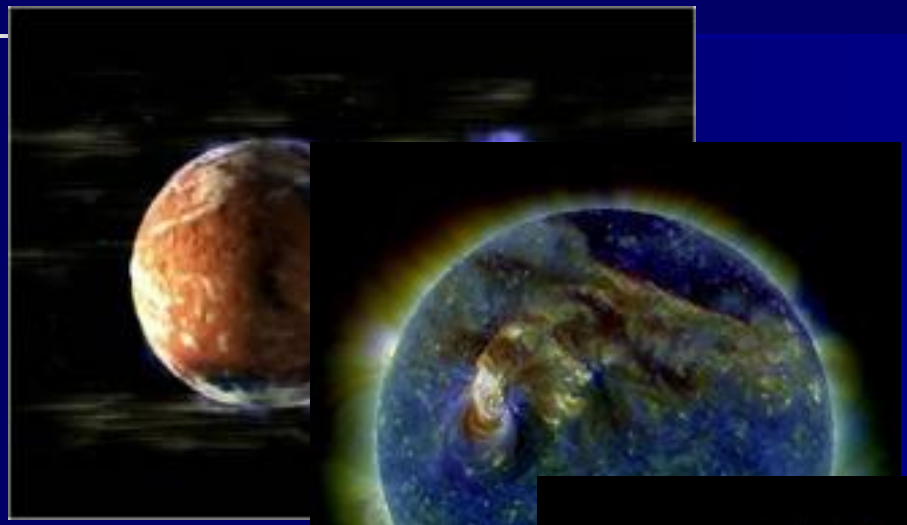
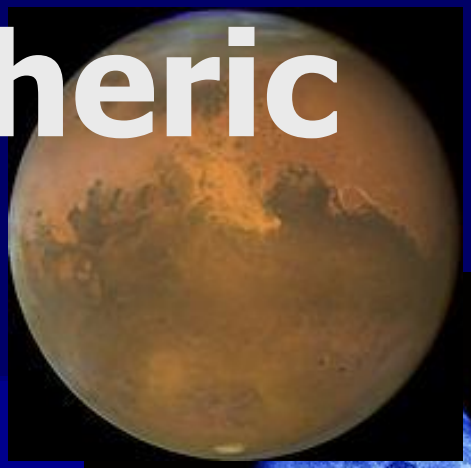
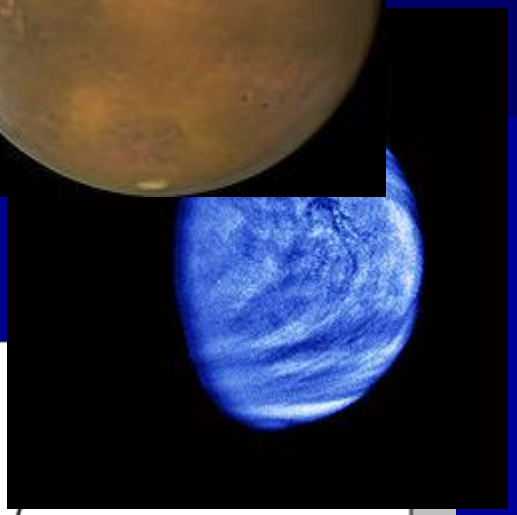
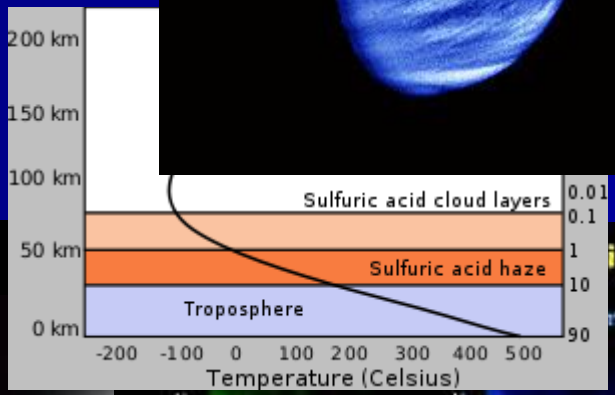
Space Physics

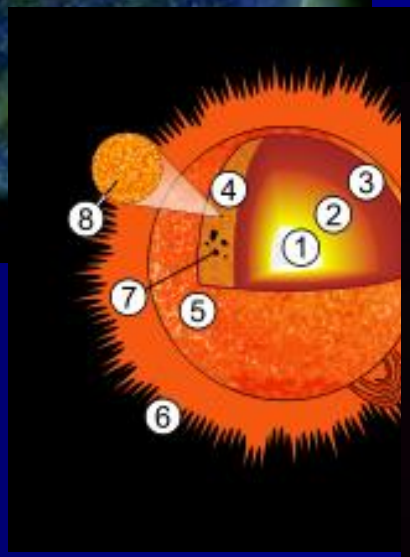
Space & Atmospheric Physics







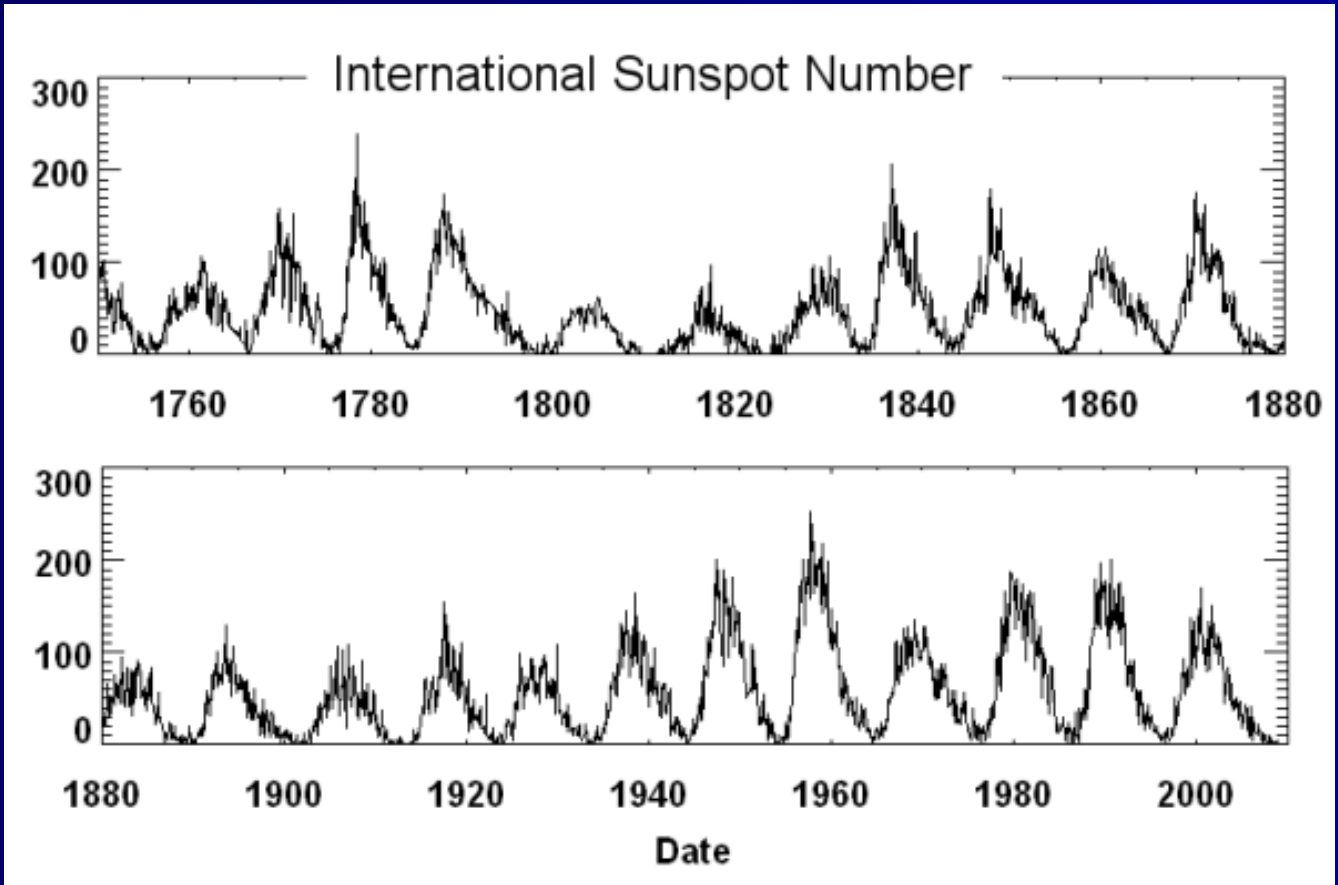




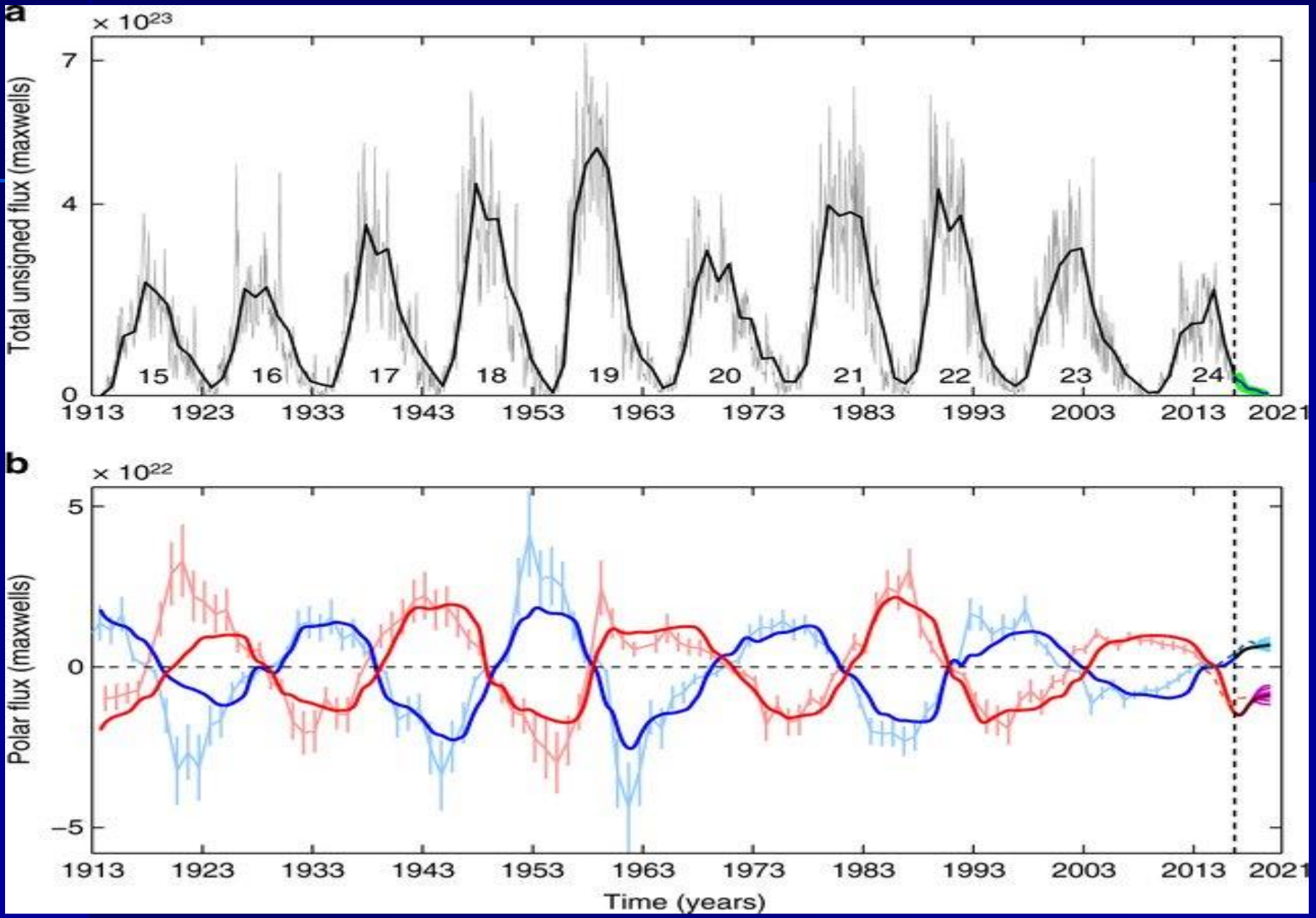
Lecture – 11 B

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**.



