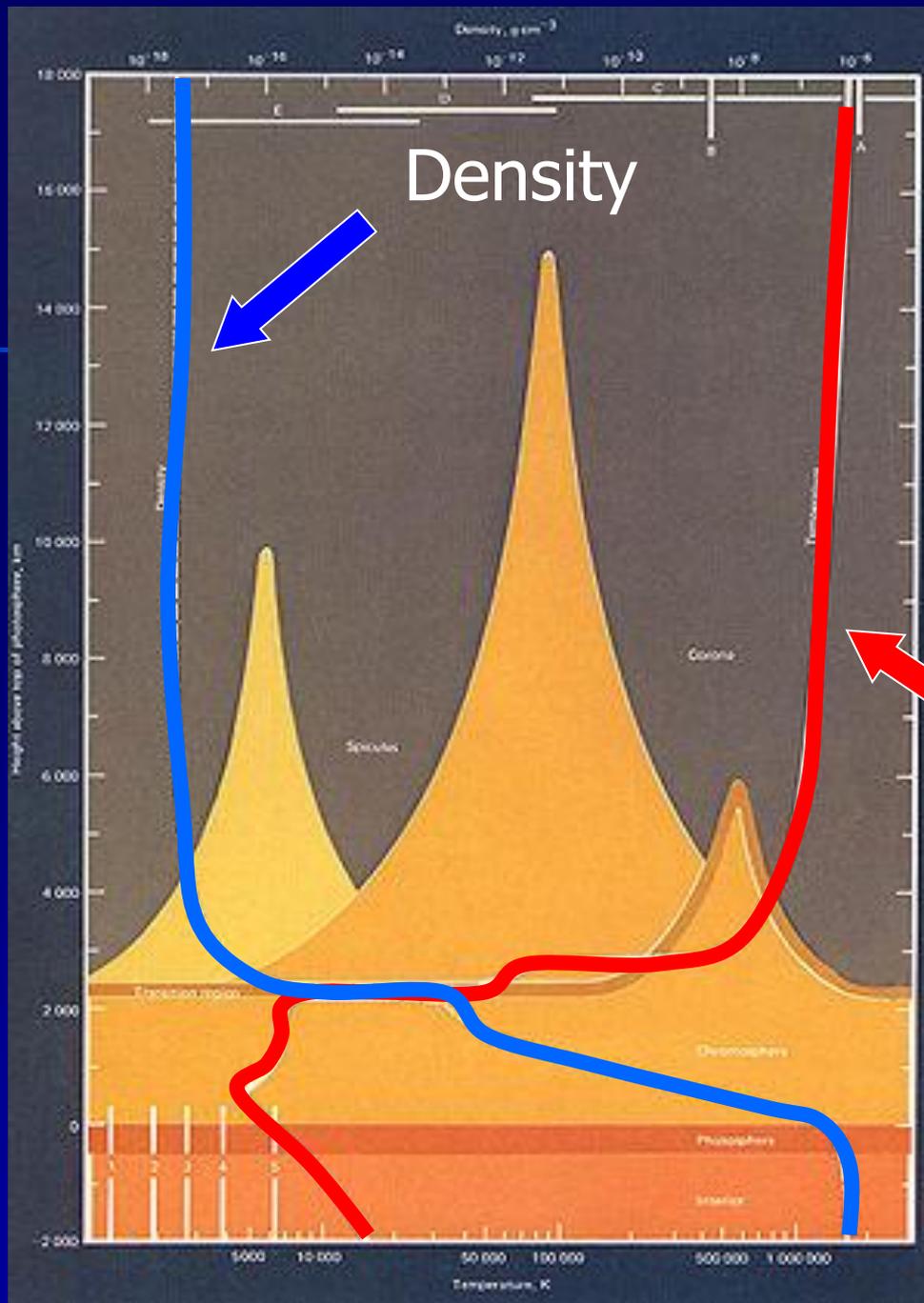
The above equation says that, the **Sun is brighter at the center of the disk ($\theta=0^\circ$) than at the limb ($\theta=90^\circ$)** where it loses more than half of its brightness. This phenomenon is called "**limb darkening**".

