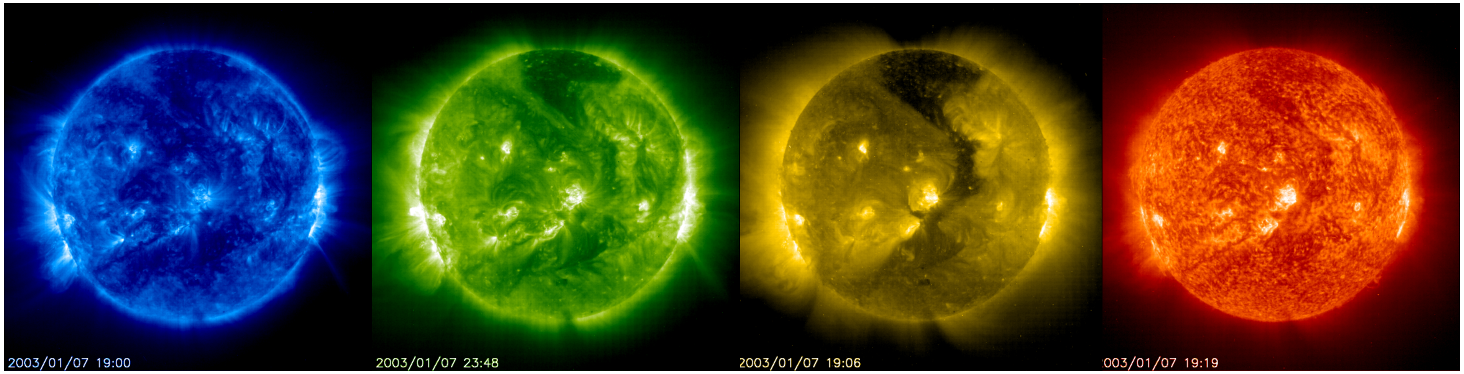
PHY392S
Physics of Climate

Lecture 6

Radiation - Overview

Radiation

- The primary source of energy that drives the Earth's climate system is the Sun.
- The Sun's energy comes to us mostly in the form of electromagnetic radiation.
- Understanding climate requires understanding the nature of electromagnetic radiation and how it interacts with a planetary atmosphere and surface.

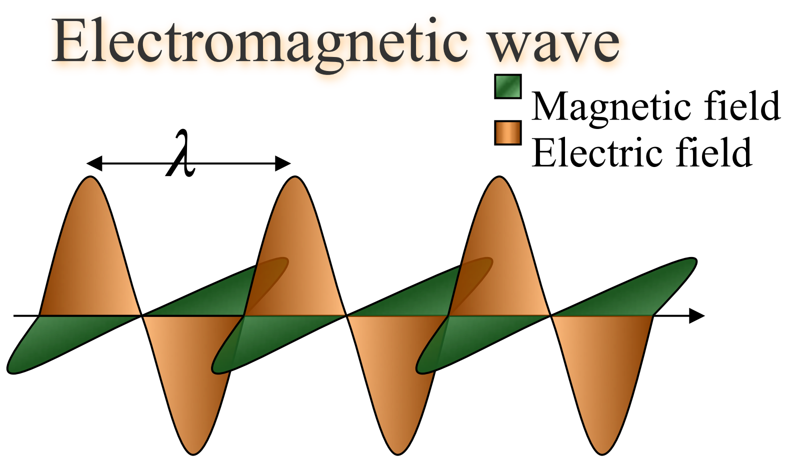


l= 171Å *l= 195Å* *l= 284Å* *l= 304Å*

Sun – SOHO observations 07/01/03, from http://sohowww.nascom.nasa.gov/

Electromagnetic Radiation

The term electromagnetic radiation refers to a phenomenon that moves energy from one place to another by electric and magnetic fields.



- Defined by the solutions of Maxwell's equations.
- As they move, electromagnetic waves are associated with electric and magnetic fields that oscillate at a certain frequency.
- Electromagnetic waves can be thought of as particles (photons) that carry energy at speed c ($c = 2.998 \times 10^8$ m/s - vacuum).

EM waves are usually specified by:

- $E \perp B \perp$ direction of propagation
- Wavelength (λ) = distance between crests
- Frequency (f or ν) = number of oscillations per second = c/λ
- Wavenumber (ν or $\bar{\nu}$) = number of crests per unit length = $1/\lambda$

Radiation as Wave Motion

The energy per unit area per unit time flowing perpendicularly into a surface is given by the Poynting vector :

$$\vec{S} = c^2 \varepsilon_o \vec{E} \times \vec{H}$$

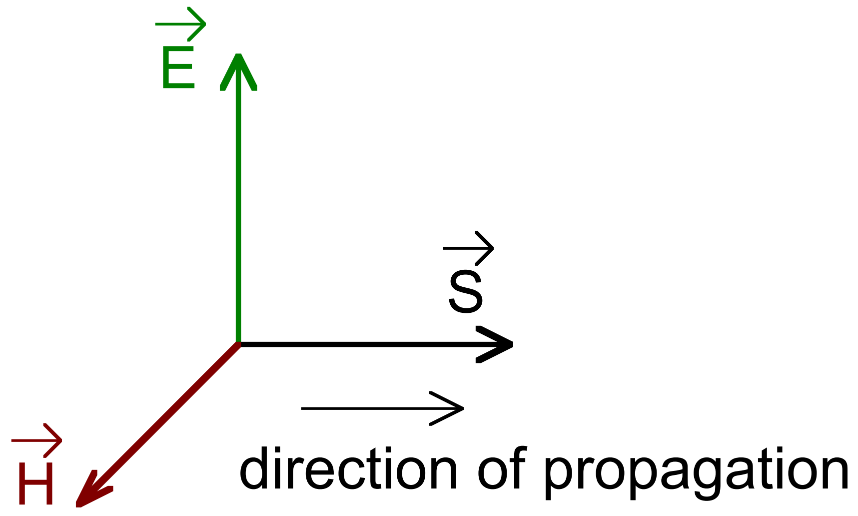
units of W/m^2

where

ε_o = vacuum permittivity

$\vec{E}$ = electric field

$\vec{H}$ = magnetic field

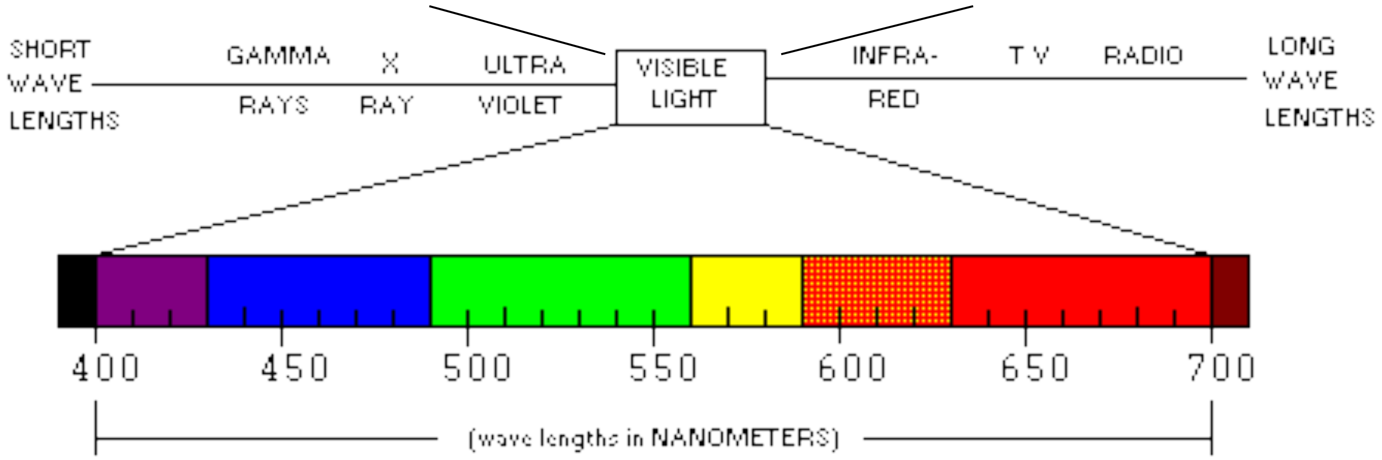


The energy transport is proportional to E^2 because the electric and magnetic fields are related by a constant of proportionality dependent on medium in which propagation occurs.