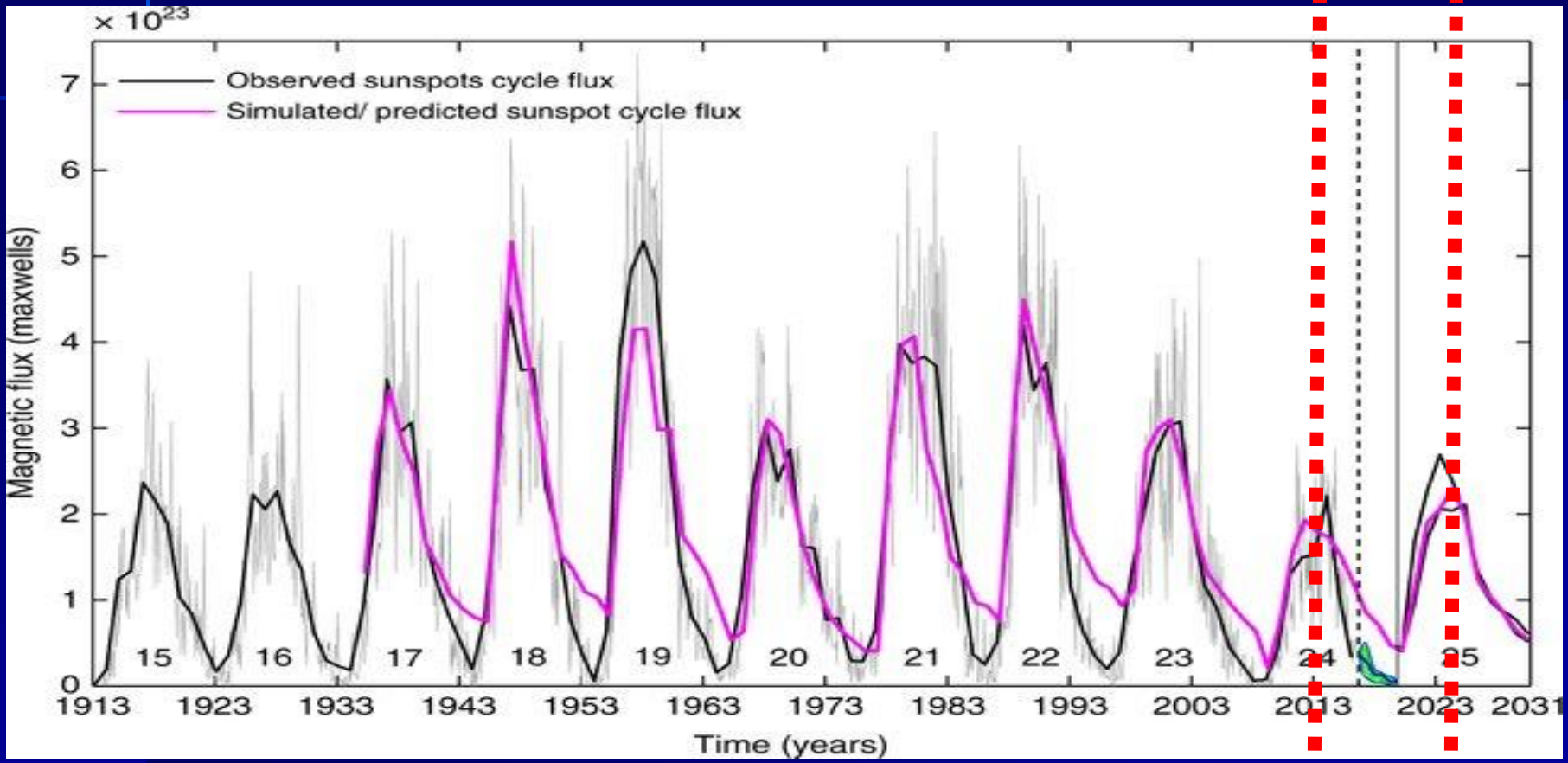
Future Sunspot Predictions



Future Sunspot Predictions

24 - April 2014

25 - October 2024

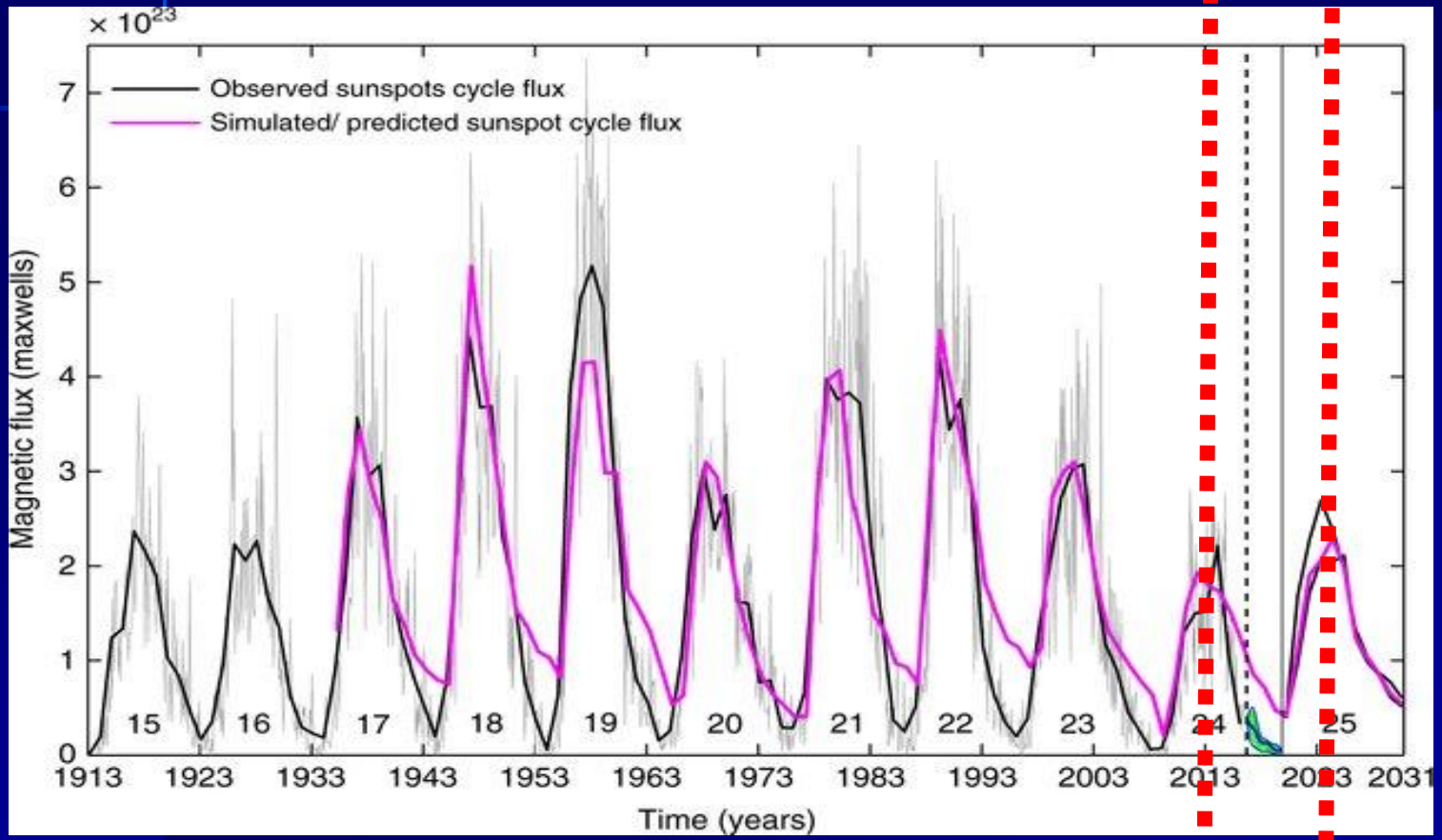


??? 26 - 2035/36

Future Sunspot Predictions

24 - April 2014

25 - October 2024



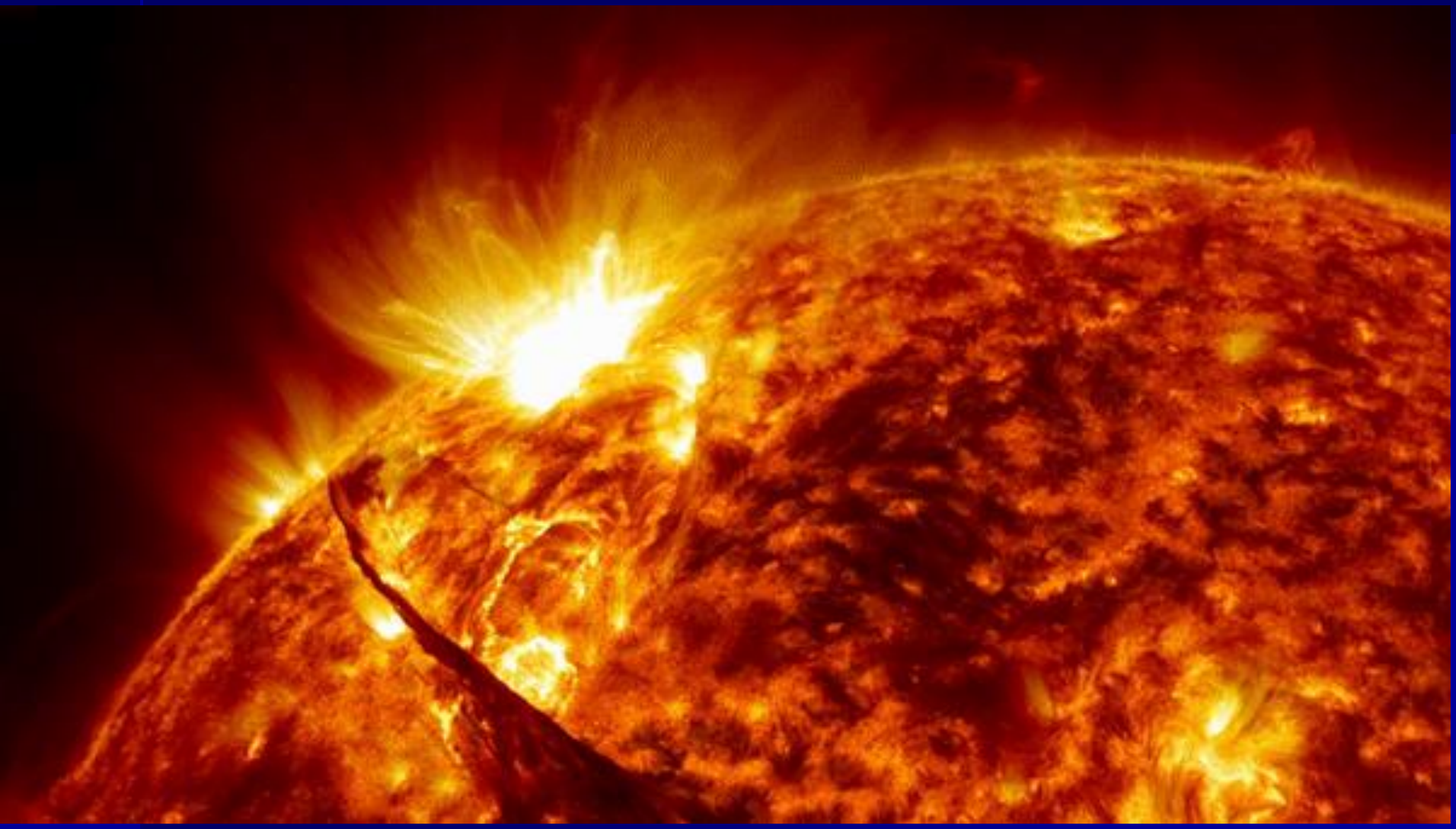
?

2034 – 2036

NASA

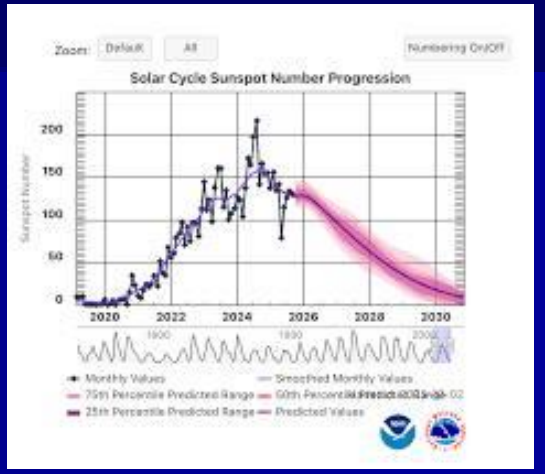
26 - 2035/36 ???

Future Sunspot Predictions :



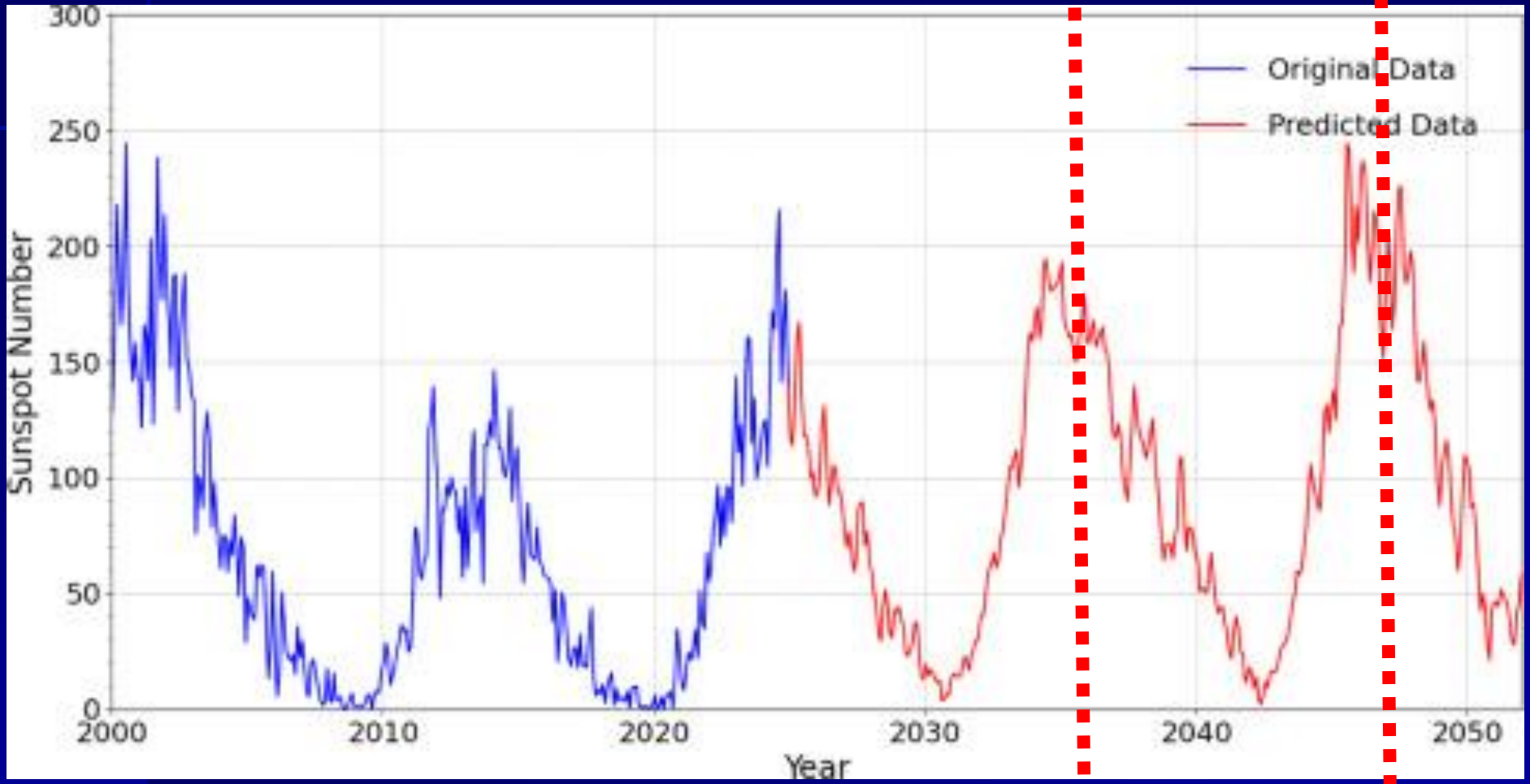
Future Sunspot Predictions : NASA Prediction

Predictions for Solar Cycles 26 and 27 suggest **Cycle 26 will peak around 2034-2036 with moderate activity, while Cycle 27 is expected to be stronger, peaking around 2044-2046**.