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%



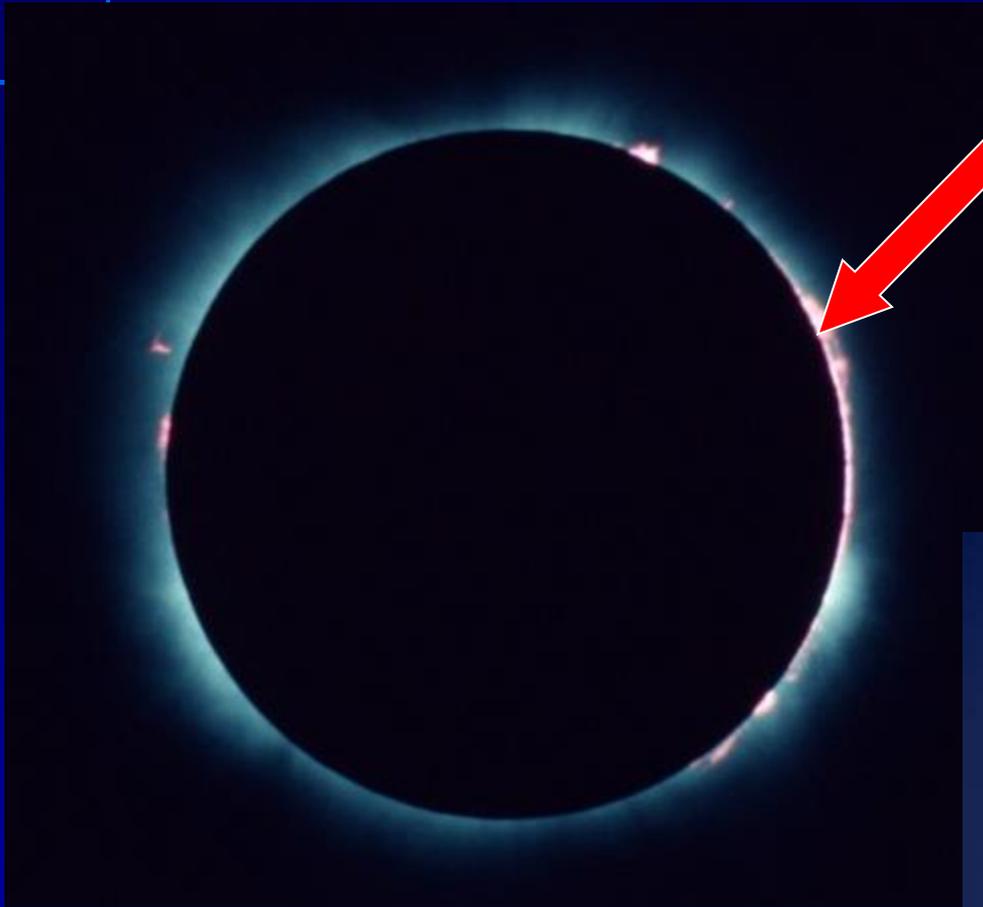


Temperature and density of the Sun's atmosphere

Temperature

The Structure of the Sun

The Chromosphere and the Corona



Chromosphere

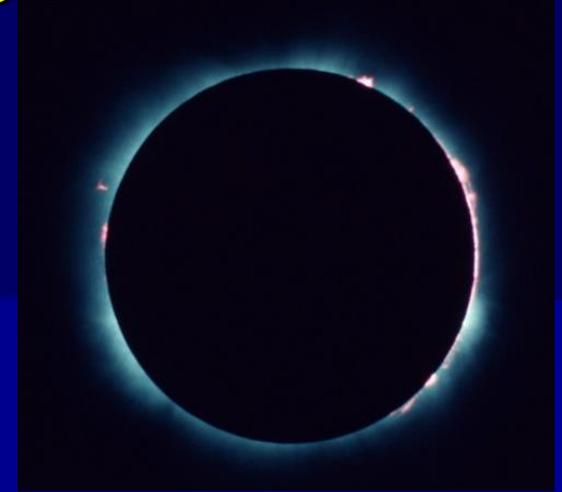


Corona



The Structure of the Sun

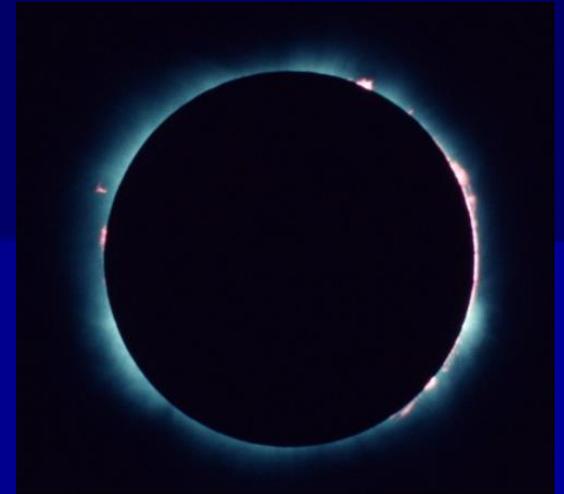
The Chromosphere and the Corona



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.**

The Structure of the Sun

The Chromosphere and the Corona



As we have seen, the **effective temperature of the Sun (5750 K)** occurs at $r=2/3$, i.e. **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.



The Structure of the Sun

The Chromosphere and the Corona

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**.



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 spicules continuously rise and fall and their average life time is close to 5 minutes.

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 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.

The Structure of the Sun

The Chromosphere and the Corona

An empirical expression which is often used for the electron density profile of the quiet corona is the

Baumbach-Allen Formula,

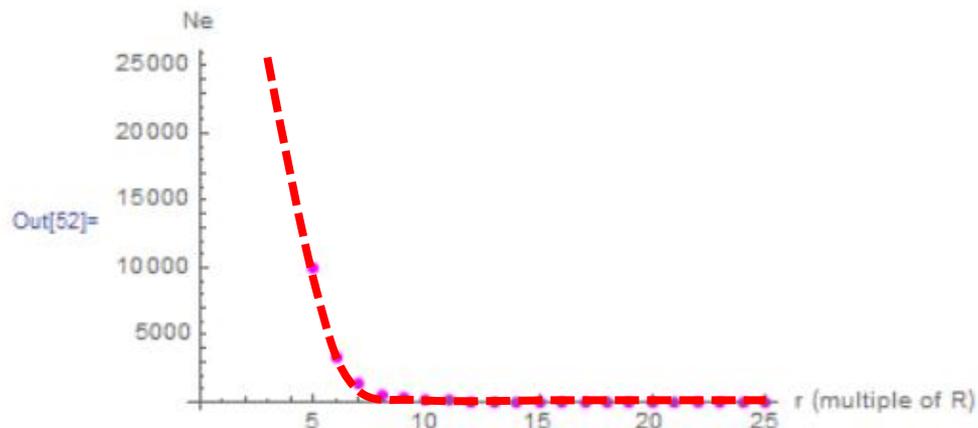
$$N_e = 10^8 (1.55 \rho^{-6} + 2.99 \rho^{-16}) \quad e^n/cm^3$$