The Electromagnetic Spectrum

Electromagnetic spectrum – the set of electromagnetic radiation of all possible wavelengths (wavenumbers).

ν from 4.3x10^{14} cps to 7.5x10^{14} cps



http://www.csun.edu./~hchum001/bookcase/light/spectrum.html

- Ultraviolet – 100 to 400 nm
- Visible – 400 to 700 nm
- Infrared – 700 nm to 1 mm
- Microwave – 1 mm to 1 m
- Radio – includes microwave to > 100 m

EM radiation in different regions of the spectrum interacts differently with matter

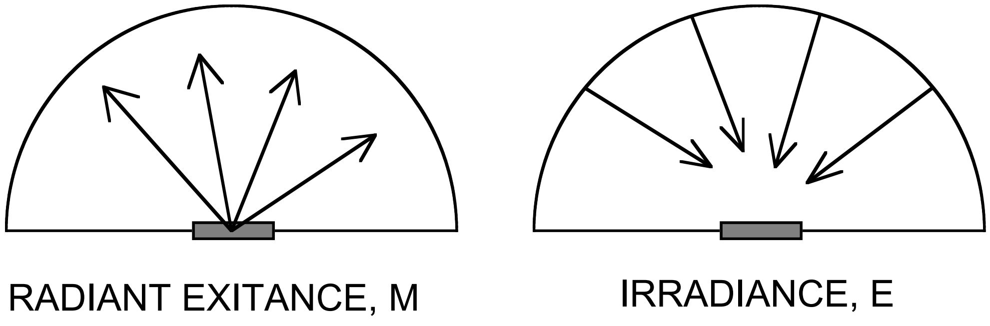
Radiant Flux Density

- The electric and magnetic fields and the Poynting vector $(\vec{E}, \vec{H}, \vec{S})$ of an EM wave oscillate rapidly, so are difficult to measure instantaneously.
- Usually measure the average magnitude over some time interval:

$$F = \langle \vec{S} \rangle$$

- This is the radiant flux density ($W\ m^{-2}$).

- The radiant flux density is redefined based on the direction of energy travel:
  - radiant exitance = radiant flux density emerging from an area
  - irradiance = radiant flux density incident on an area



Blackbodies - 1

- A <u>blackbody</u> is a <u>perfect emitter</u> - it emits the maximum possible amount of radiation at each wavelength.
- A blackbody is also a <u>perfect absorber</u>, absorbing at all wavelengths of radiation incident on it. Therefore, it looks black.

Blackbody energy distribution

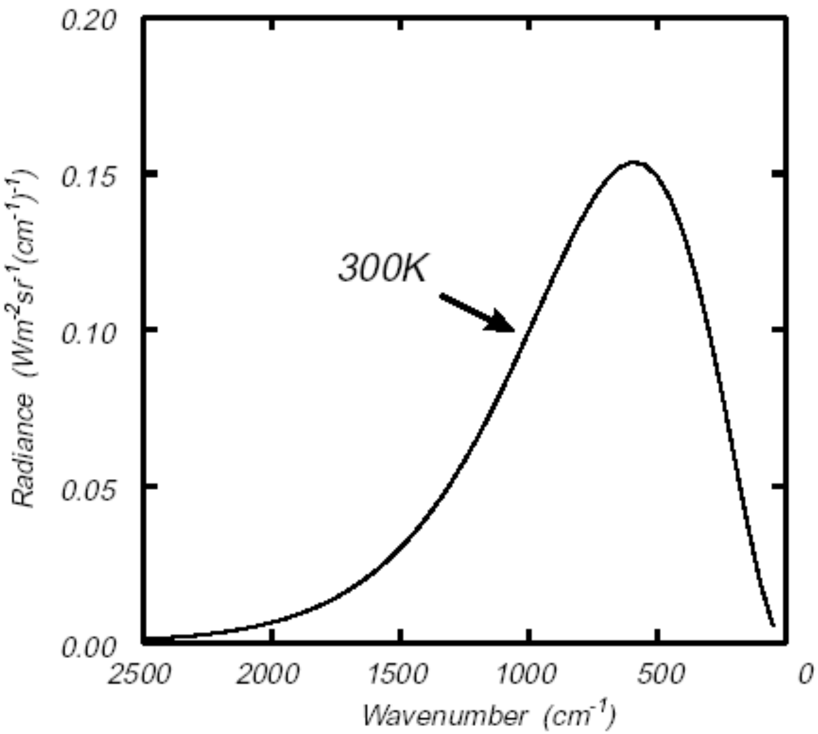


Figure 9: Blackbody Emission Curve

- Independent of the type of material
- Isotropic in nature (i.e., the same in all directions)
- Total energy is proportional to T^4

Planck's Blackbody Function - 2

- Planck derived the blackbody function, describing the radiance emitted by a blackbody, where

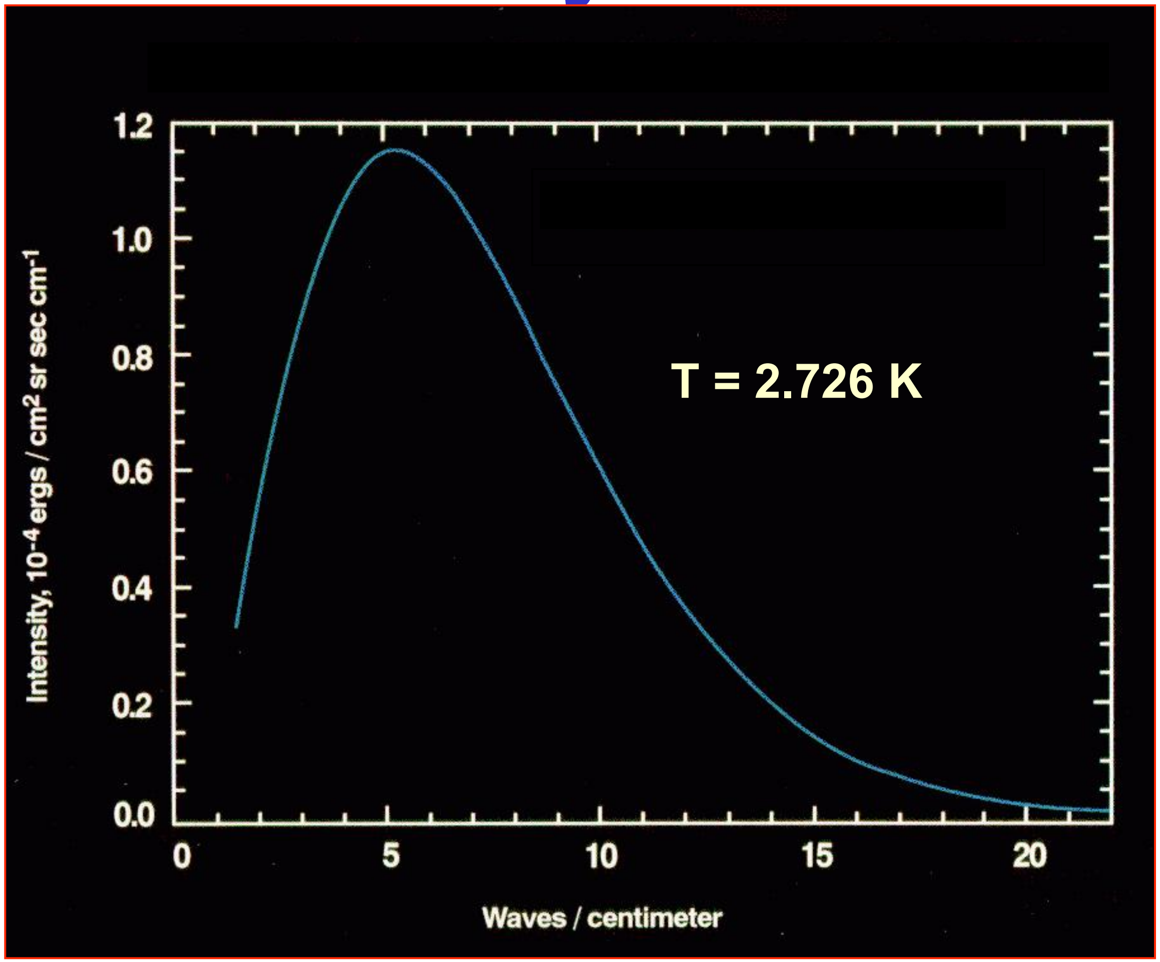
$$B_\lambda(T) = \frac{2hc^2\lambda^{-5}}{\exp\left(\frac{hc}{\lambda kT}\right) - 1}$$