Current activity is around Solar Cycle 25's maximum (**late 2024/early 2025**), and researchers are refining long-term forecasts for future cycles, with varying models predicting different peak times and intensities, but generally expecting continued activity without immediate grand minima.

Future Sunspot Predictions :



26 - 2034 – 2036 NASA

27 - 2044 – 2046 NASA

Future Sunspot Predictions :

ELSEVIER

New Astronomy

Volume 117, July 2025, 102353

Prediction of solar cycles 26 and 27 based on LSTM-FCN

Shuguang Zeng [a b c], Shuo Zhu [a b], Yao Huang [a b], Xiangyun Zeng [a b], Sheng Zheng [a b], Linhua Deng [d]

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https://doi.org/10.1016/j.newast.2025.102353

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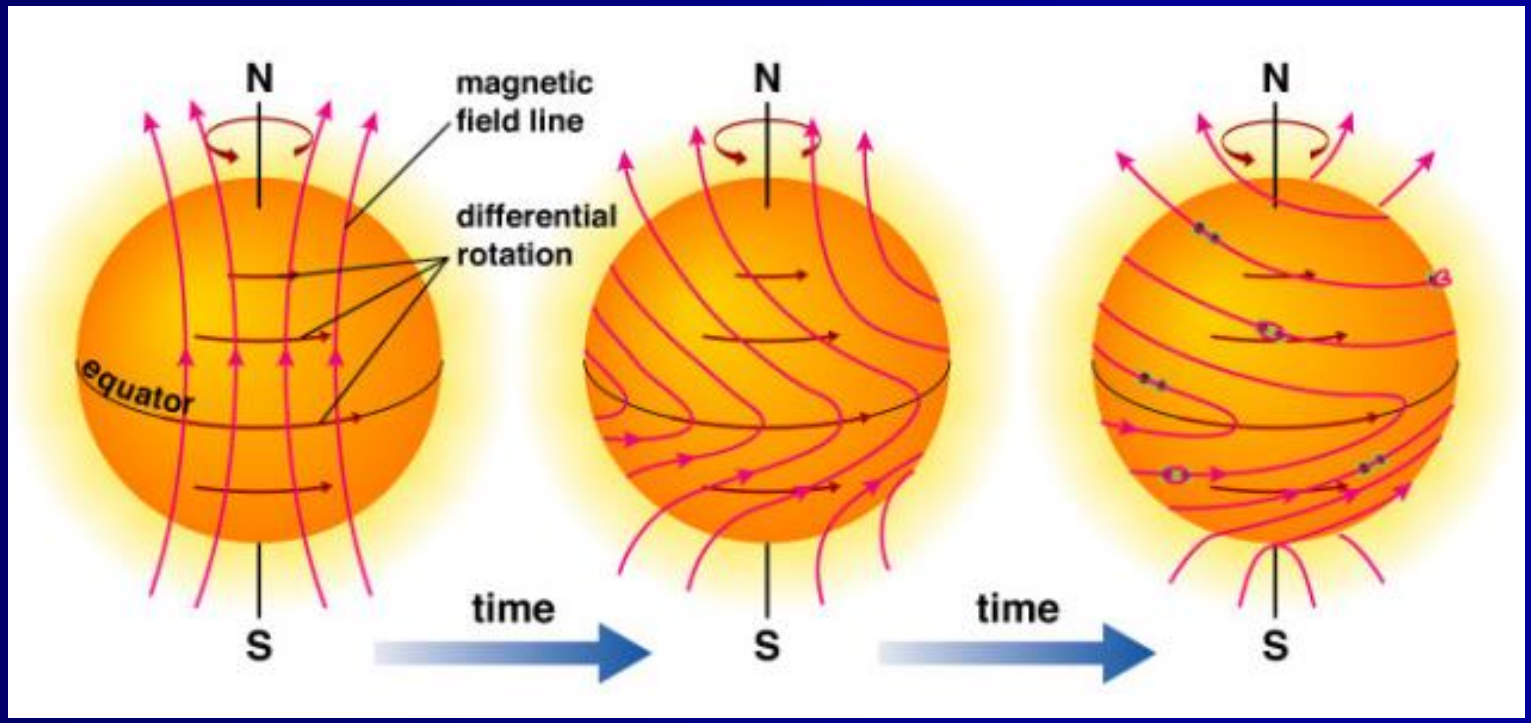
In more recent years it has been found that all other manifestations of solar activity follow essentially the same **11 year cycle**. It should be mentioned that the cycle of the various indices show considerable differences over the 11 year cycle and their maxima might differ by a year or more.

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

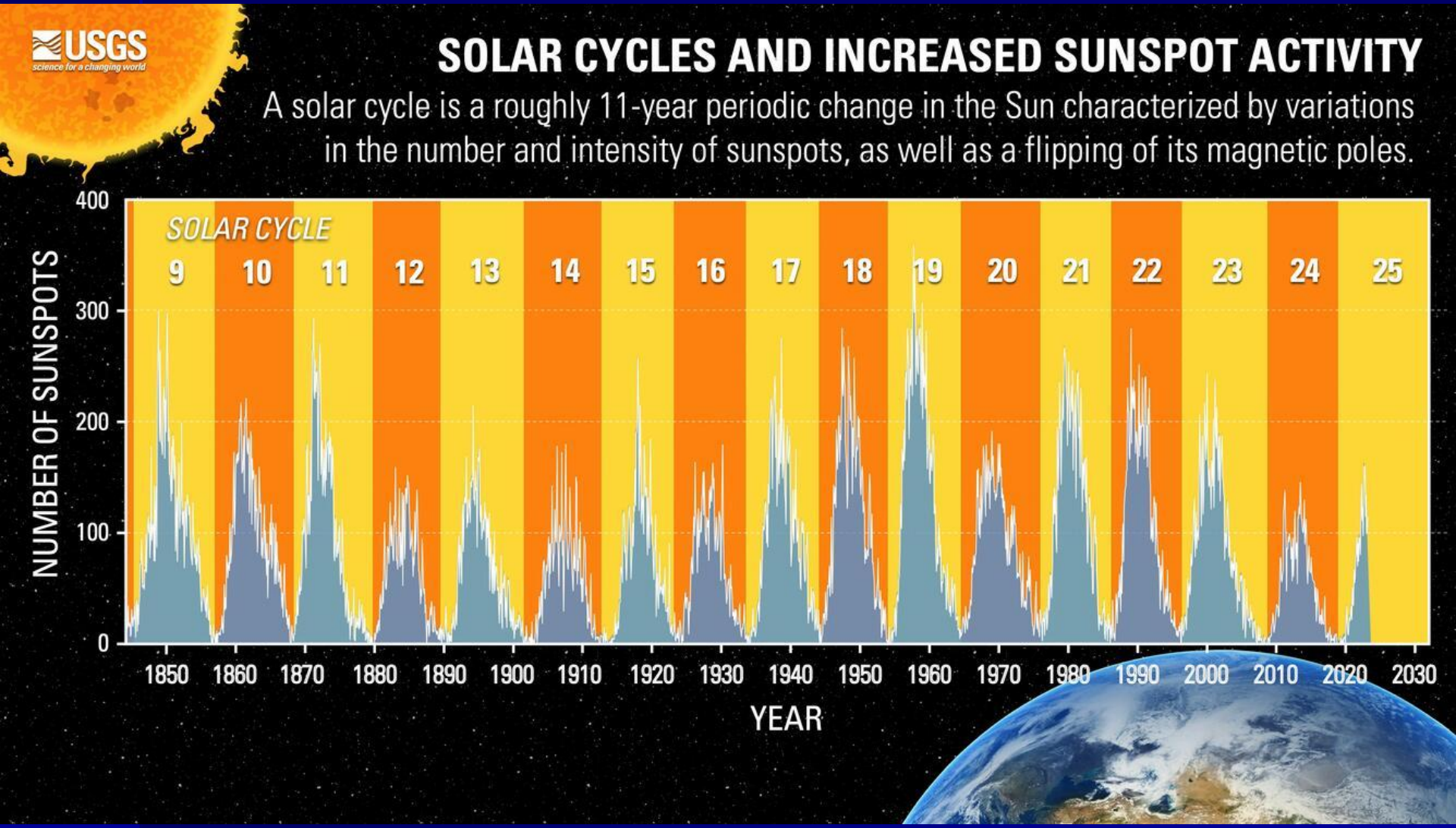
In 1908 **George Ellery Hale**'s observations revealed that the Solar Cycle is a **magnetic cycle with an average duration of 22 years**. However, because very nearly all manifestations of the solar cycle are insensitive to magnetic polarity, it remains common usage to speak of the " **11 years solar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

Future Sunspot Predictions :



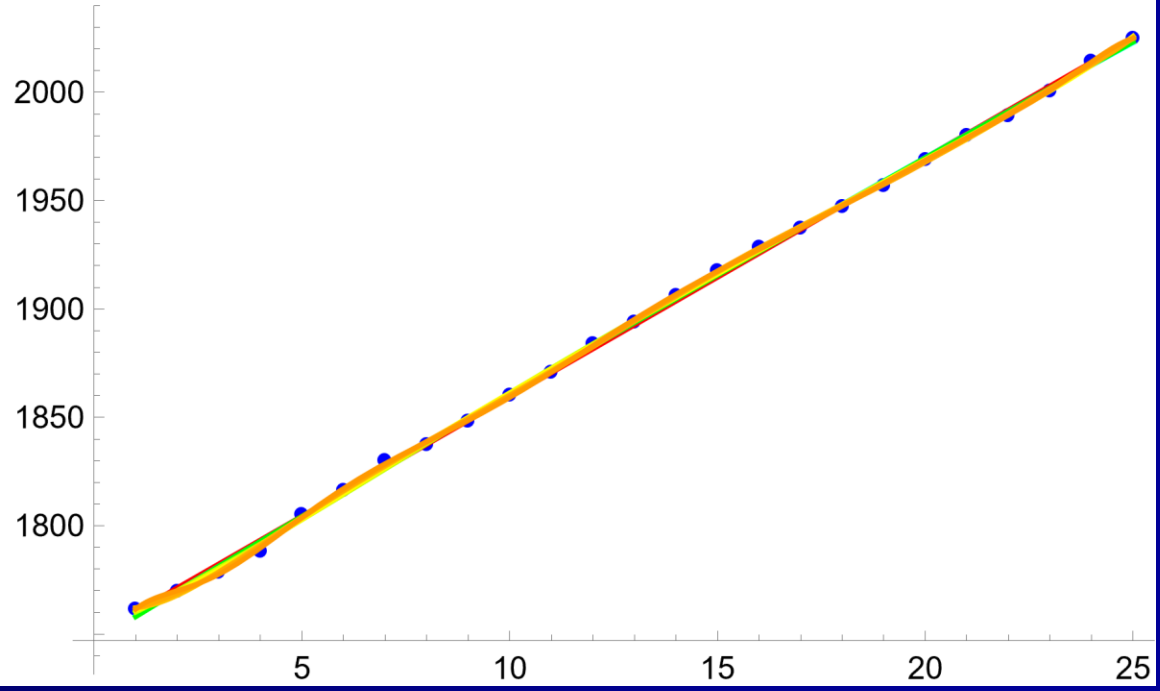
Future Sunspot Predictions :

```
(* Next Solar Maxima - 26th one *)
data = {{1, 1761.5}, {2, 1769.75}, {3, 1778.41}, {4, 1788.16}, {5, 1805.16},
    {6, 1816.41}, {7, 1829.92}, {8, 1837.25}, {9, 1848.16}, {10, 1860.16}, {11, 1870.67},
    {12, 1884.0}, {13, 1894.08},|{14, 1906.16}, {15, 1917.66}, {16, 1928.41},
    {17, 1937.41}, {18, 1947.41}, {19, 1957.0}, {20, 1968.91}, {21, 1980}, {22, 1989.11},
    {23, 2000.5}, {24, 2014.33}, {25, 2024.83}};
Table[{i, data[[i + 1, 2]] - data[[i, 2]]}, {i, 1, Length[data] - 1}];
g1 = ListPlot[data, PlotStyle → {Blue, Pointsize[0.02]}];
mm = 10 ; (* no of polynomials *)
mod = Table[Table[t^n, {n, 0, m}], {m, 1, mm}];
ff = Table[Fit[data, mod[[i]], t], {i, 1, Length[mod]}];
ss = ff /. t → (Length[data] + 1);
Do[Print["Next Maxima is from ", i, " order ploynomial ", ss[[i]]], {i, 1, mm}]
g2 = Table[Plot[ff[[i]], {t, First[data][[1]], Last[data][[1]]}, PlotStyle → Hue[1 / i]],
    {i, 1, Length[mod]}];
Show[{g1, g2}]
```

Future Sunspot Predictions :

```
Next Maxima is from 1 order polynomial 2035.99
Next Maxima is from 2 order polynomial 2033.47
Next Maxima is from 3 order polynomial 2033.96
Next Maxima is from 4 order polynomial 2038.58
Next Maxima is from 5 order polynomial 2037.84
Next Maxima is from 6 order polynomial 2042.01
Next Maxima is from 7 order polynomial 2031.94
Next Maxima is from 8 order polynomial 2033.01
Next Maxima is from 9 order polynomial 2045.74
Next Maxima is from 10 order polynomial 2014.35
```

Out[ ]=



Future Sunspot Predictions :

Next Maxima is from 1 order polynomial **2035.99**
Next Maxima is from 2 order polynomial 2033.47
Next Maxima is from 3 order polynomial **2033.96**
Next Maxima is from 4 order polynomial 2038.58
Next Maxima is from 5 order polynomial 2037.84
Next Maxima is from 6 order polynomial 2042.01
Next Maxima is from 7 order polynomial 2031.94
Next Maxima is from 8 order polynomial 2033.01
Next Maxima is from 9 order polynomial 2045.74
Next Maxima is from 10 order polynomial 2014.35

…. **Cycle 26 will peak around 2034-2036 …. - NASA**

Future Sunspot Predictions :

Space and Atmospheric Physics 11 Find Nest Solar Maxima.nb * - Wolfram Mathematica 13.2