In which $\rho = r/R_0$ is the ratio of the radial distance r from the center of the Sun to the **radius R_0 of the photosphere**.

The **electron density of the corona over an active region has approximately the same profile but multiplied by a factor of 10 or 20**. The Baumbach-Allen formula applies only to **values of ρ less than about 5**, because at larger distances, the density of the solar corona falls of very nearly like the square of the distance, i.e. like ρ^{-2} .

```
In[48]:= r = Table[R * i, {i, 1, 25}];
(* R = Radius of the Sun *)
rho = r/R;
(* r = Radial Distance from the center of the Sun*)
ne = 10^8 * (1.55 * (rho^(-6)) + 2.99 * (rho^(-16)));
(* electrons per cubic meter *)
nevsr = Transpose[{r/R, ne}]
ListPlot[nevsr, PlotStyle -> {Magenta, PointSize[0.02]},
  AxesLabel -> {"r (multiple of R)", "Ne"}]
```

```
Out[51]:= {{1, 4.54 × 108}, {2, 2.42644 × 106}, {3, 212 627.}, {4, 37 841.9}, {5, 9920.},
  {6, 3322.19}, {7, 1317.48}, {8, 591.278}, {9, 291.66}, {10, 155.},
  {11, 87.4935}, {12, 51.9092}, {13, 32.1123}, {14, 20.5856}, {15, 13.6077},
  {16, 9.23872}, {17, 6.42152}, {18, 4.55719}, {19, 3.29466}, {20, 2.42188},
  {21, 1.80724}, {22, 1.36709}, {23, 1.04704}, {24, 0.811081}, {25, 0.63488}}
```



The Structure of the Sun

The Chromosphere and the Corona



The sharp rise of the temperature in the transition zone and the heating of the **corona** to temperatures several hundred times higher than the effective temperature of the Sun, represent a very difficult problem which has not been worked out yet in its full complexity. The basic process, can be described in the following simple terms.

Sound (acoustic) **waves** are generated by turbulence and convection below the photosphere and they start moving up carrying only about 1% of the total energy flux.