  - B_λ = monochromatic radiance (W m^{-2} sr^{-1} μm^{-1})
  - k = Boltzmann's constant
  - T = absolute temperature
- This can be written as:

$$B_\lambda(T) = \frac{c_1\lambda^{-5}}{\exp\left(\frac{c_2}{\lambda T}\right) - 1}$$

  where
  - c_1 = first radiation constant (1.191×10^{-16} W m^2 sr^{-1})
  - c_2 = second radiation constant (1.439×10^{-2} m K)
- ∴ The radiance emitted by a blackbody depends only on λ and T.
  - $B_\lambda(T)$ increases with temperature
  - the λ of maximum $B_\lambda(T)$ decreases with temperature

Blackbody Radiation

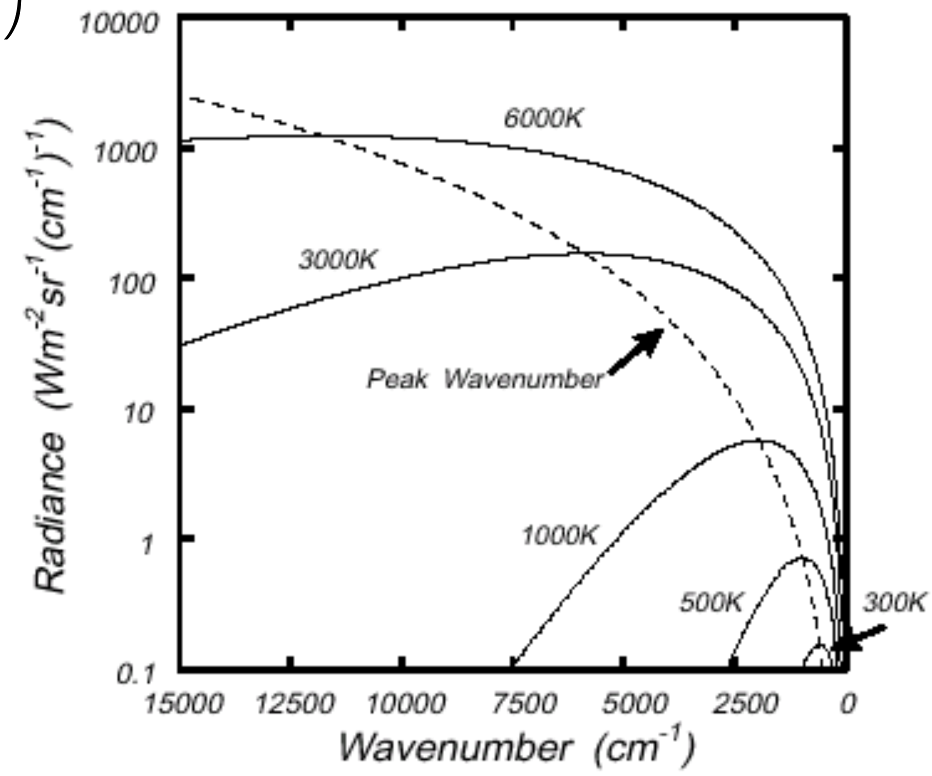


Planck's Blackbody Function - 3

We can show that the equivalent form of Planck's function as function of wavenumber is:

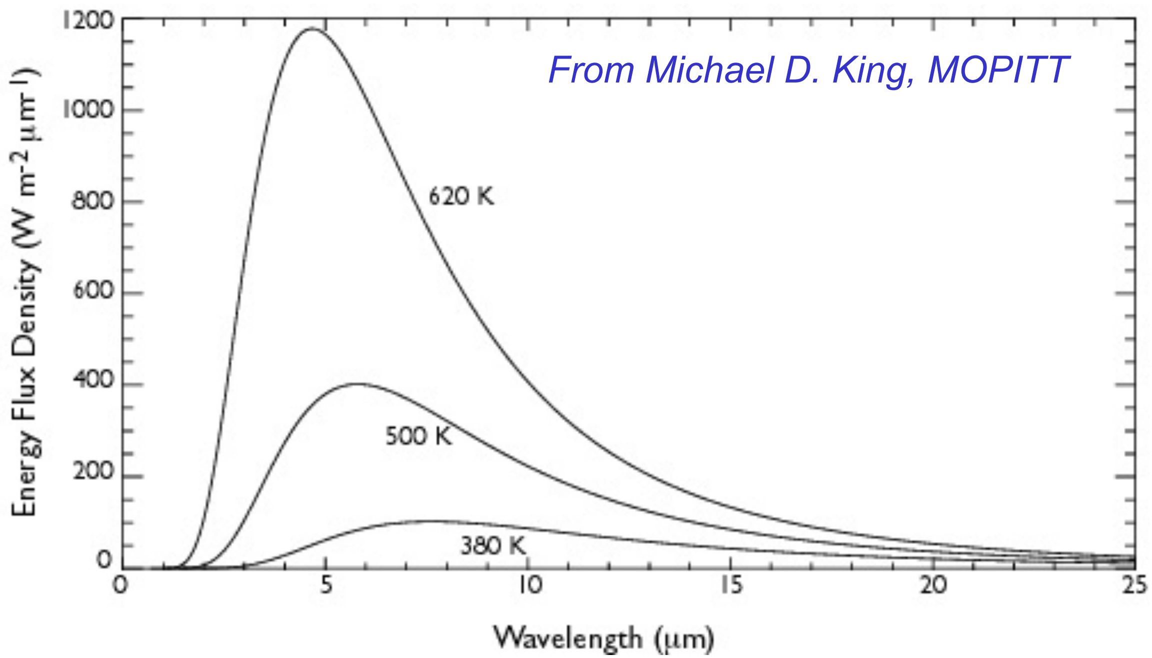
$$B_{\bar{\nu}}(T) = \frac{2hc^2\bar{\nu}^3}{\exp\left(\frac{hc\bar{\nu}}{kT}\right)-1} = \frac{c_1\bar{\nu}^3}{\exp\left(\frac{c_2\bar{\nu}}{T}\right)-1}$$