File Edit Insert Format Cell Graphics Evaluation Palettes Window Help

Input

```
(* Next Solar Maxima - 26th one *)
data = {{1, 1761.5}, {2, 1769.75}, {3, 1778.41}, {4, 1788.16}, {5, 1805.16},
   {6, 1816.41}, {7, 1829.92}, {8, 1837.25}, {9, 1848.16}, {10, 1860.16}, {11, 1870.67},
   {12, 1884.0}, {13, 1894.08}, {14, 1906.16}, {15, 1917.66}, {16, 1928.41},
   {17, 1937.41}, {18, 1947.41}, {19, 1957.0}, {20, 1968.91}, {21, 1980}, {22, 1989.11},
   {23, 2000.5}, {24, 2014.33}, {25, 2024.83}};
Table[{i, data[[i + 1, 2]] - data[[i, 2]]}, {i, 1, Length[data] - 1}];
g1 = ListPlot[data, PlotStyle → {Blue, Pointsize[0.02]}];
mm = 10 ; (* no of polynomials *)
mod = Table[Table[t^n, {n, 0, m}], {m, 1, mm}];
ff = Table[Fit[data, mod[[i]], t], {i, 1, Length[mod]}];
ss = Table[ff[[i]] /. t → {26, 27, 28}, {i, 1, mm}];
Do[Print["Next Three Maximas (26th, 27th & 28th) are from ", i, " order polynomial ",
   ss[[i]]], {i, 1, mm}];
g2 = Table[Plot[ff[[i]], {t, First[data][[1]], Last[data][[1]]}, PlotStyle → Hue[1 / i]],
   {i, 1, Length[mod]}];
Show[{g1, g2}]
```

125%

Future Sunspot Predictions :

Next Three Maximas (26th, 27th & 28th) are from 1 order polynomial {2035.99,2047.01,2058.04}

Next Three Maximas (26th, 27th & 28th) are from 2 order polynomial {2033.47,2043.92,2054.32}

Next Three Maximas (26th, 27th & 28th) are from 3 order polynomial {2033.96,2044.63,2055.3}

Next Three Maximas (26th, 27th & 28th) are from 4 order polynomial {2038.58,2052.03,2068.91}

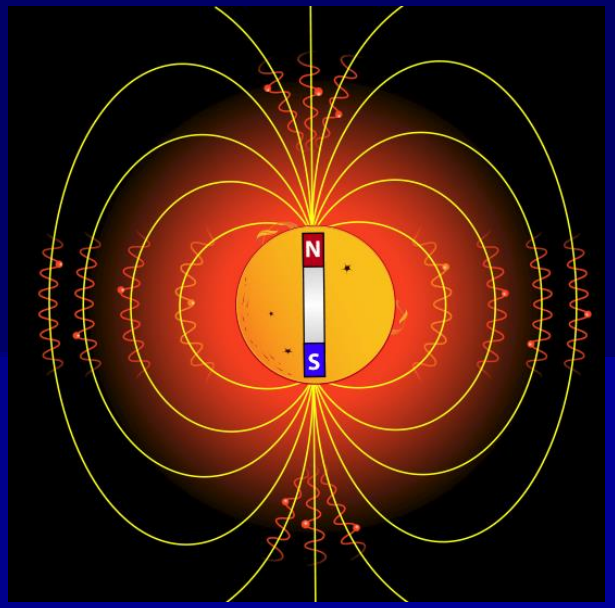
Next Three Maximas (26th, 27th & 28th) are from 5 order polynomial {2037.84,2051.21,2065.32}

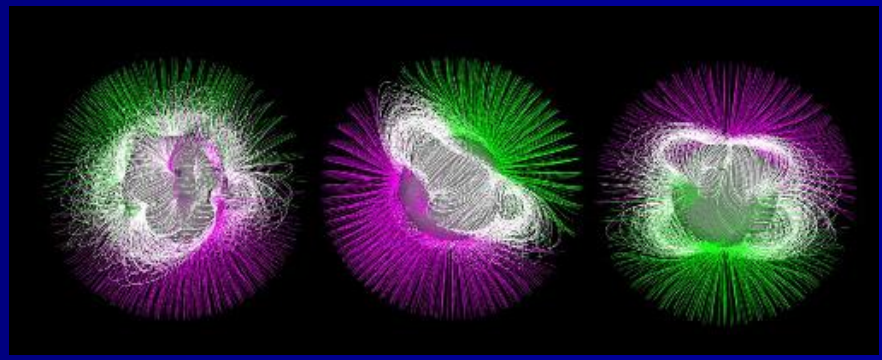
Next Three Maximas (26th, 27th & 28th) are from 6 order polynomial {2042.01,2062.12,2087.97}

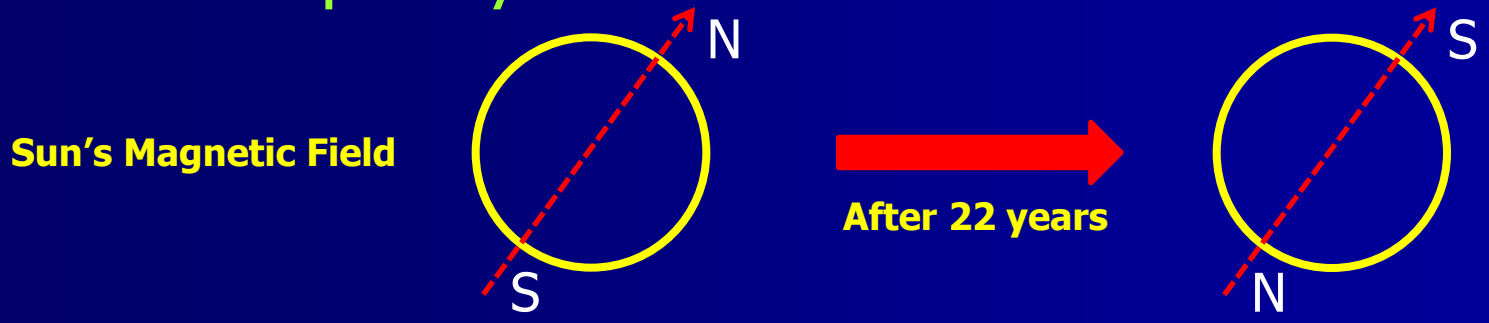
... Cycle 27 is expected to be around 2044-2046.....

NASA

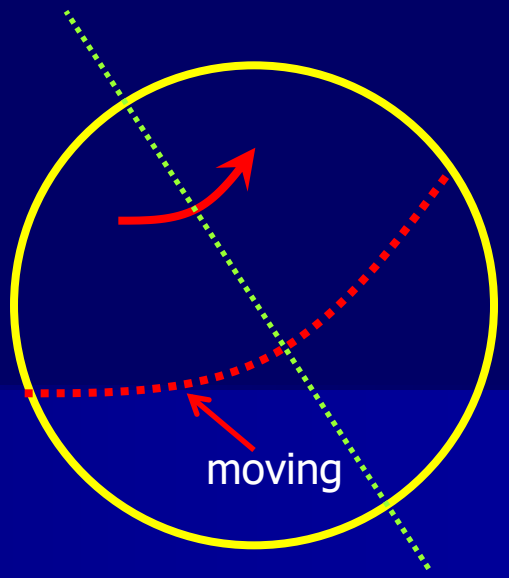
Half a century later, Harold Babcock and Horace Babcock (father and son) showed that the solar surface is magnetized even outside of the sunspots; that this **weaker magnetic field** is to first order a dipole; and that this dipole also undergoes polarity reversals with the same period (22 years) as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

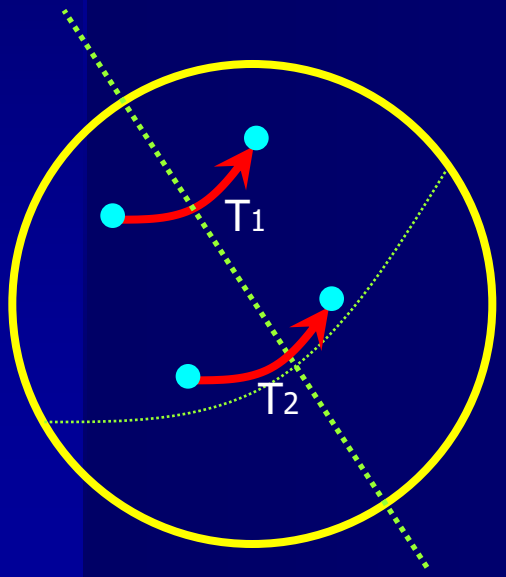






If the Sun is rotating, the sunspots are also rotating. **If we analyzed the two sunspots, the gap between those two sunspots are changing due to the Sun's rotating.** Because the surface of the Sun is not a solid sphere.

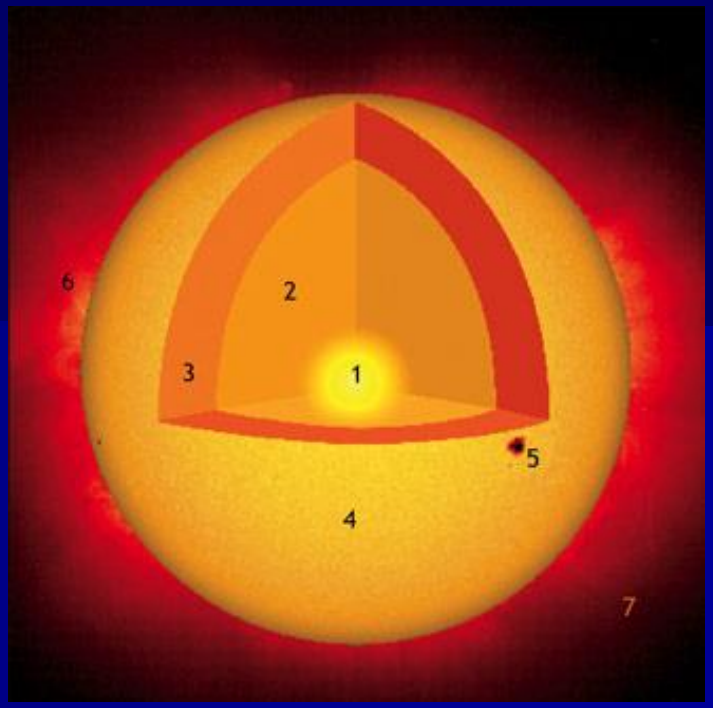




$T_1 \neq T_2$

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.

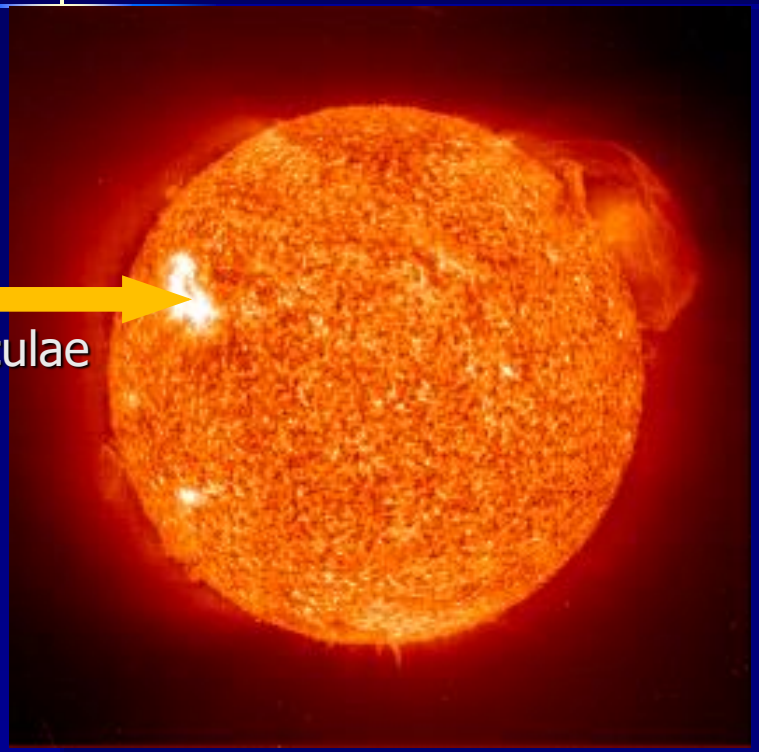
The Active Sun



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

Faculae (දීප්ත) , Flares & Prominences

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

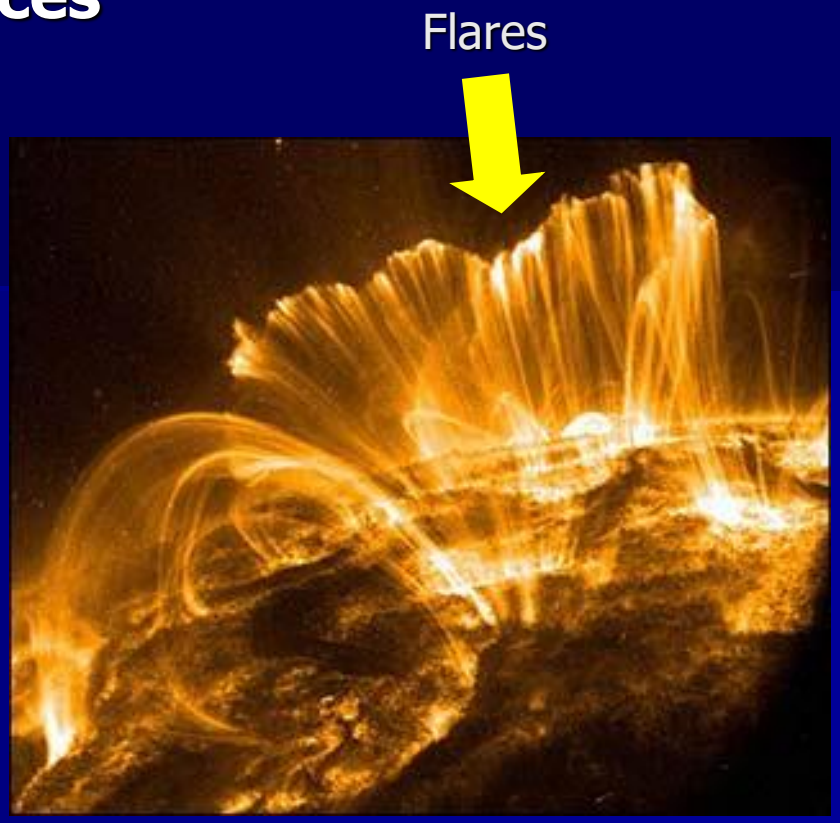


The first sign of solar activity is the appearance of a bright area which, when near the limb of the Sun, is brighter than the photosphere even in white light. These bright areas are called "**Faculae**", or more precisely "**Photospheric Faculae**"