The Active Sun

The Sun and Stars

Introduction of the Active Sun

The Photosphere

The Chromosphere and the Corona

Sunspots and the Solar Cycle

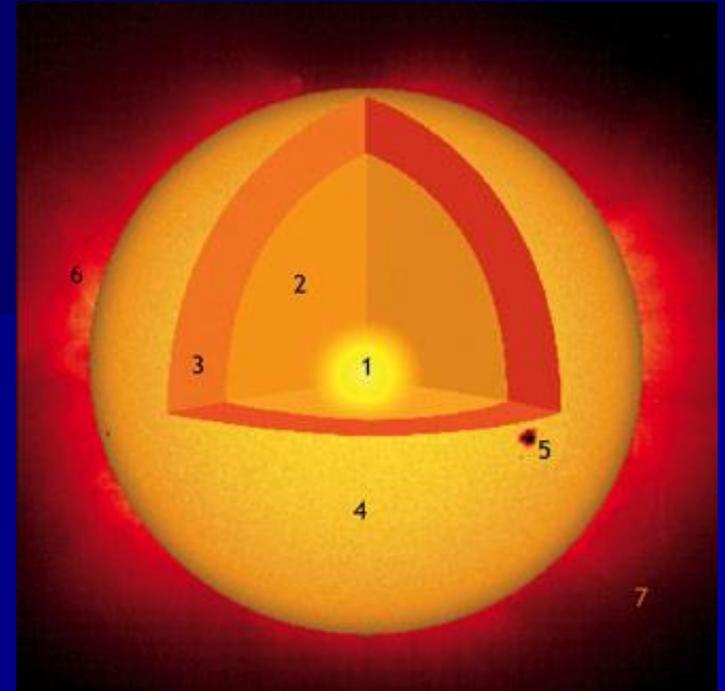
Faculae, Flares and Prominences

Radio and X-ray Bursts from the Sun

The Development of an Active Region on the Sun

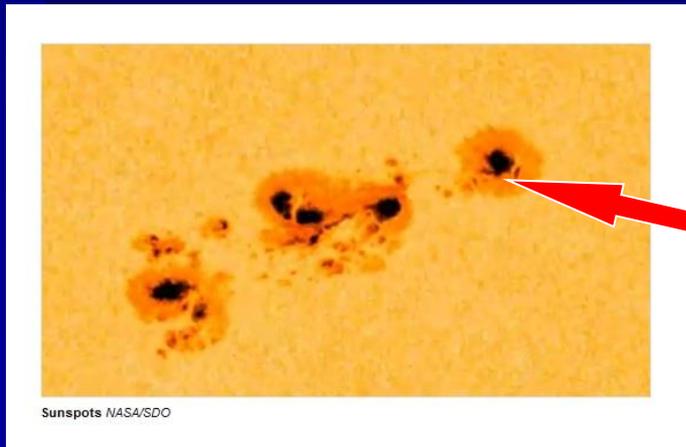
Effect of the Solar Cycle

Life Cycle of the Sun



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

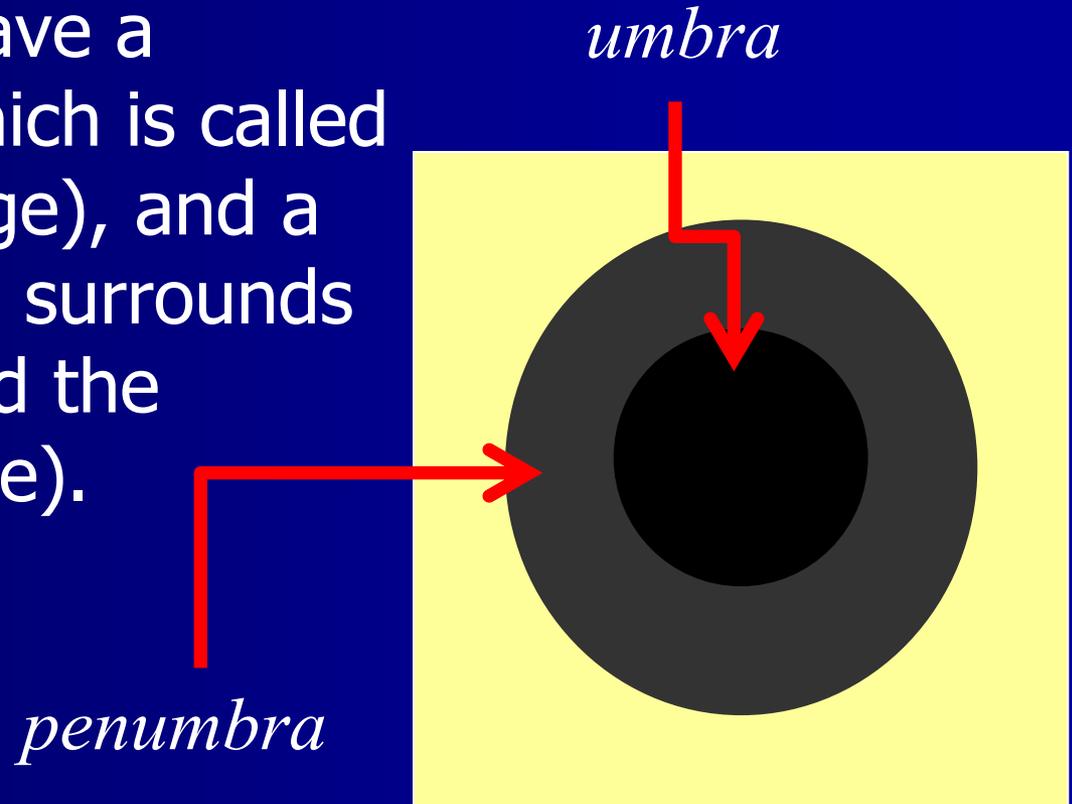
Sunspots Sunspots



SDO/HMI Sun-Looker Continuum 20101018_024000

Sunspots & the Solar Cycle

Sunspots were observed for first time through a telescope in year 1611 by several people, including Galileo, in three different countries. Sunspots have a central dark region which is called the **umbra** (total image), and a less dark region which surrounds the umbra and it called the **penumbra** (sub image).



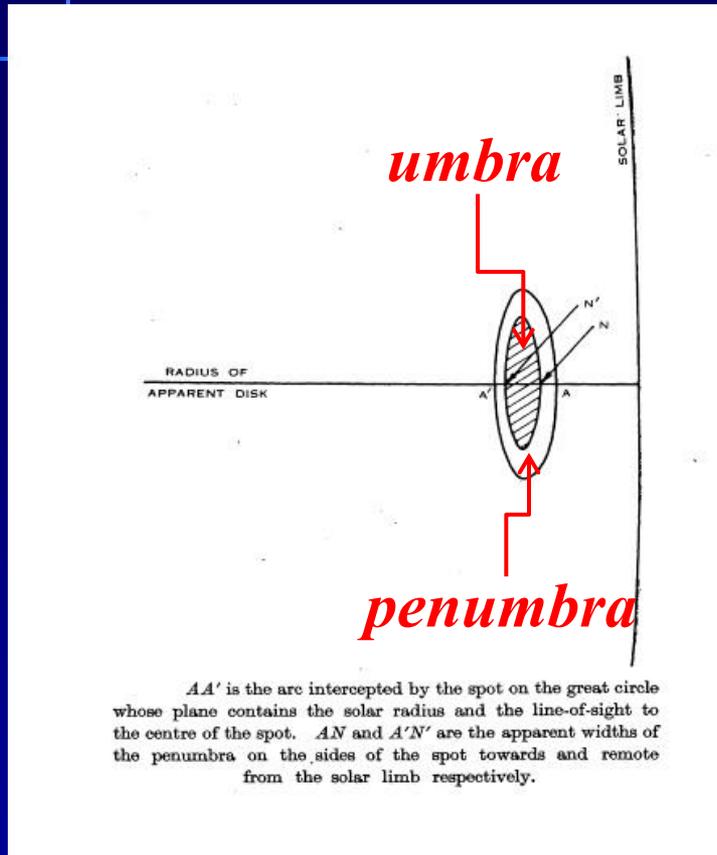
Sunspots & the Solar Cycle

The umbra is nearly featureless but the penumbra consists of many radial filaments which are believed to be due to roll convection of photospheric matter along the radial magnetic field lines of the sunspot.