Peak wavenumber
for blackbody emission

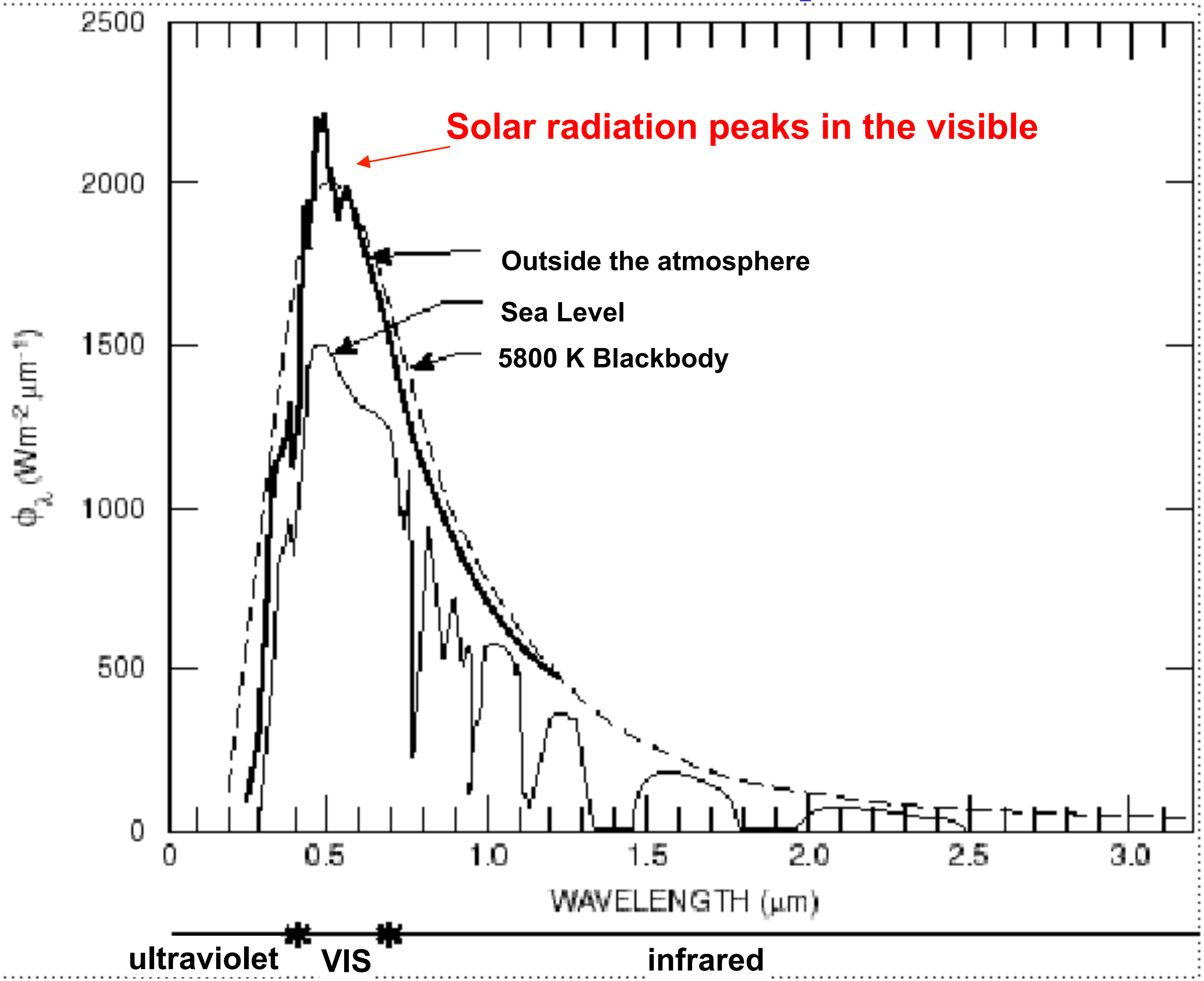


Wien's Displacement Law

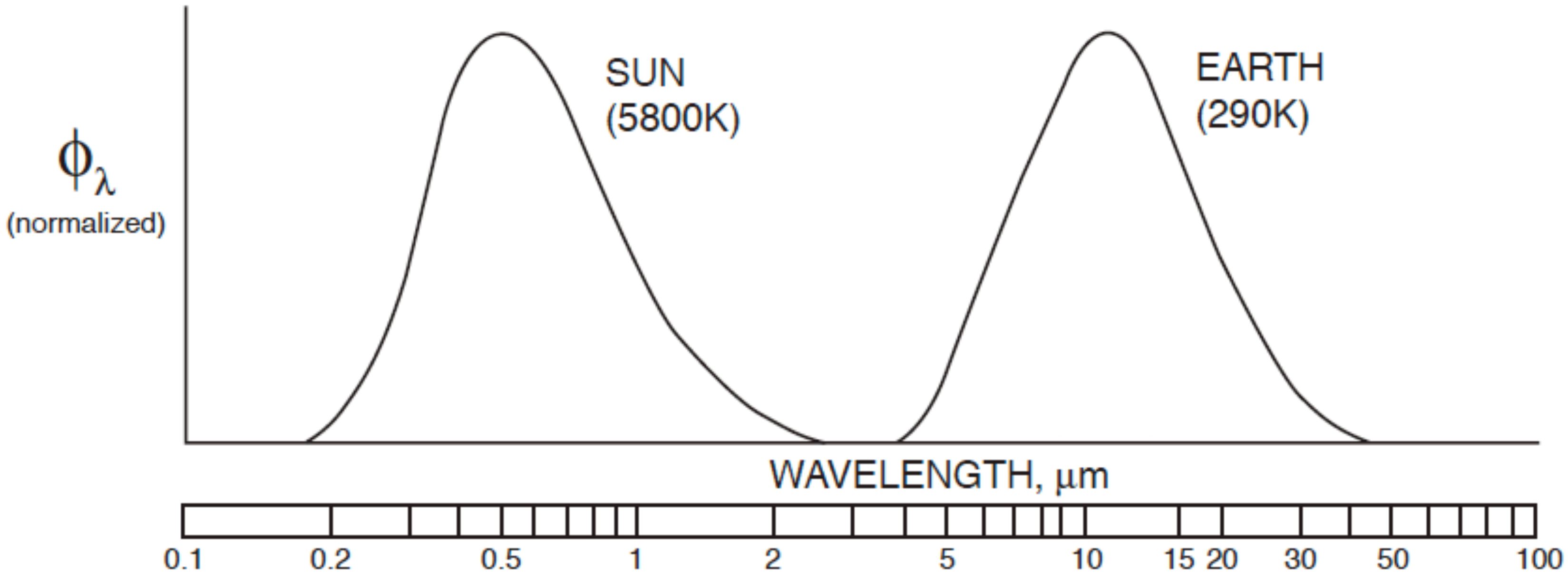
- The wavelength at which $B_\lambda(T)$ is a maximum is determined using: $$\frac{\partial B_\lambda(T)}{\partial \lambda} = 0$$
- This gives: $\lambda_m = \frac{2897.9}{T}$ μm (T in K) → Wien's Displacement Law.
- Or for wavenumbers: $$\bar{\nu}_m = 1.962T \cong 2T \quad cm^{-1}$$
- The hotter the object, the shorter the λ of its maximum intensity (e.g., element on a stove). This law can be used to determine the T of a blackbody from the position of the maximum monochromatic radiance