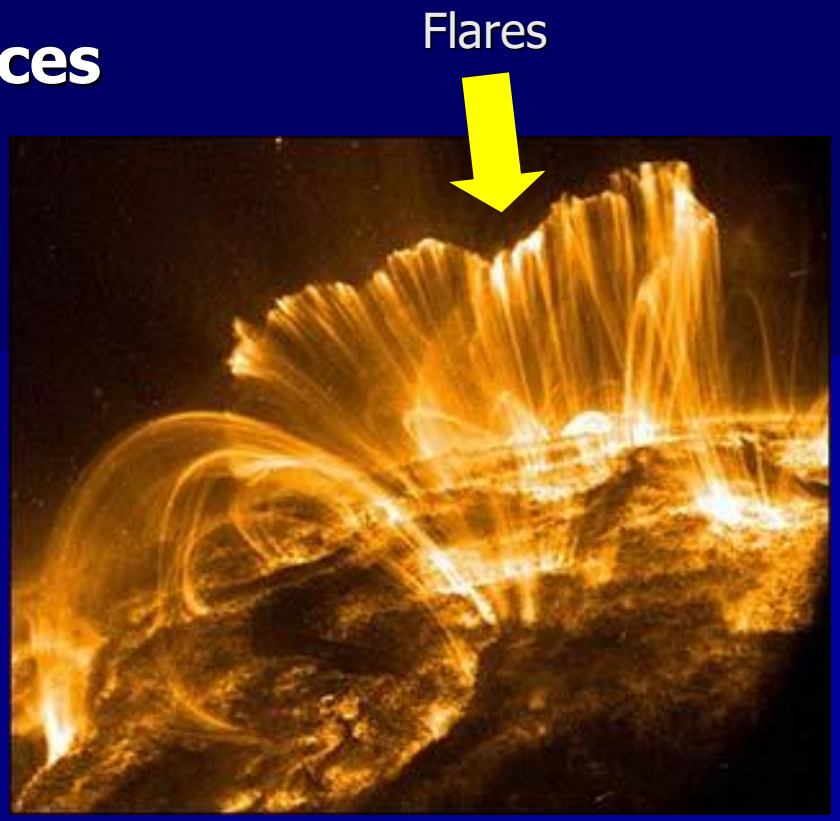
Faculae usually engulf (ගිලදමනවා) a sunspot group, but they become noticeable before the appearance of the sunspots and often survive them by a month or two.

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.



Faculae , Flares & Prominences



A flare is the optical effect produced by the sudden release of tremendous (very large) amount of energy ($6x10^{25}$ 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.

Faculae , Flares & Prominences

When seen in projection at the limb of the Sun, flares appear to have different shapes…

Mounds (ගල්ගොඩ), **Spikes** (කූරු), **Cones** (කේතු), **Loops** (වළලු), …. **ect,**

that start chromosphere and extend into the lower corona. Typical heights range between 3000 km and 20,000 km. **Large Flares** can be seen in the **white light**, but **flares are usually observed in the H-alpha line** where they can be seen much better.

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

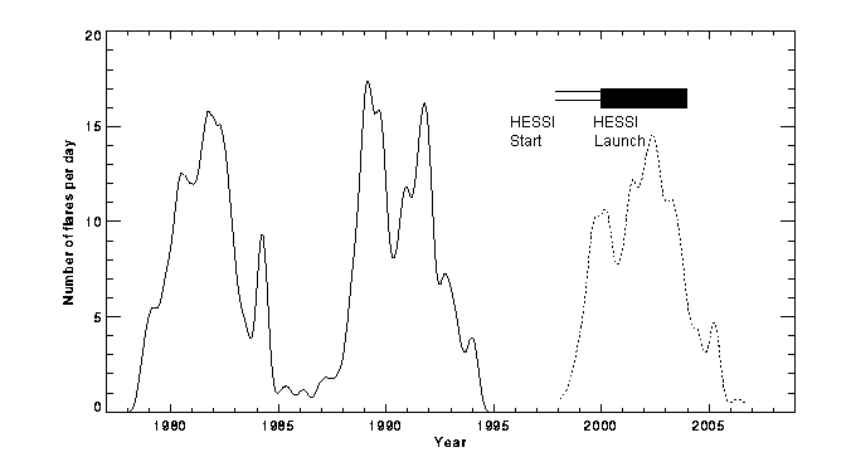
Mean Sunspot Number

$$N_t = \alpha \left[\overline{R} - 10\right]$$

Observatory Constant

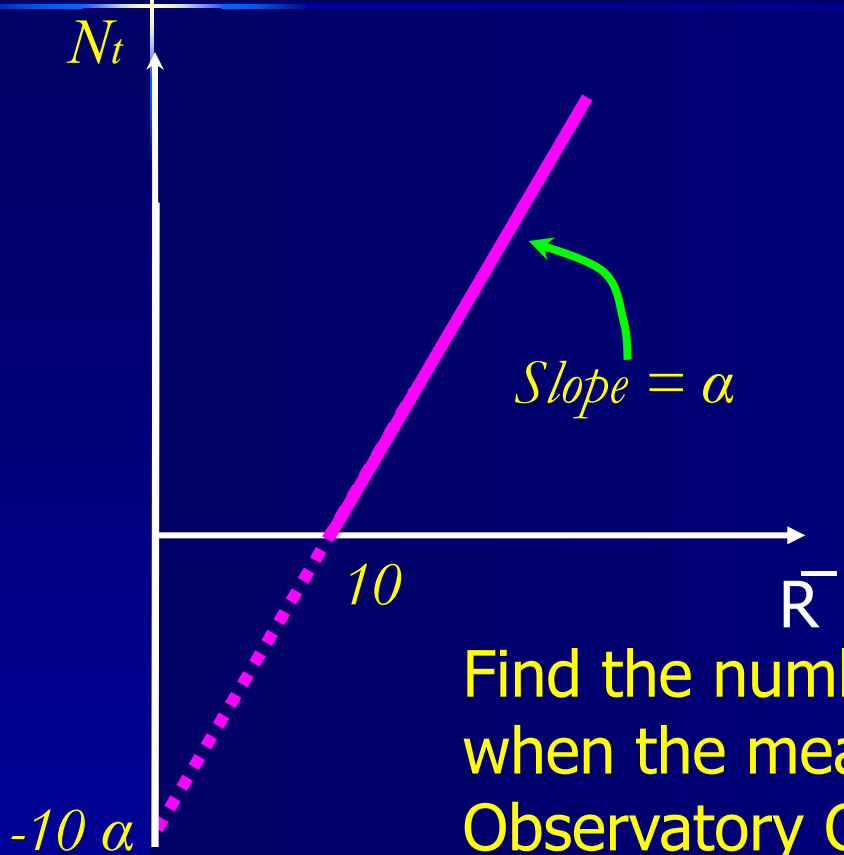
~ 1.5 – 2.0

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



Solar Activity & Solar Flares

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



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

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

y m x - c

If, Nt =0 → $\bar{R}$ =10

If, $\bar{R}$ = 0 → Nt = -10 α

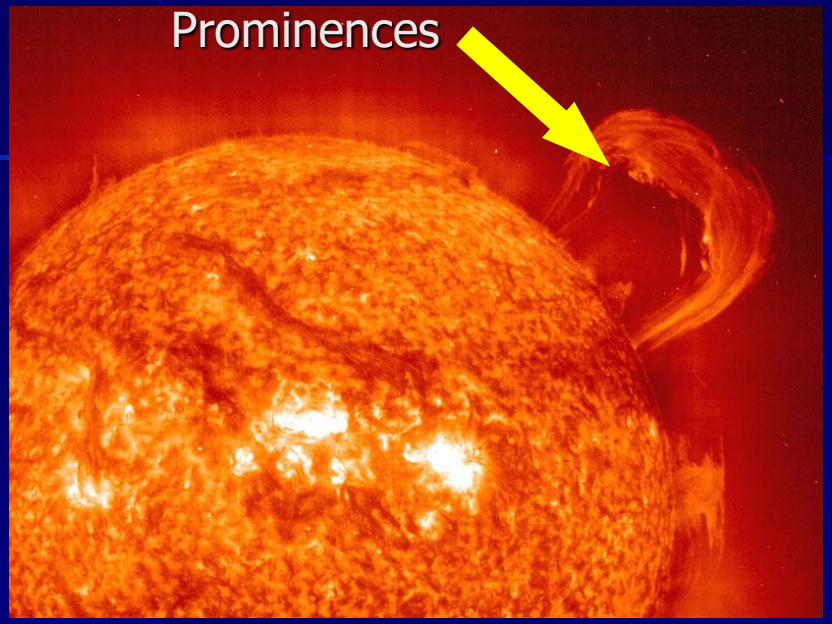
Eg:

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

$$N_t = \alpha \left[\bar{R} - 10\right] \Rightarrow N_t = 1.6 \left[25 - 10\right]$$

$$\Rightarrow N_t = 24$$

Faculae , Flares & Prominences (නෙරුම)

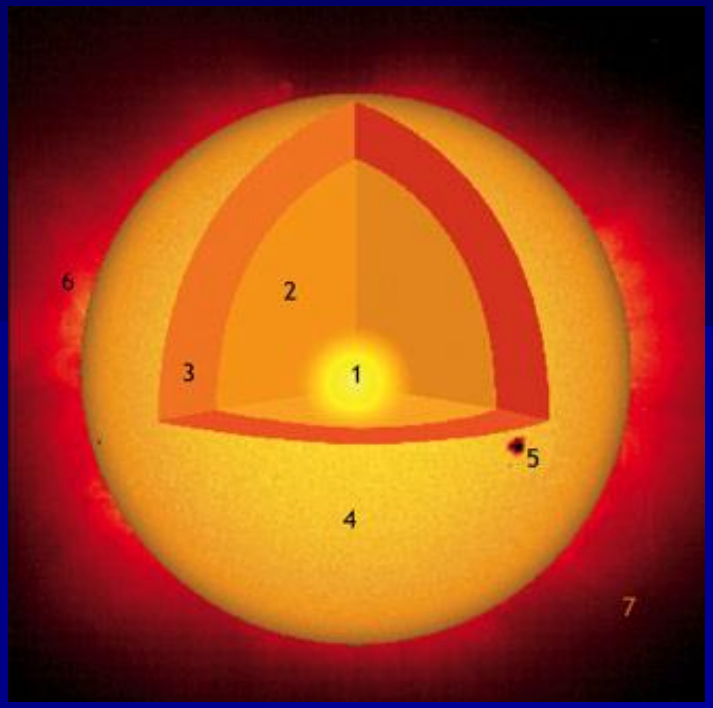


Solar **prominence** (**more gases emitted place**) have been recorded in same very impressive sequences with time-lapse photography. When seen at the limb of the Sun, prominence appear as luminous arch-like structures with continuous internal motion. These arches are about 200,000 km long but only a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

The Active Sun



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Radio & X-ray Bursts from the Sun

In the specific meaning of the term, a solar flare is the sudden brightening of a small region of the solar disc. More generally it is an explosive event in the atmosphere of the Sun which produces not only optical effect but also radio, X-ray and corpuscular radiation (ලවක විකිරණය).

While the **optical flux from the Sun never varies by more than 1%,** the enhancement in the X-ray region and in the radio domain during a flare event can exceed the respective flux from the quiet Sun by several orders of magnitude. X-ray bursts from the Sun can be detected either directly with special instruments flown on rockets and satellites, or indirectly from the ground by the effects which they produce in the terrestrial ionosphere. **Solar radio bursts are observed directly from the ground through the radio window of the terrestrial atmosphere.**

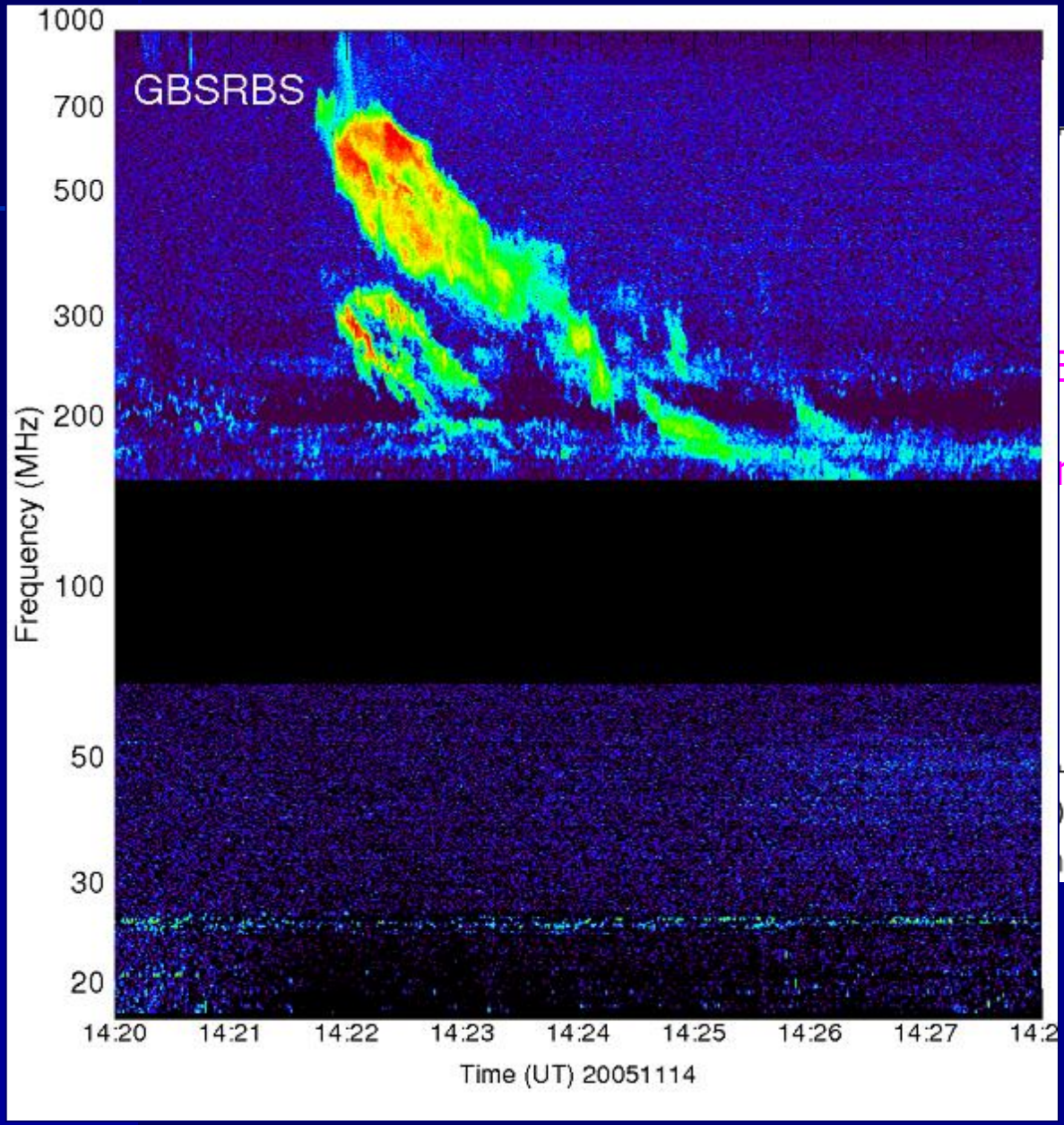
When a flare event is triggered in an active region on the Sun, it produces a sharp burst of energetic electrons and protons which stream **with velocities** of the order of $v \sim 10^8$ m/s both **outwards towards the corona and inwards towards the chromosphere.**

Radio & X-ray Bursts from the Sun

The downward stream of the relativistic electrons produces immediately a **burst of hard X-rays** through collisions with ions in the **corona** or with neutral hydrogen atoms in the **chromosphere.**

Besides the downward burst of high energy electrons, there is usually also an upward burst of energetic particles which speed through the solar corona exciting plasma waves. These compression waves of the coronal plasma use part of their energy to generate radio waves at the local plasma frequency $\mathbf{f_p}$.
As these energetic particles move with high velocities ($v \sim 10^8$ m/s) outwards through layers of continuously lower electron density, the peak frequency of the radio burst drifts rapidly toward lower values.