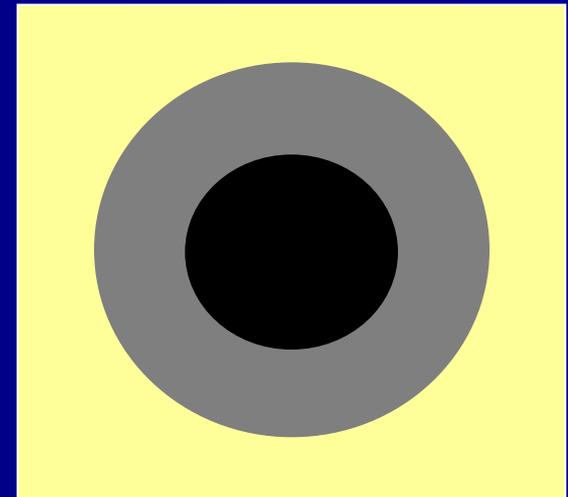
A significant contribution in the study of the sunspots and in general of the solar atmosphere, was the discovery of the **Wilson Effect** by Alexander Wilson in 1976. **Wilson observed that while the sunspots have an essentially symmetric penumbra when they are near the center of the Solar Disk, they develop an asymmetric penumbra as they move closer to the limb** (edge of something) **with the narrower side of the penumbra further away from the limb.**

Sunspots & the Solar Cycle

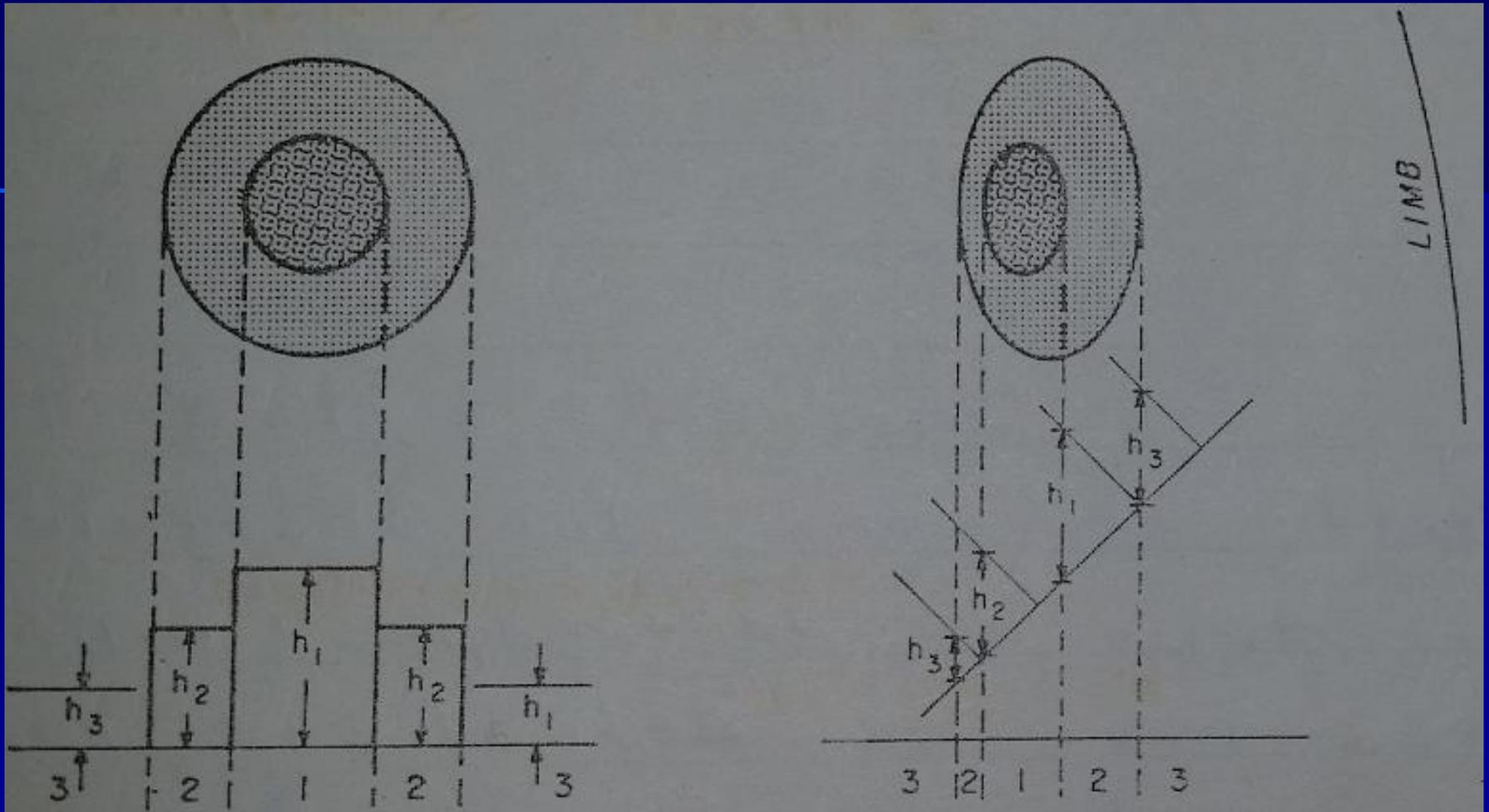
This is shown diagrammatically in the following figure.