Solar Radiation Spectrum

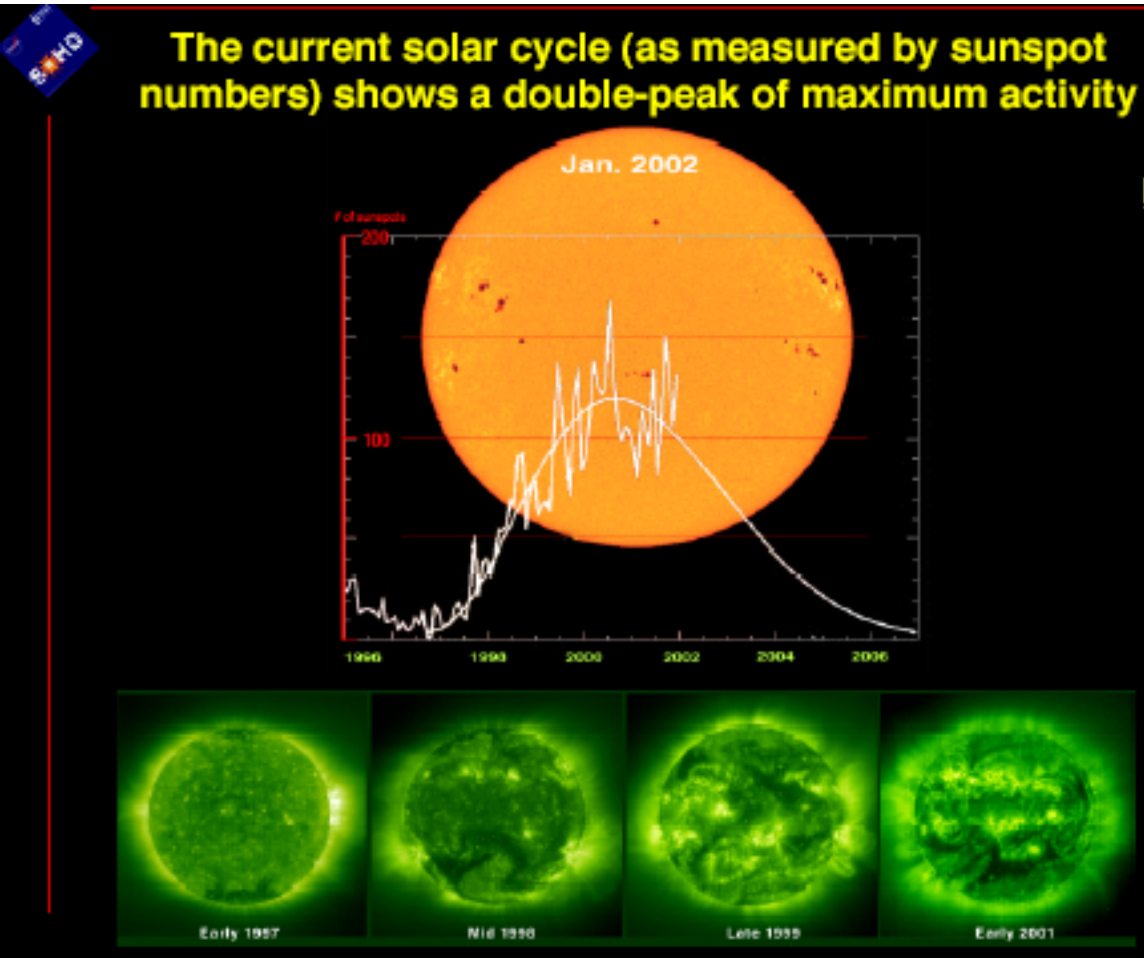


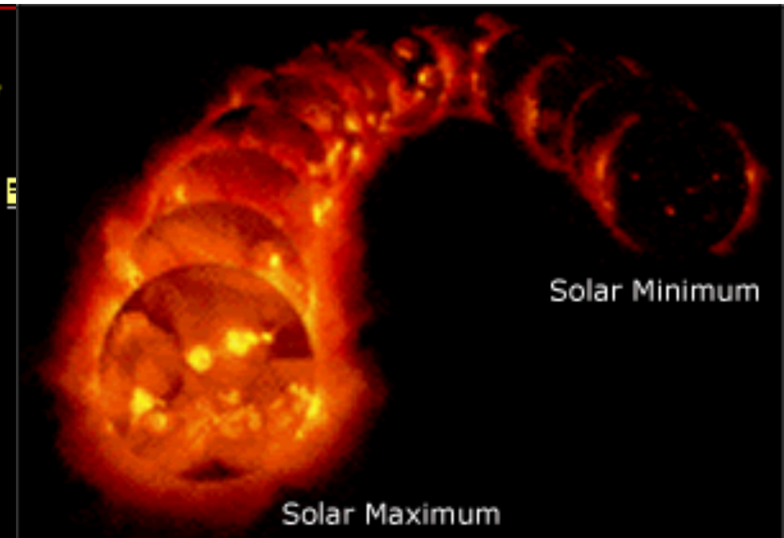
Solar and Terrestrial Radiation

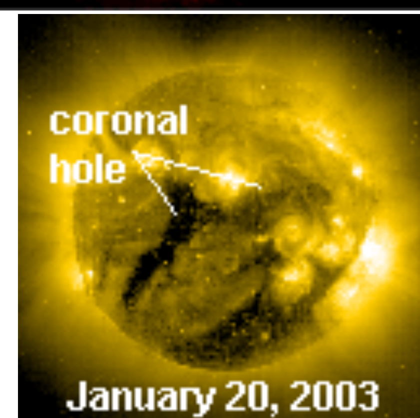


The Solar Cycle

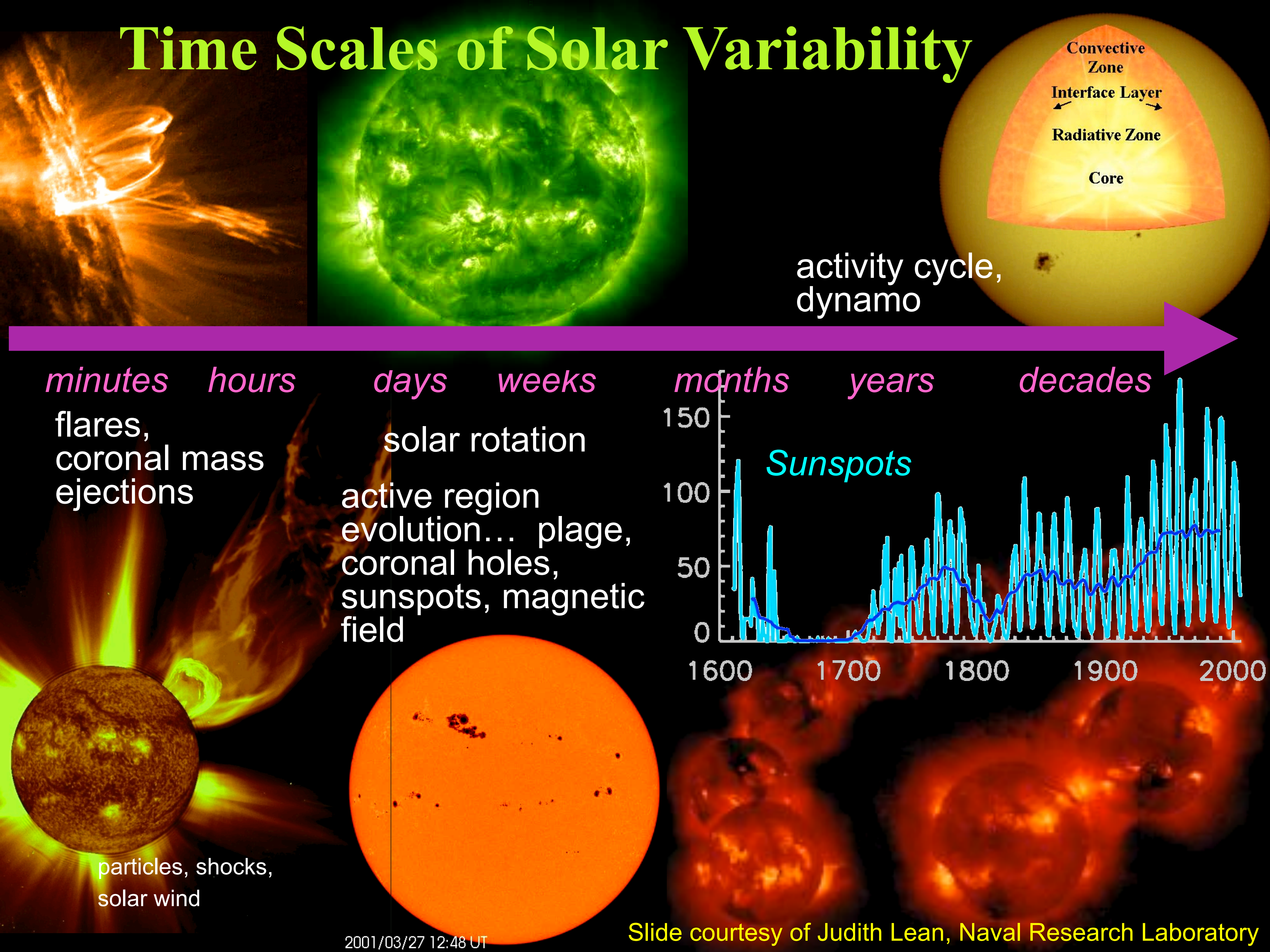
The approximately 11-year quasi-periodic variation in frequency or number of sunspots, coronal mass ejections, solar flares, and other solar activity.