Radio & X-ray Bursts (සූර්ය) from the Sun



Bursts

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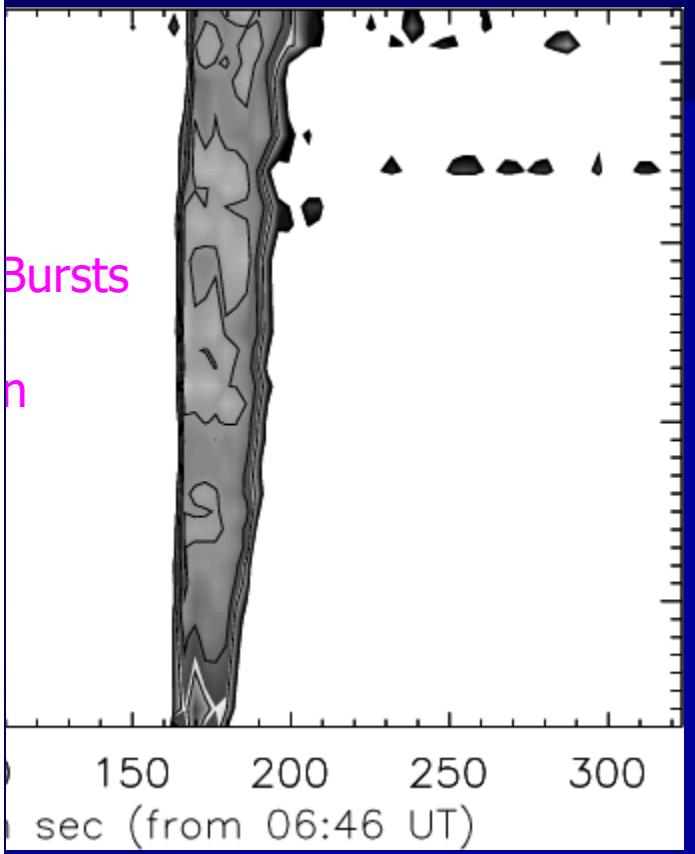
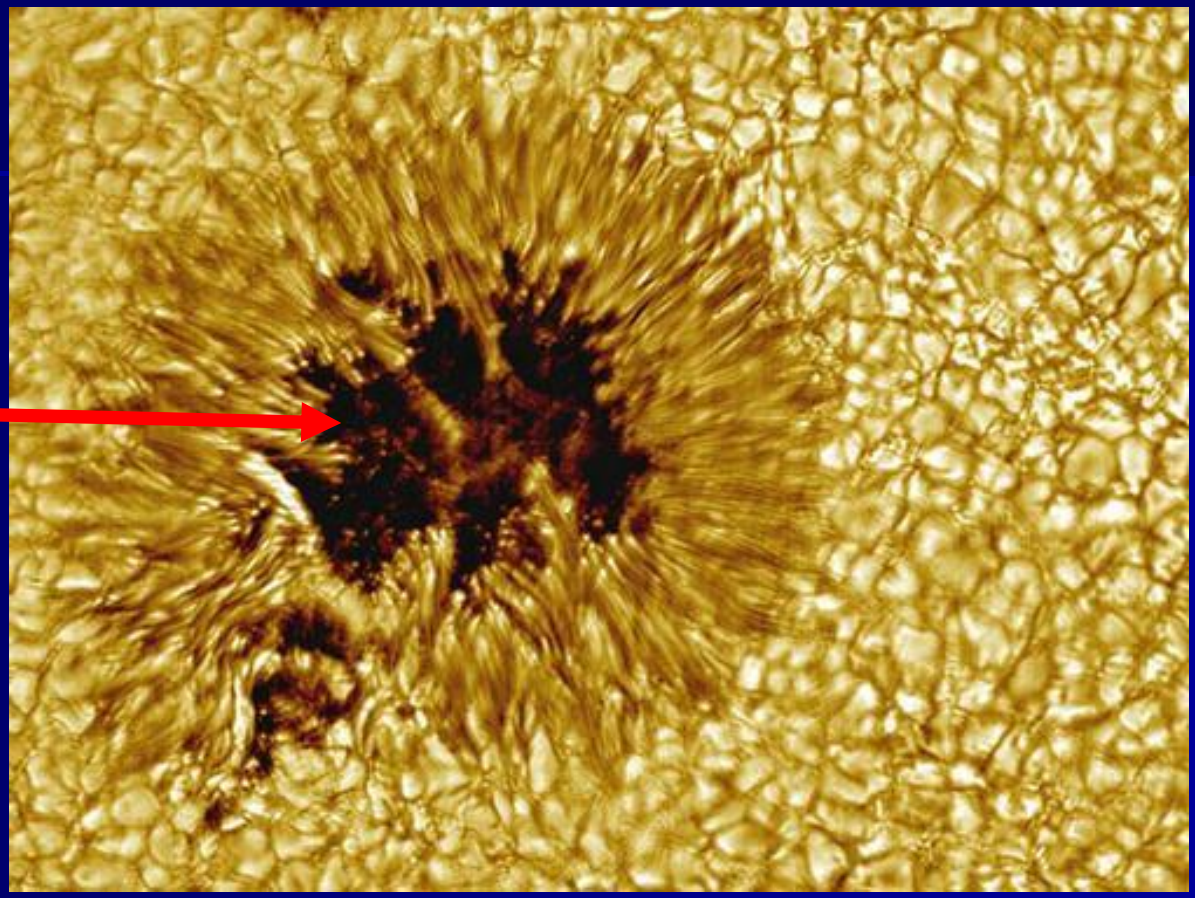
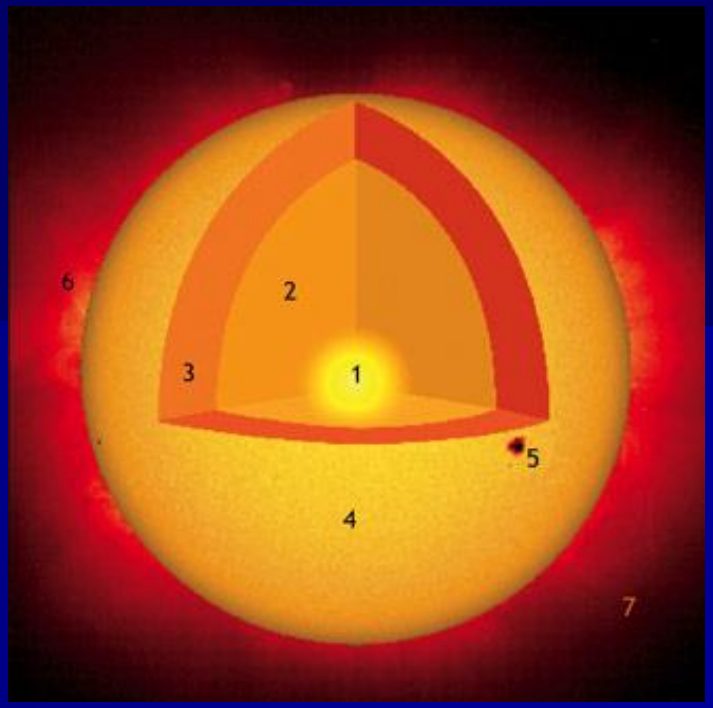


Radio & X-ray Bursts from the Sun

X ray Bursts
of
the Sun



The Active Sun



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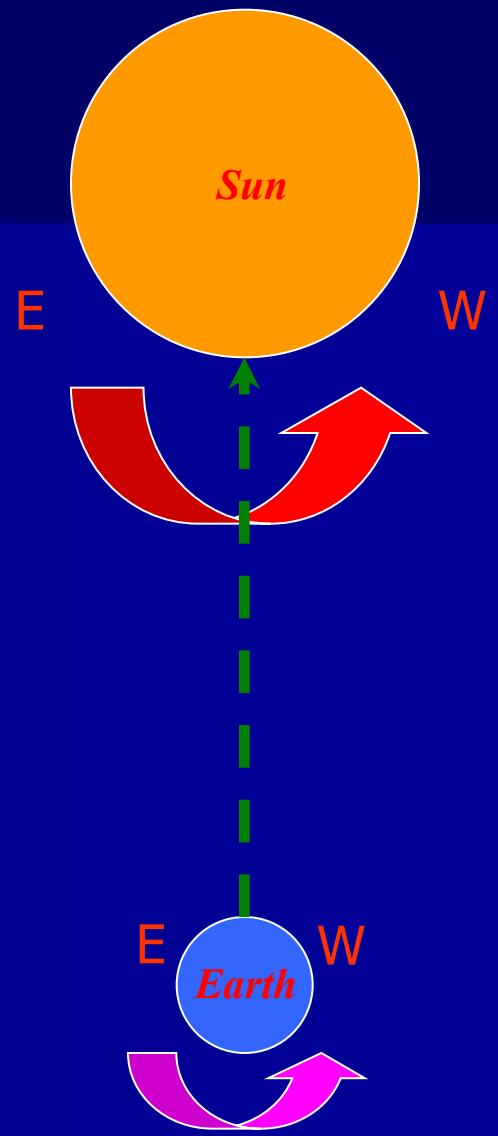
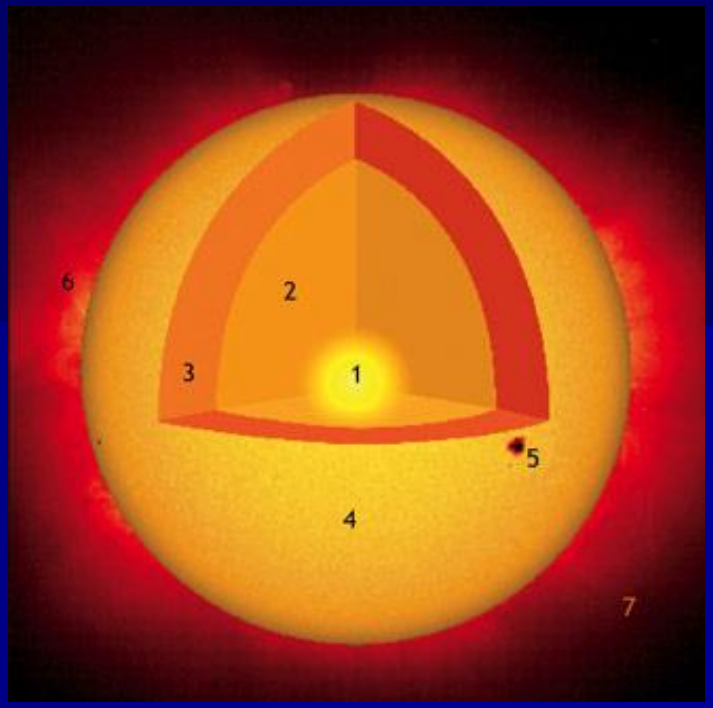
The Development of an Active Region on the Sun

Now that we have studies all the different manifestation of the solar activity, we must try to tie tem together into a chronological (time base) sequence of events. For this reason we will summarize in this section the life history of an active region of the Sun. Note that according to an established convention that Sun rotates from the east limb to the west limb. As seen from the following figure, a terrestrial observer of the Sun from a position on the noon meridian has west to his right both for the Earth and the Sun.



The first sign usually is the appearance of a small bright speck (dot) which is the beginning of the facular region. If this region is located near the limb it might be visible in **white light**, but at any rate it will always be visible in the H-alpha line of Hydrogen or K-line of Calcium. The magnetic field of the region increases rapidly to 100 Gauss or more and a few hours later the first dark pores (very tiny hole) appear.