Wilson himself offered a geometric explanation for this effect by suggesting that sunspots are **saucer-shaped** depression on the surface of the Sun.

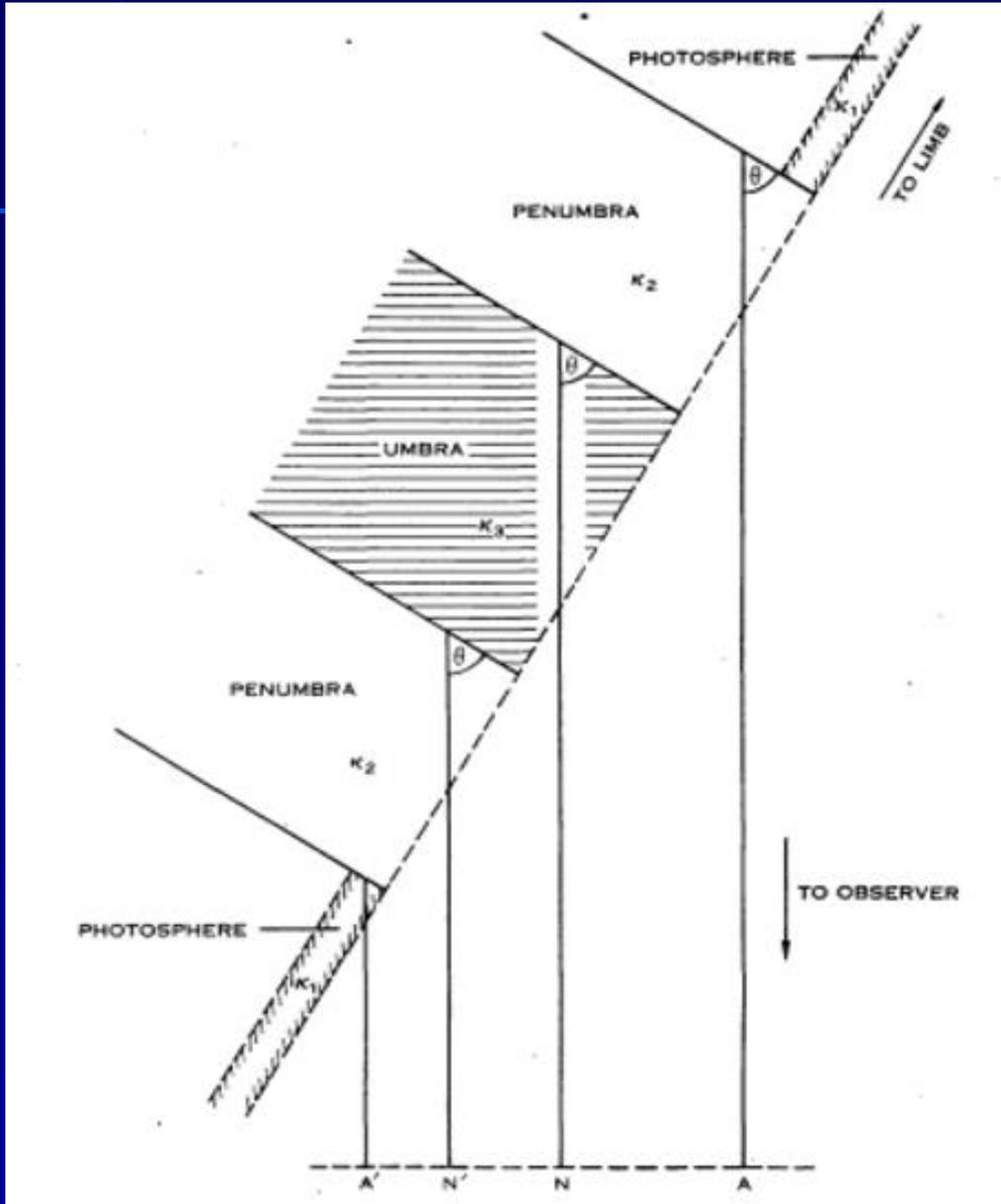


Sunspots & the Solar Cycle



The Wilson effect of the sunspots as they approach the limb of the solar disk.

Sunspots & the Solar Cycle



A simple model of a sunspot. The figure shows a section of the spot by the plane of the grate circle containing the solar radius and the line of sight to the spot.