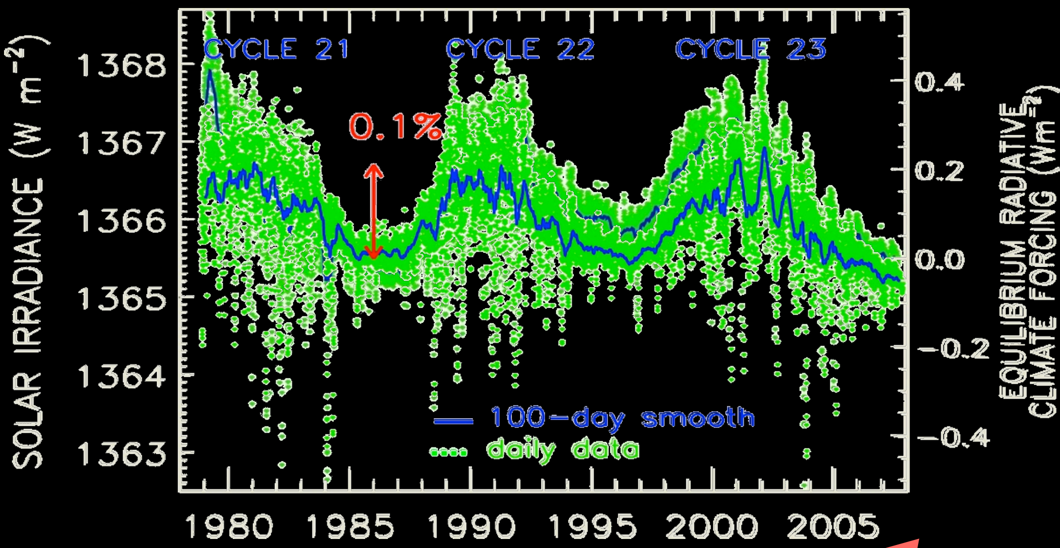




http://sohowww.nascom.nasa.gov/


Time Scales of Solar Variability
Convective Zone
Interface Layer
Radiative Zone
Core
activity cycle, dynamo
minutes
hours
days
weeks
months
years
decades
flares, coronal mass ejections
solar rotation
active region evolution… plage, coronal holes, sunspots, magnetic field
Sunspots
150
100
50
0
1600
1700
1800
1900
2000
particles, shocks, solar wind
2001/03/27 12:48 UT
Slide courtesy of Judith Lean, Naval Research Laboratory

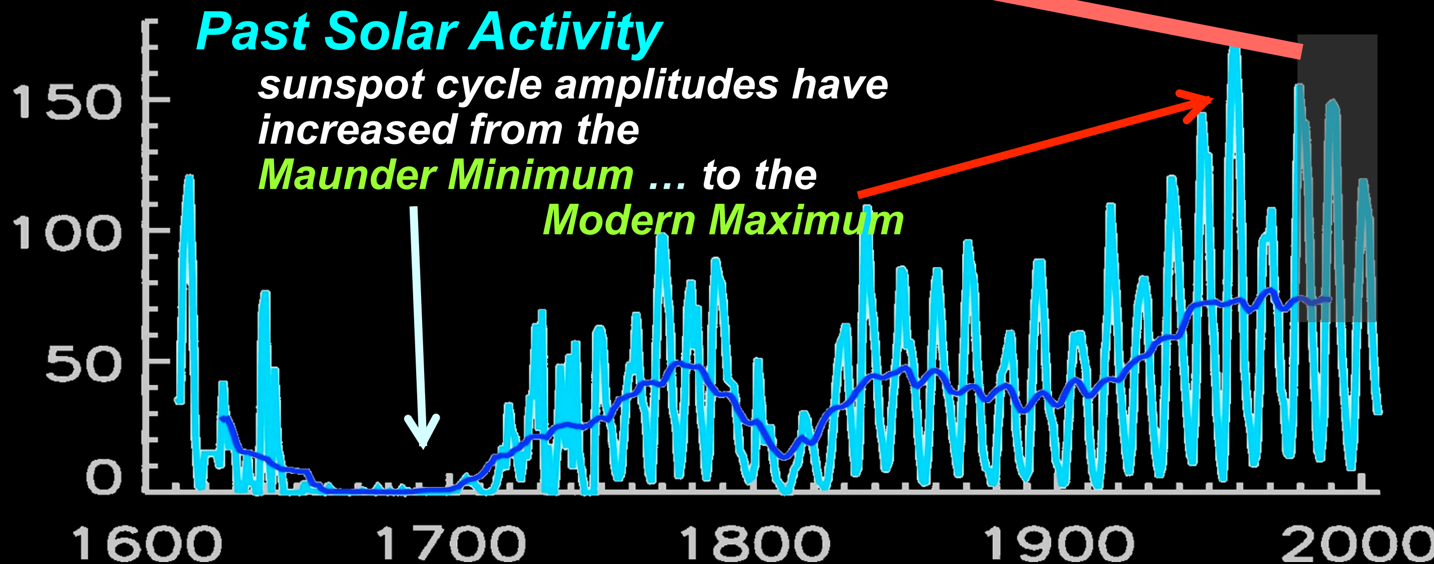
The Sun's Brightness Varies Continuously



- ✧ 5-min oscillation ~ 0.003%
- ✧ 27-day solar rotation ~ 0.2%
- ✧ 11-year solar cycle ~ 0.1%
- ✧ longer-term variations not yet detectable –

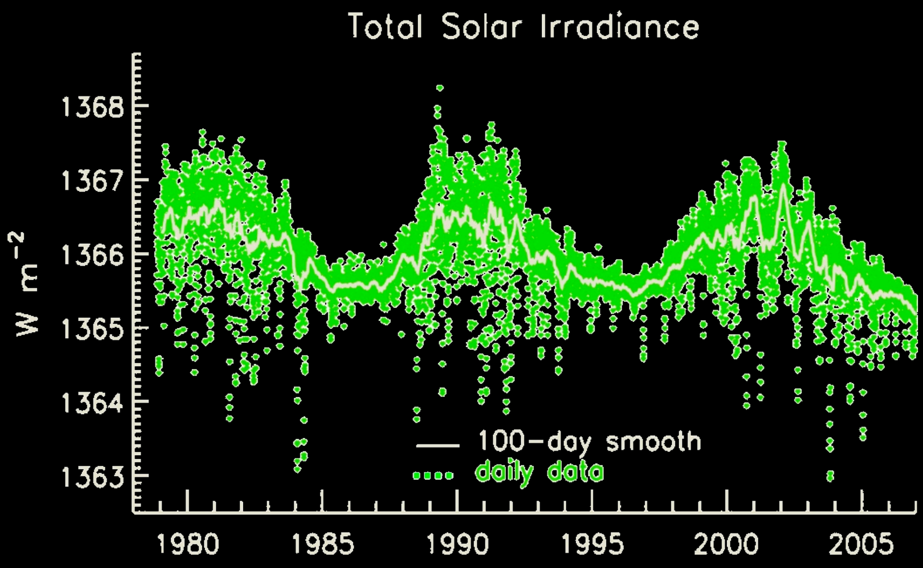
  ……*do they occur?*

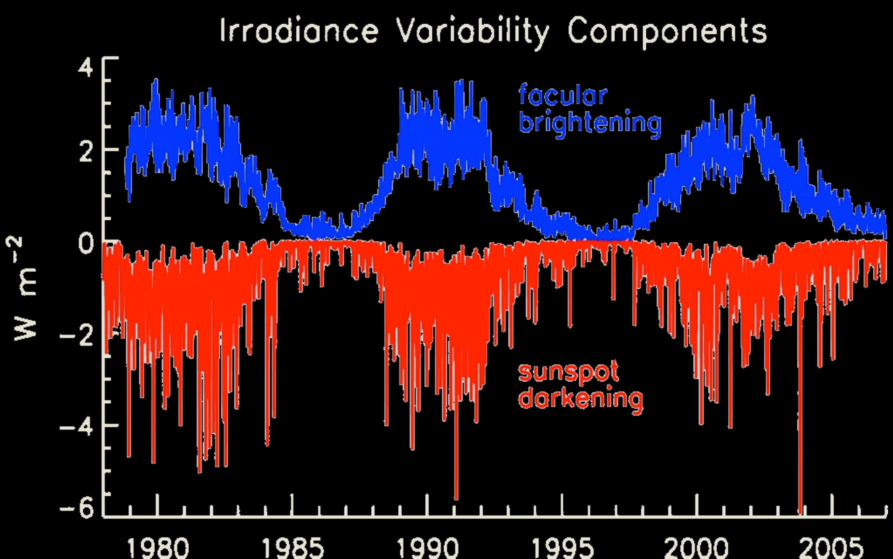
data: Fröhlich & Lean, AARev, 2004 http://www.pmodwrc.ch