The Active Sun



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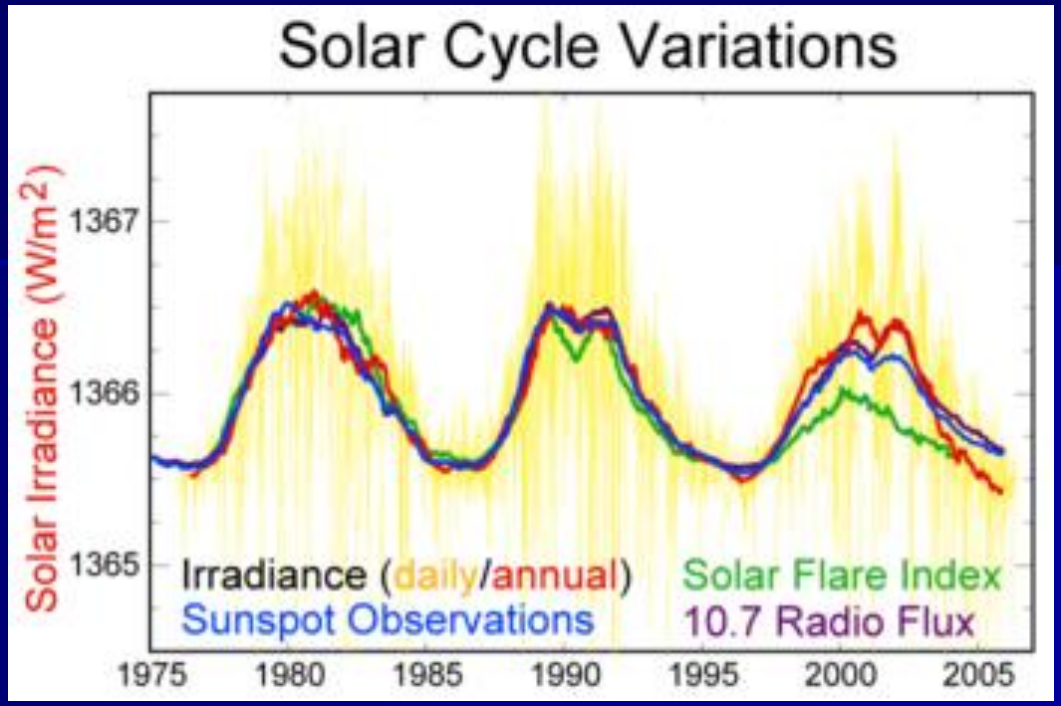
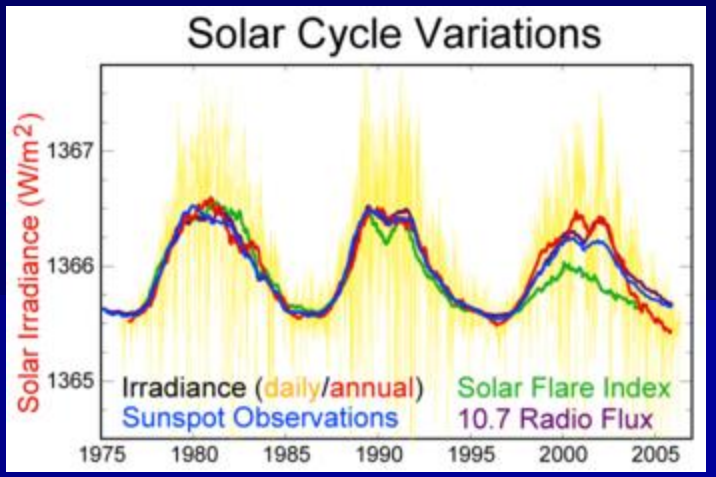
Effects of the Solar Cycle :



The Suns magnetic field structures its atmosphere and outer layers all the way through the corona and into the solar wind. Its spatiotemporal variations lead to a host of phenomena collectively known as solar activity. All of solar activity is strongly modulated by the solar magnetic cycle.

Effects of the Solar Cycle :



- Surface Magnetism
  Sunspots may exist anywhere from a few days to a few months, but they eventually decay, and this releases magnetic flux in the solar photosphere.

- Solar Irradiance (shinning)
  The total solar irradiance is the amount of solar radiative energy incident on the Earth's upper atmosphere.

Effects of the Solar Cycle :

- Short-wavelength Radiation
  With a temperature of 5870 K, the photosphere of the Sun emits very little short wavelength radiation, such as extreme UV and X-rays. The solar UV, EUV, and X-ray varies markedly in the course of the solar cycle.

- Solar Radio Flux
  Emission from the Sun at centi-metric (radio) wavelength is due to primarily to coronal plasma trapped in the magnetic fields overlying active regions.

Effects of the Solar Cycle :

Sunspot activity has a major effect on long distance radio communication particularly on the shortwave bands although medium wave and low VHF frequencies are also affected.

High levels of sunspot activity lead to improved signal propagation on higher frequency bands, although they also increase the level of solar noise and ionospheric disturbances. These effects are caused by impact of the increased level of solar radiation on the ionosphere.

Effects of the Solar Cycle :

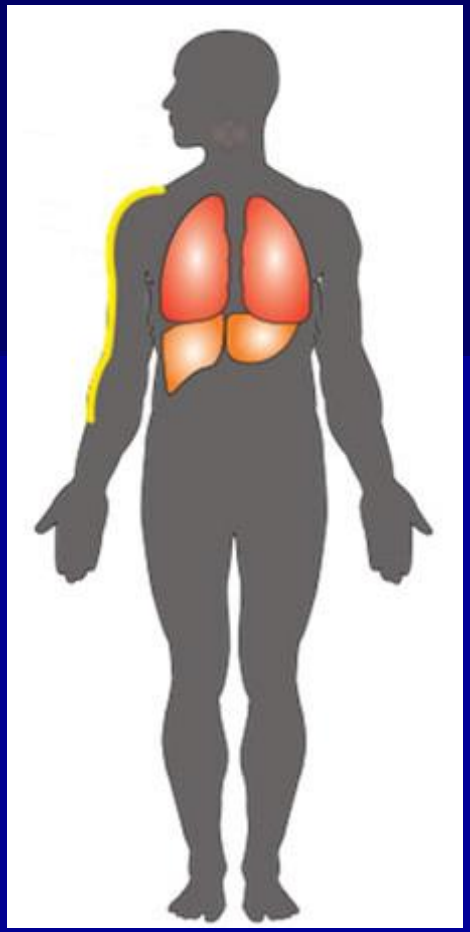
- Geo-effective eruptive (breaking) phenomena Complex coronal magnetic field structures evolve in response to fluid motions at the solar surface, and emergence of magnetic flux produced by dynamo action in the solar interior. Sometimes, these structures lose stability, leading to **coronal mass ejections** into interplanetary space. Or flares caused by sudden localized release of magnetic energy driving copious (huge) emission of **UV** and X-ray radiation as well as energetic particles.

Effects of the Solar Cycle :

- Cosmic Ray Flux
  The outward expansion of solar ejecta into interplanetary space provides over densities of plasma that are efficient at scattering high energy cosmic rays entering the solar system from elsewhere in galaxy.

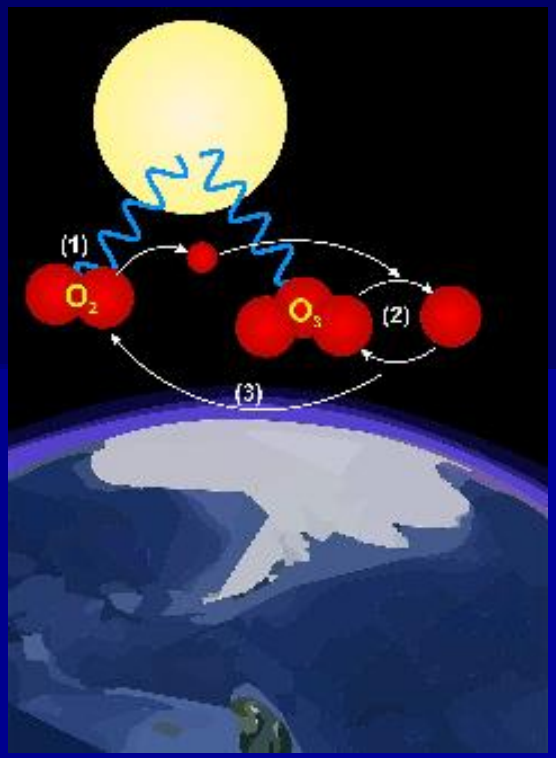
Some high energy cosmic rays entering Earth's atmosphere collide hard enough with molecular atmospheric constituents to cause occasionally nuclear **spallation reactions**.

The Solar Cycle, Effects on Earth



The impact of Solar cycle on living organisms has been investigated (see chronobiology). Some researchers claim to have found connections with human health.

The Solar Cycle, Effects on Earth



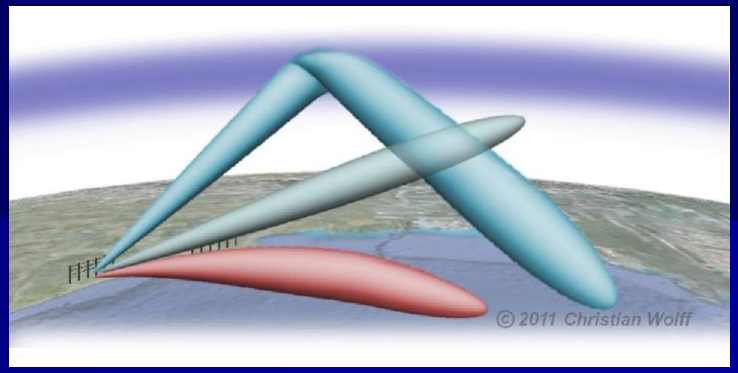
The amount of UV-B light at 300 nm reaching the Earth varies by as much as 400% over the solar cycle due to variations in the protective Ozone Layer. In the stratosphere, ozone is continuously regenerated by the splitting of O2 molecules by ultraviolet light. During a solar minimum, the decrease in ultraviolet light received from the Sun leads to a decrease in the concentration of ozone, allowing increased UV-B to penetrate to the Earth's surface.

The Solar Cycle, Effects on Earth

The sunspot cycle has been implicated in having effects on climate, and may play a part in determining global temperature.

The Solar Cycle, Effects on Earth

Sky-wave modes of radio communication operate by bending (reflecting) radio waves (electro-magnetic radiation) off of the Ionosphere.



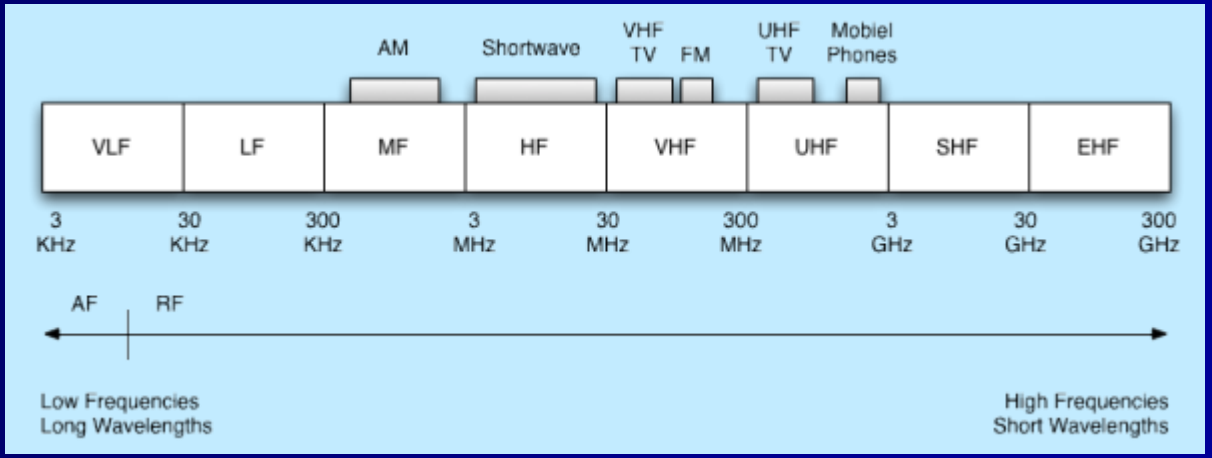
During the "peaks" of the solar cycle, the ionosphere becomes ionized by solar photons and cosmic rays.

This affects the path (propagation) of the radio wave in complex ways which can both facilitate (easy) or hinder (blocked) local and long distance communications.

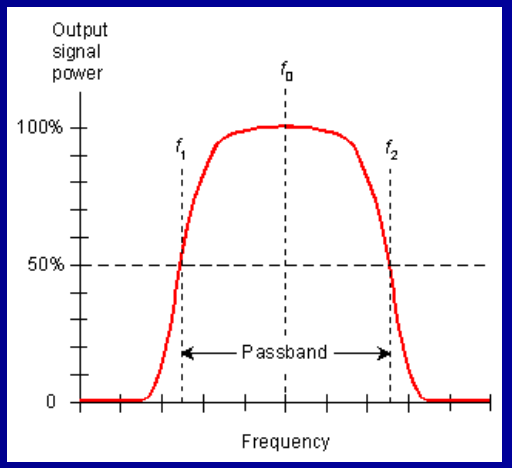
Forecasting of sky-wave modes is of considerable interest to commercial marine and aircraft communication, amateur radio operators, and short wave broad casters.

The Solar Cycle, **Effects on Earth**

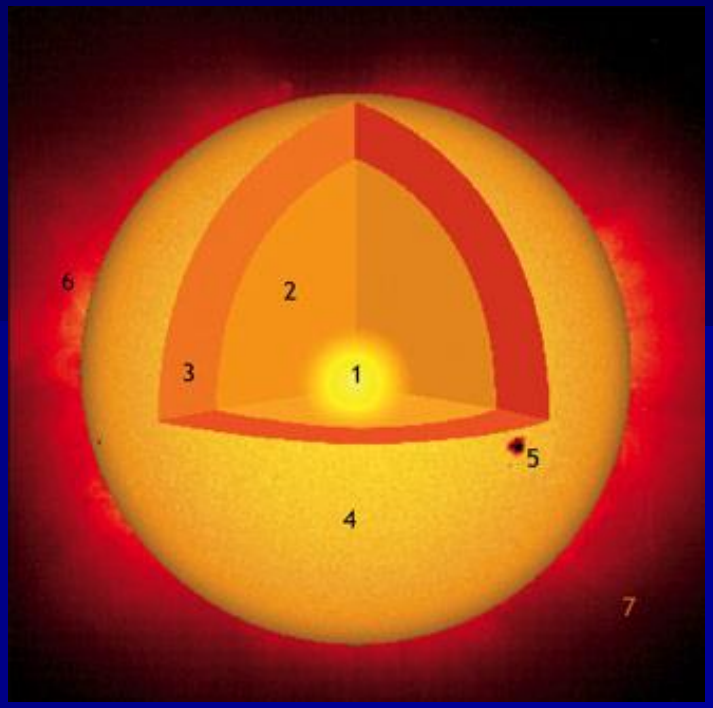
- These users utilize frequencies within the high-frequency or 'HF' radio spectrum which are most **affected by these solar and ionospheric variance**s.



- Changes in solar output affect the maximum usable frequency, a limit on the highest frequency usable for communications.