The Wilson Effect in Sunspots - Loughhead, R. E. & Bray, R. J. (Australian Journal of Physics, vol. 11, p.177)

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,

Sunspots & the Solar Cycle

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

Calibration Factor → k

$10g$ → *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

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

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

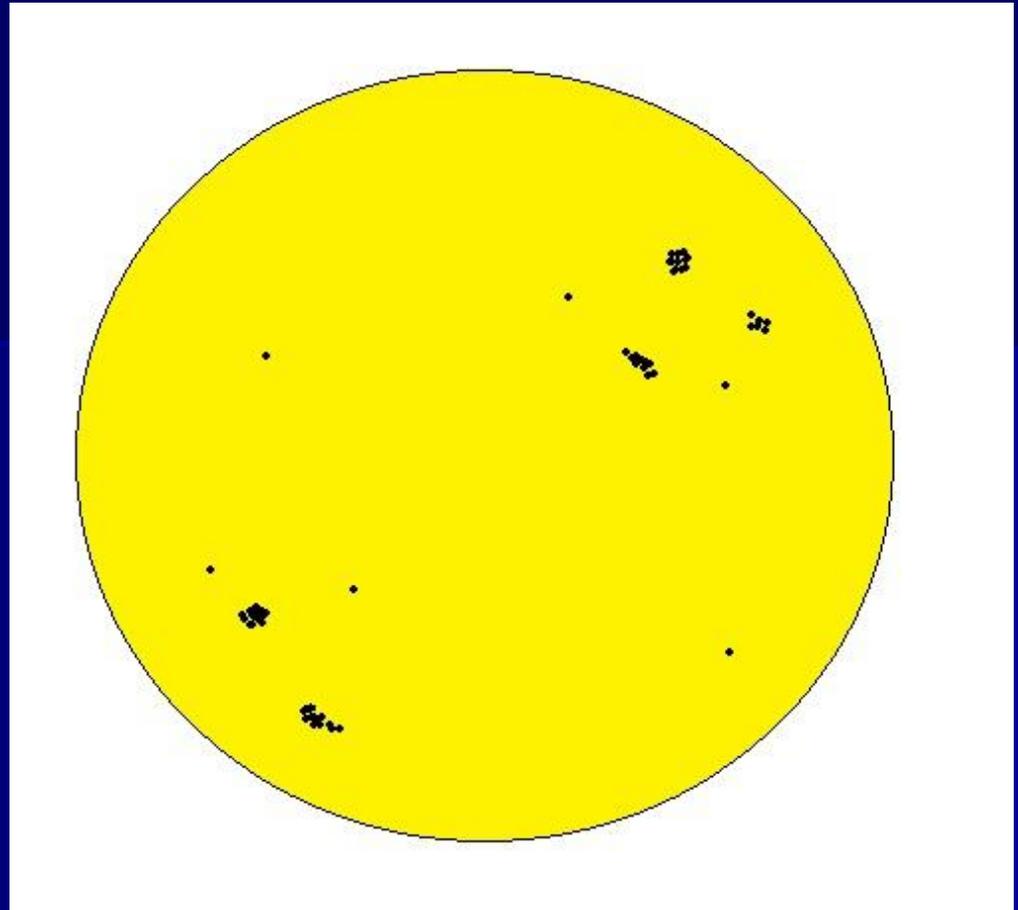
Wolf sunspot number or **Zurich sunspot number**.