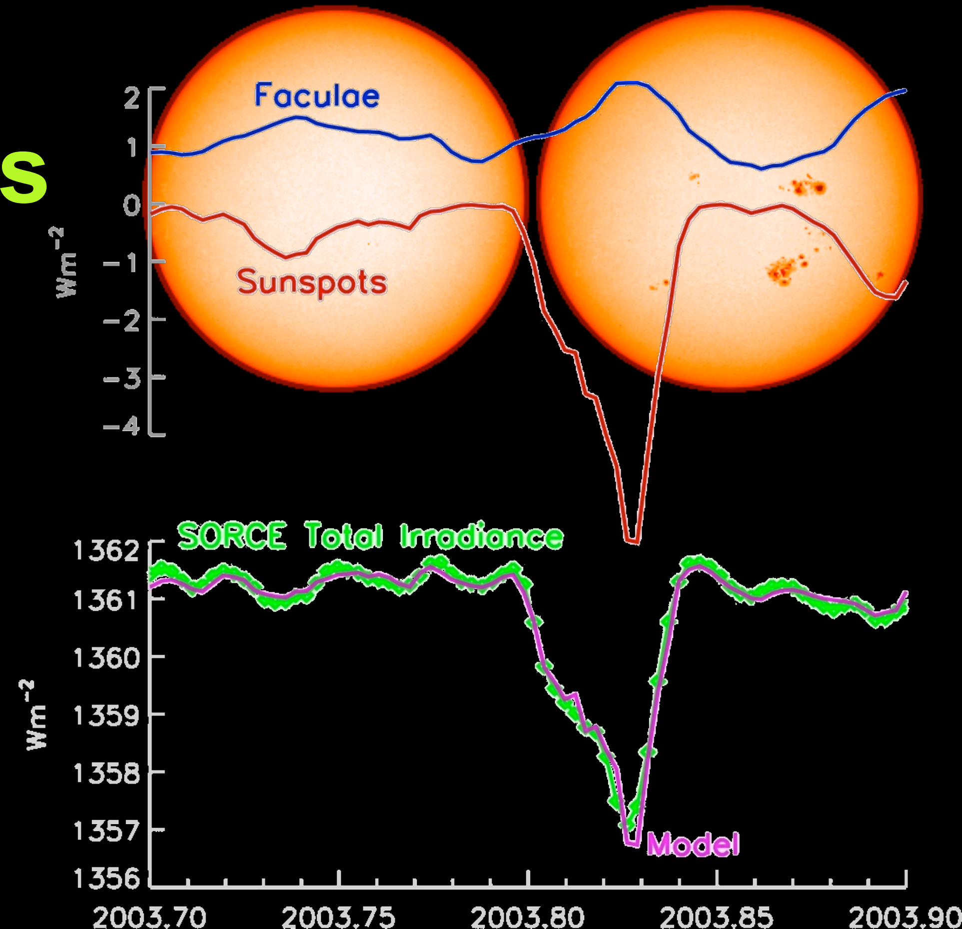


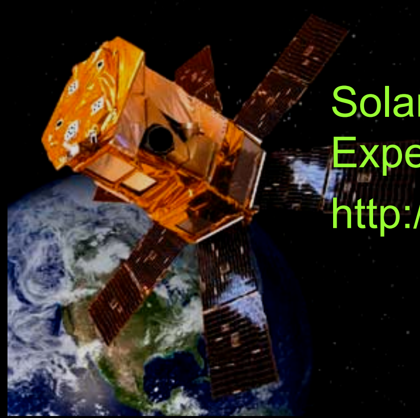
Slide courtesy of Judith Lean, Naval Research Laboratory

Sources of Solar Irradiance Variations









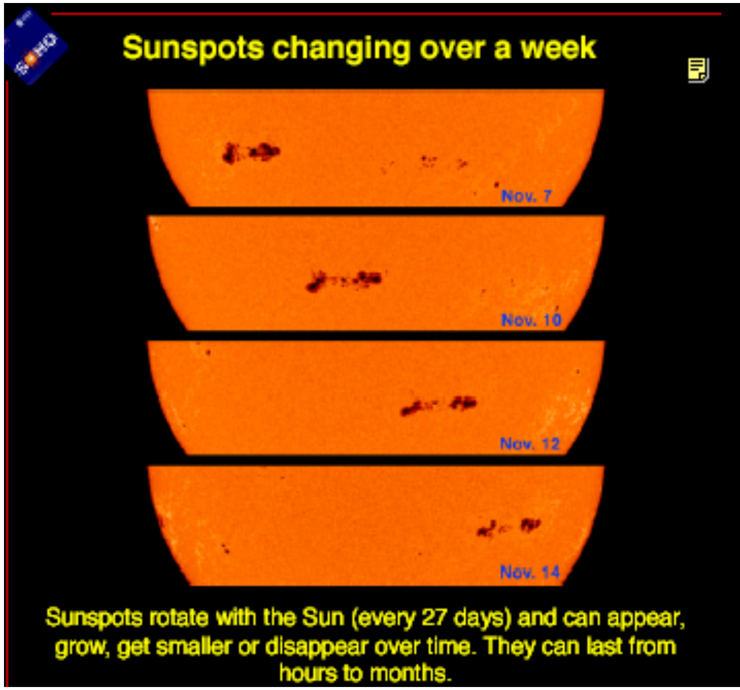
Solar Radiation and Climate Experiment (SORCE)

http://lasp.colorado.edu/sorce

Slide courtesy of Judith Lean, Naval Research Laboratory

Sunspots

- Temporary disturbed areas in the solar photosphere that appear dark because they are cooler than the surrounding areas.
- Consist of concentrations of strong magnetic flux.
- Usually occur in pairs or groups of opposite polarity that move in unison across the face of the Sun as it rotates.
- High magnetic activity also creates faculae and plages, which are bright hot regions.