The Active Sun



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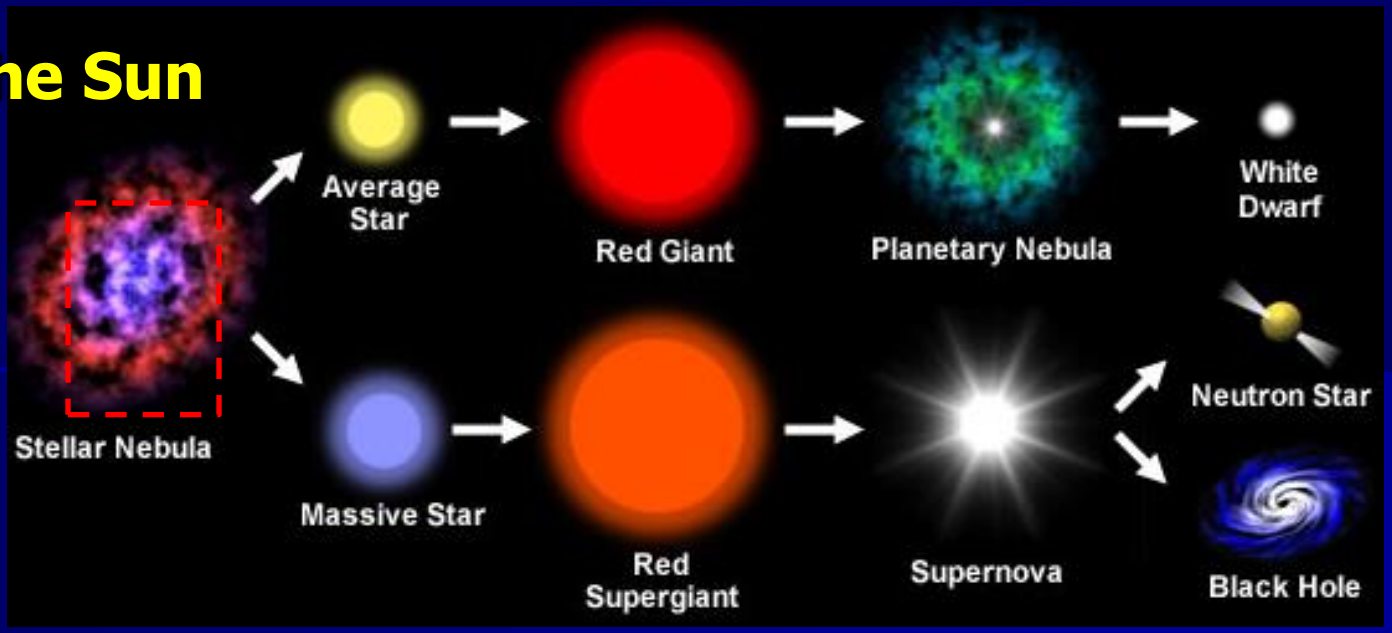
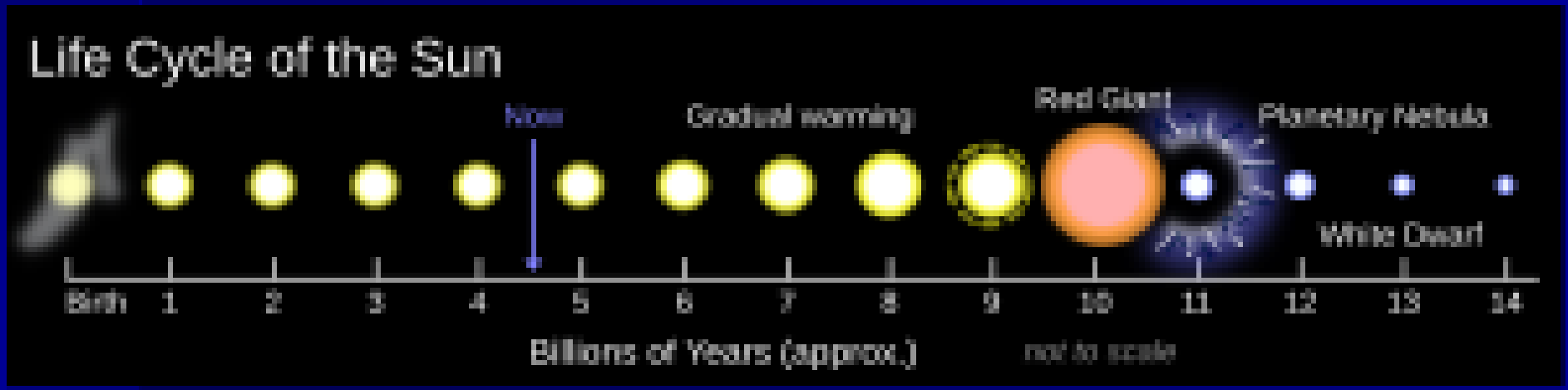
Life cycle of the Sun



The Sun was formed about **5 billion years ago** (4.57), when a hydrogen molecular cloud collapsed. The Sun is about halfway through its main-sequence evolution, during which nuclear fusion reactions in its core fuse **hydrogen into helium**. Each second, more than four million metric tons of matter are converted into energy within the Sun's core producing neutrinos and solar radiation. At this rate the Sun has so far converted around 100 Earth masses of matter into energy. The Sun will spend a total of approximately **10 billion years** as a main sequence star.

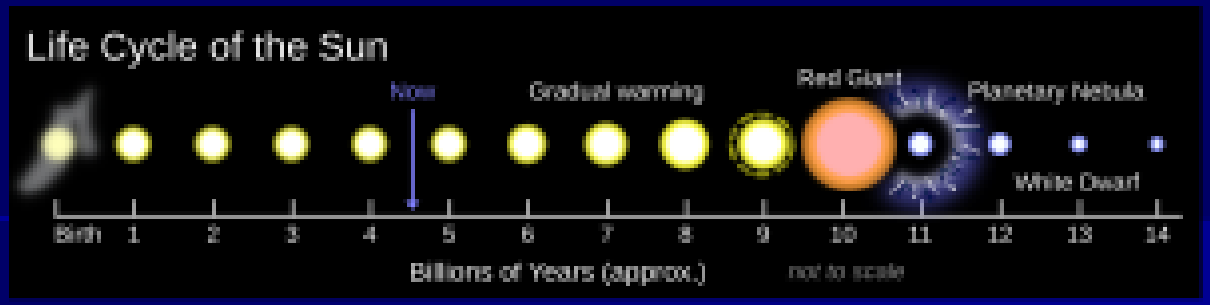
Life cycle of the Sun

The Sun does not have enough mass to explode as a supernova. Instead, in about 5 billion years, it will enter a red giant phase, its outer layers expanding as the hydrogen fuel in the core is consumed and the core contracts and heats up. **Helium fusion** will begin when the core temperature reaches around 100 million Kelvins and will produce Carbon, enterning the asympotic giant branch phase.



Life-cycle of the Sun; sizes are not drawn to scale.

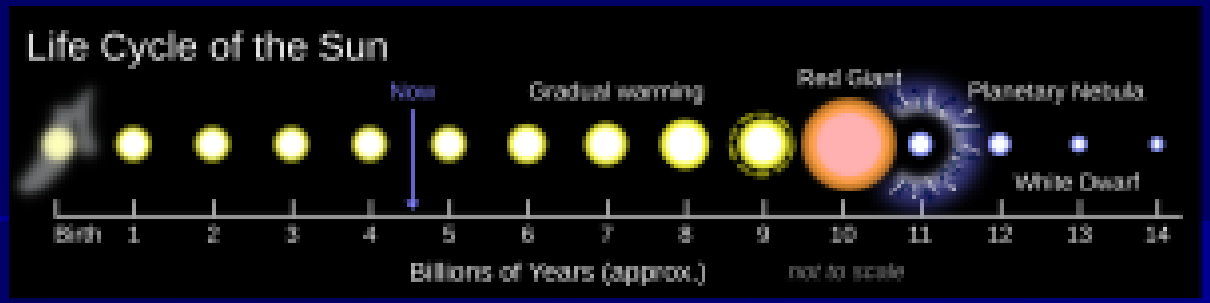
Life cycle of the Sun



Earth's fate is precarious (can not predicted). **As a red giant, the Sun will have a maximum radius beyond the Earth's current orbit, 1 AU (~1.5x10^{11} m), 250 times the present radius of the Sun.**

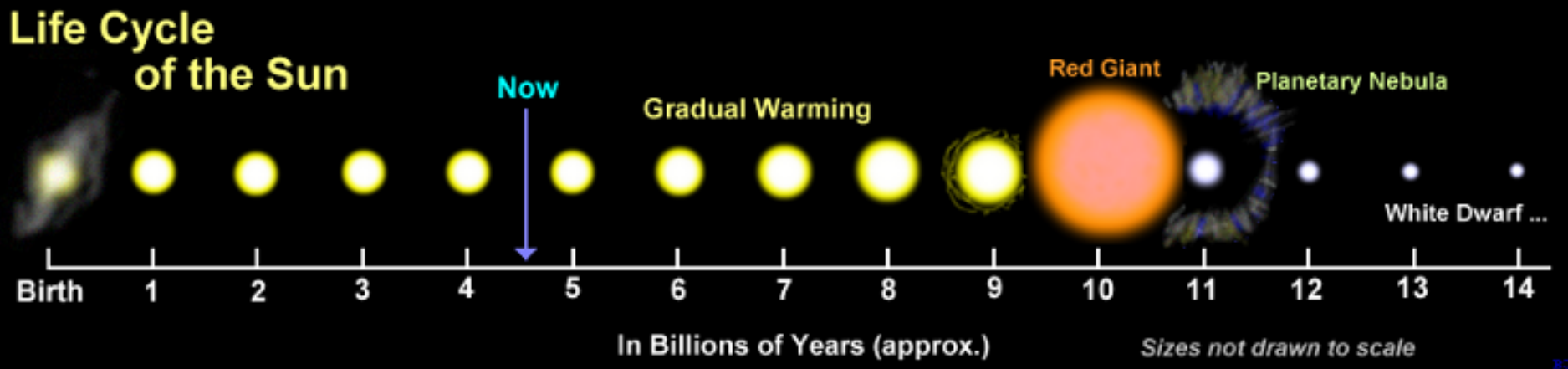
Even during its current life in the main sequence, the Sun is gradually becoming more **luminous** (about 10% every 1 billion years), and its surface temperature is **slowly rising**.

Life cycle of the Sun

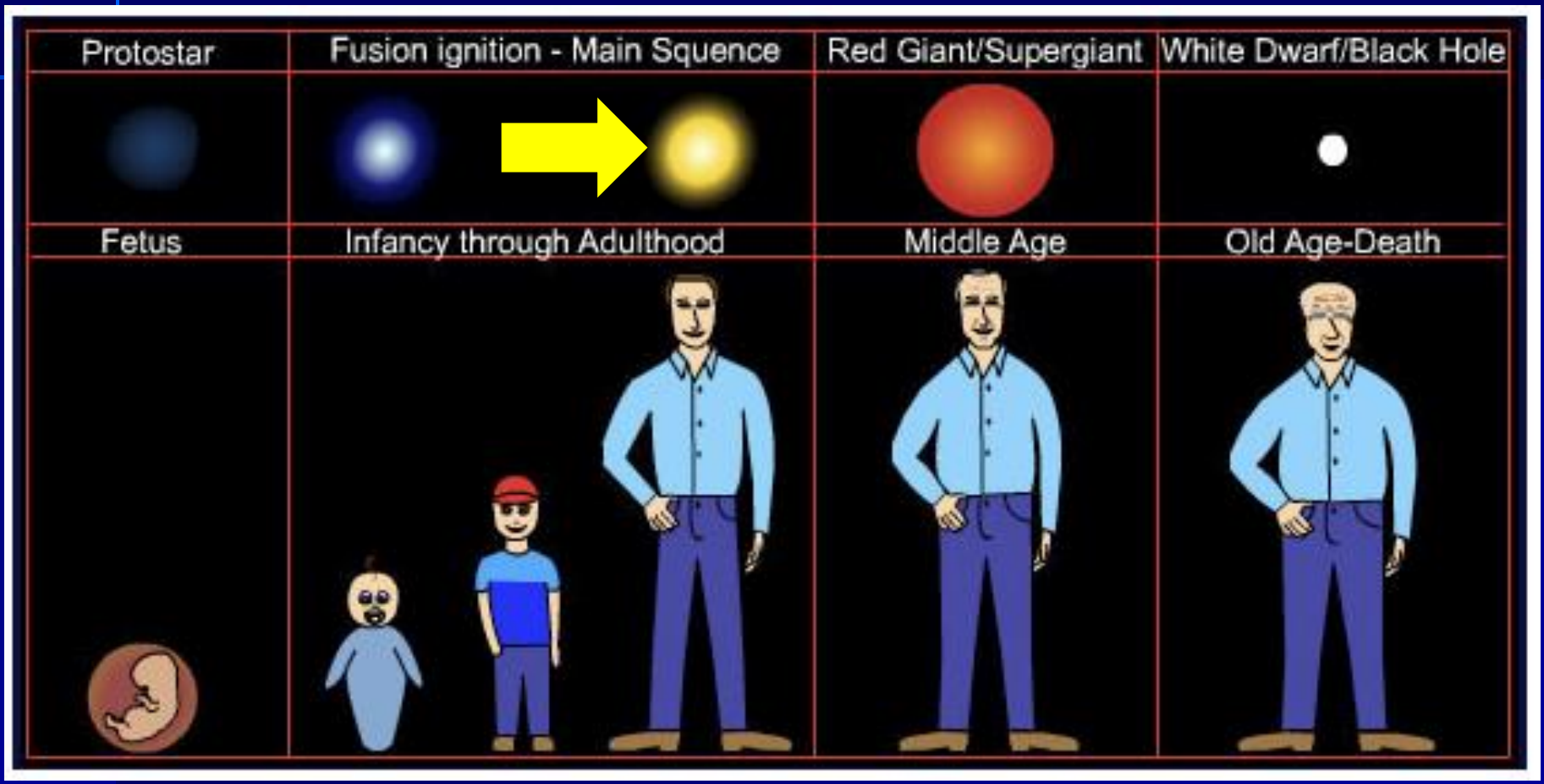


Following the red giant phase, intense thermal pulsations will cause the Sun to throw off its outer layers, forming a planetary nebula. The only object that will remain after the outer layers are ejected is the extremely hot stellar core, which will slowly cool and fade as a white dwarf over many billions of years. This **stellar** (about the planets) **evolution** scenario is typical of low-to medium mass stars.

Life cycle of the Sun



Life cycle of the Sun



Thank You !