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

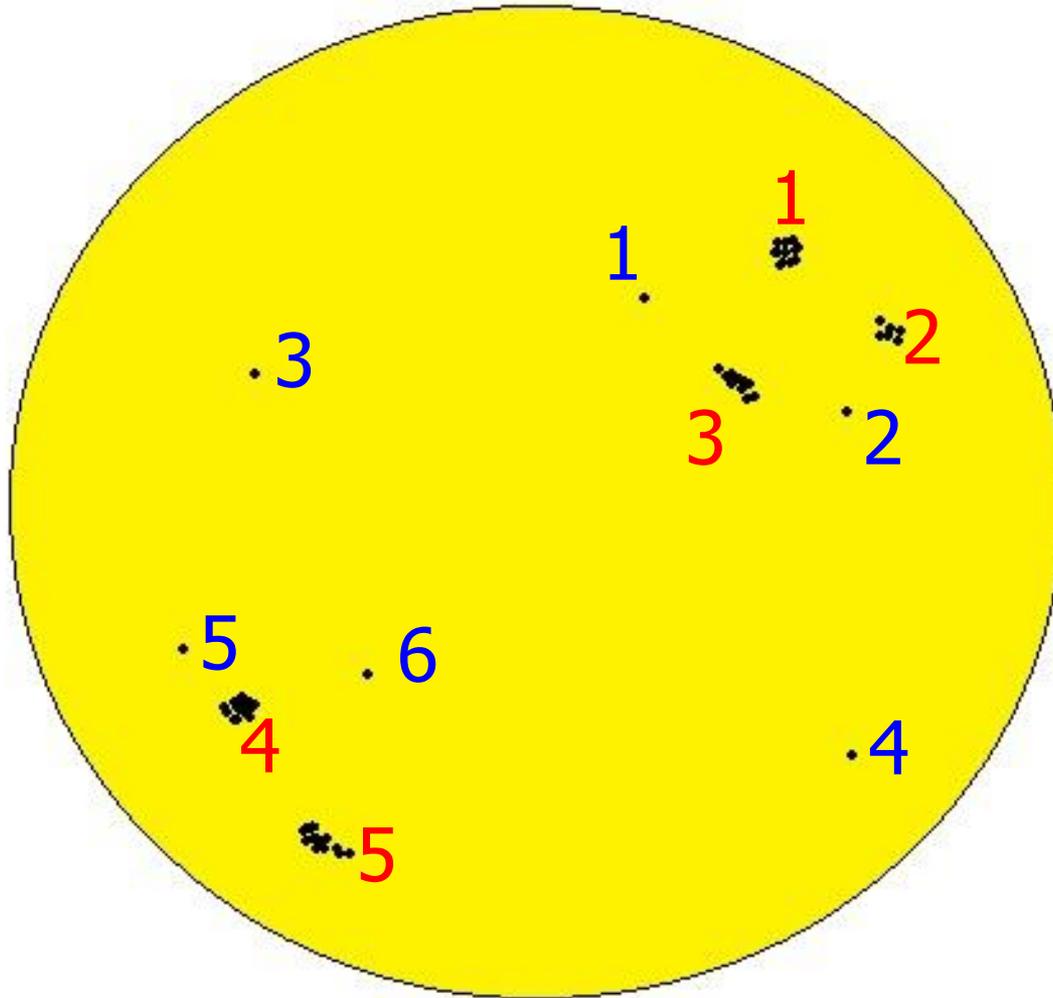


Eg:

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,

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

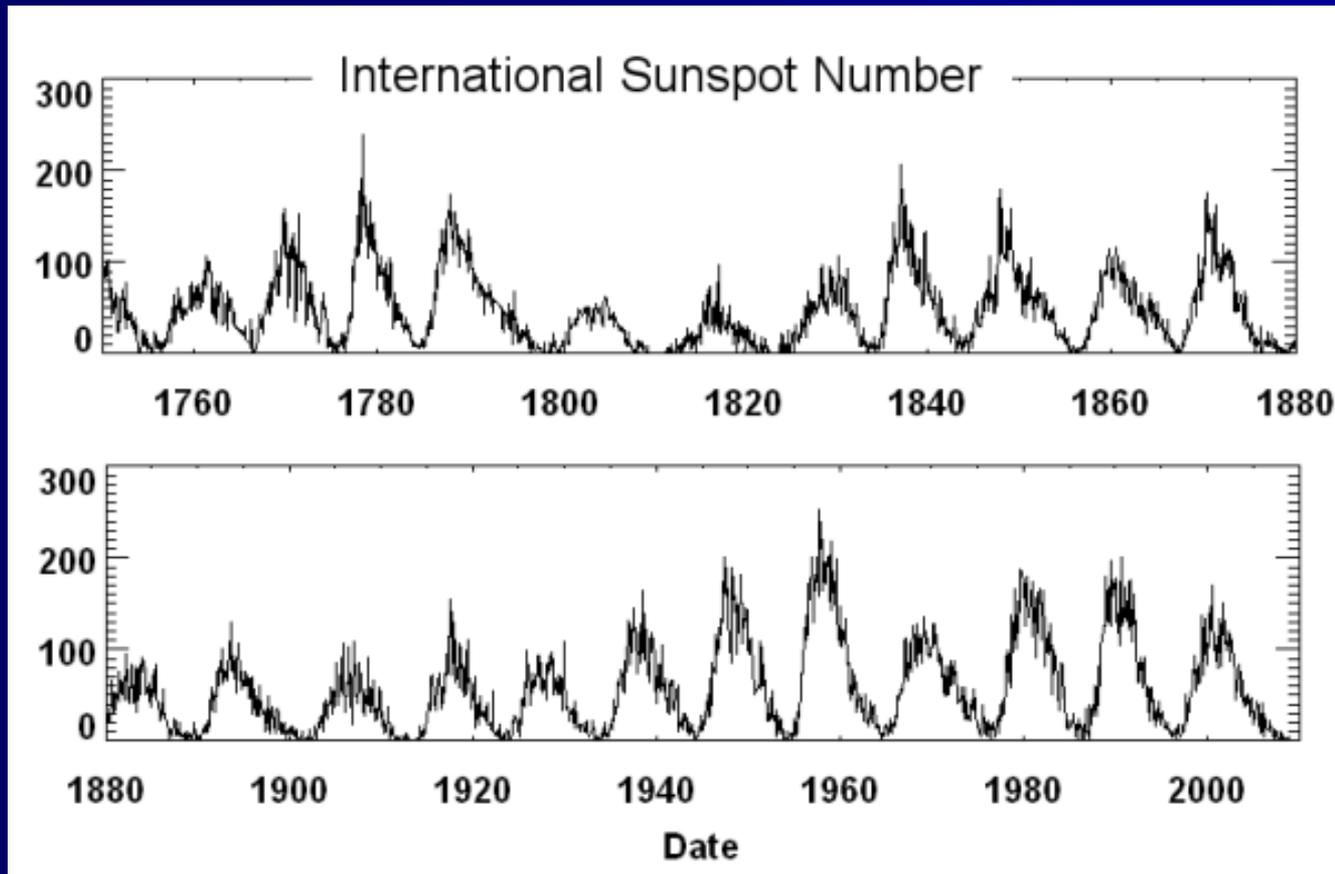
$$R = k [10 \times 5 + 6]$$

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**.



Thank You !