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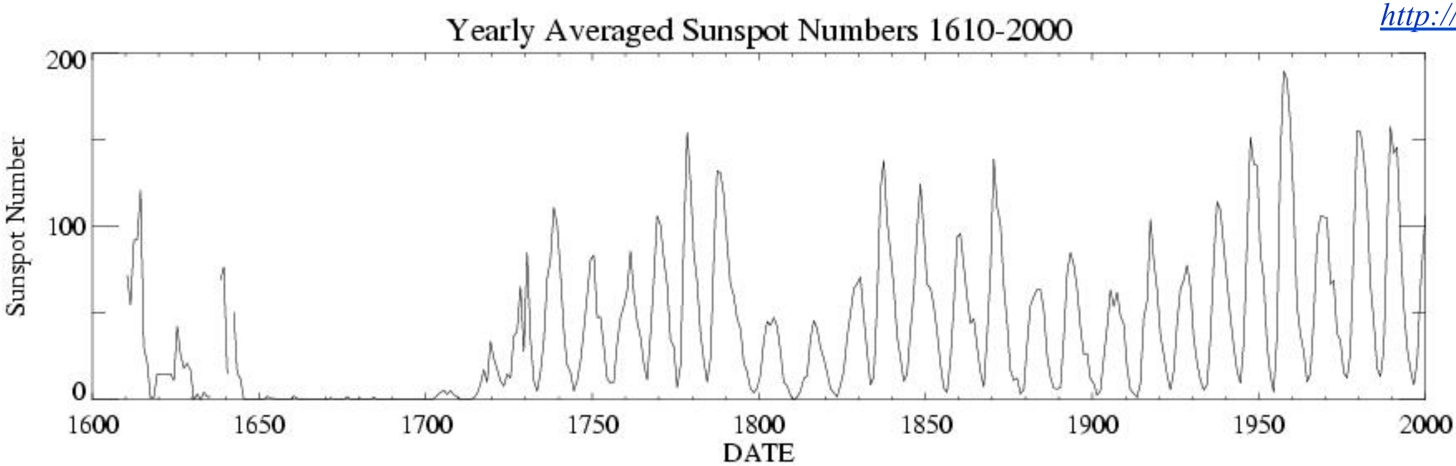
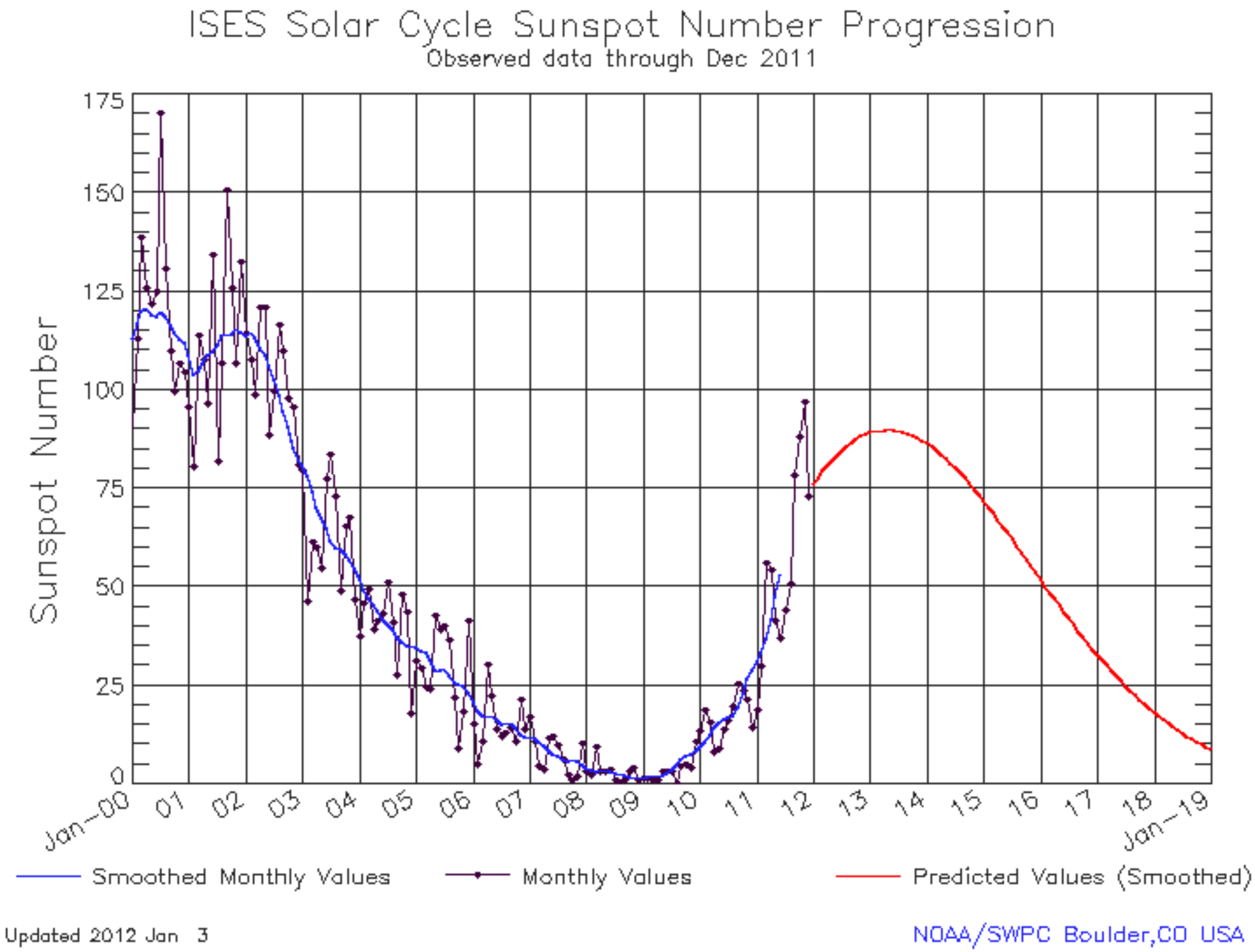


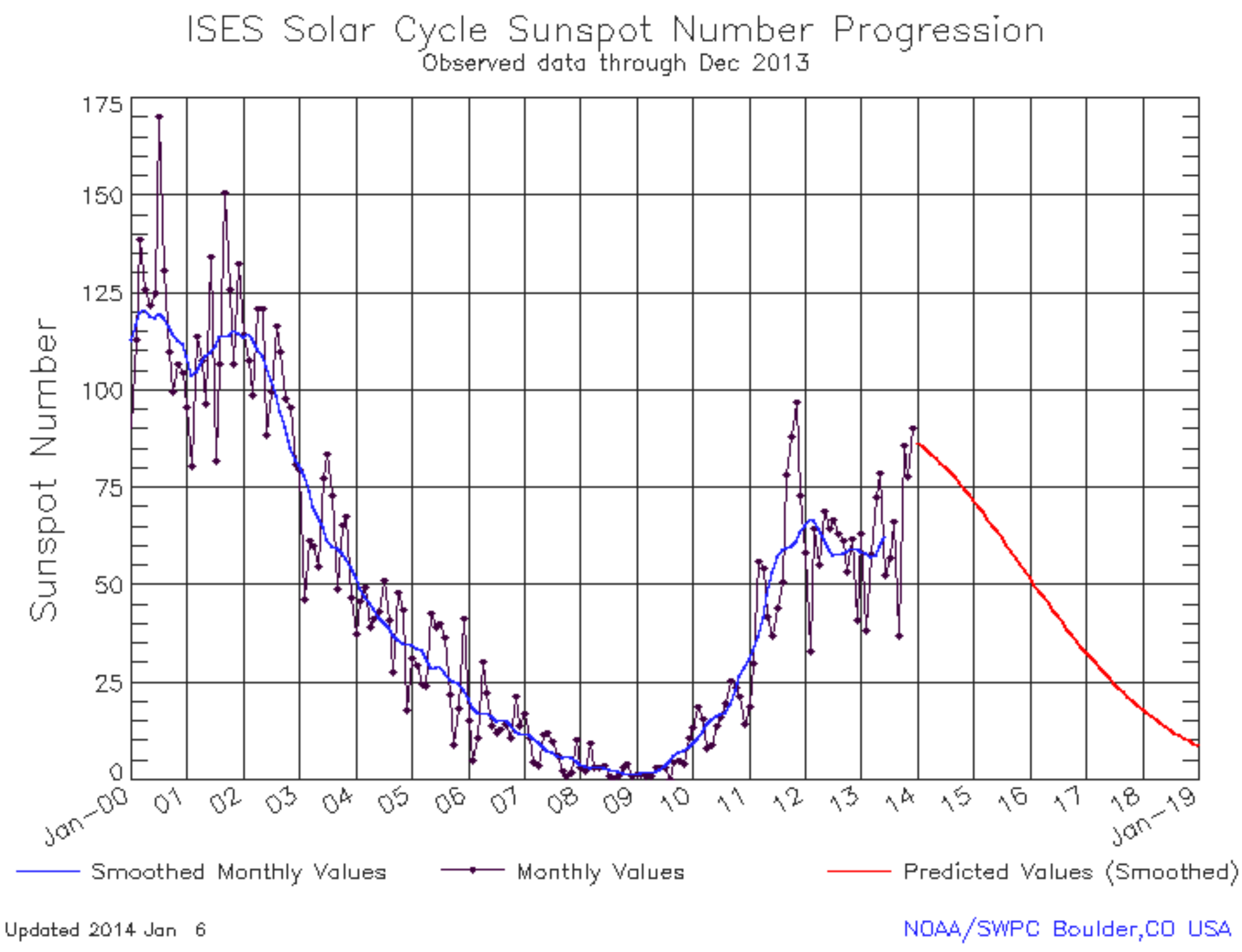
Current Solar Cycle (Jan 2012)



ISES = International Space Environment Service
http://www.ises-spaceweather.org/

NOAA Space Weather Prediction Center
http://www.swpc.noaa.gov/SolarCycle/

Current Solar Cycle (Jan 2014)



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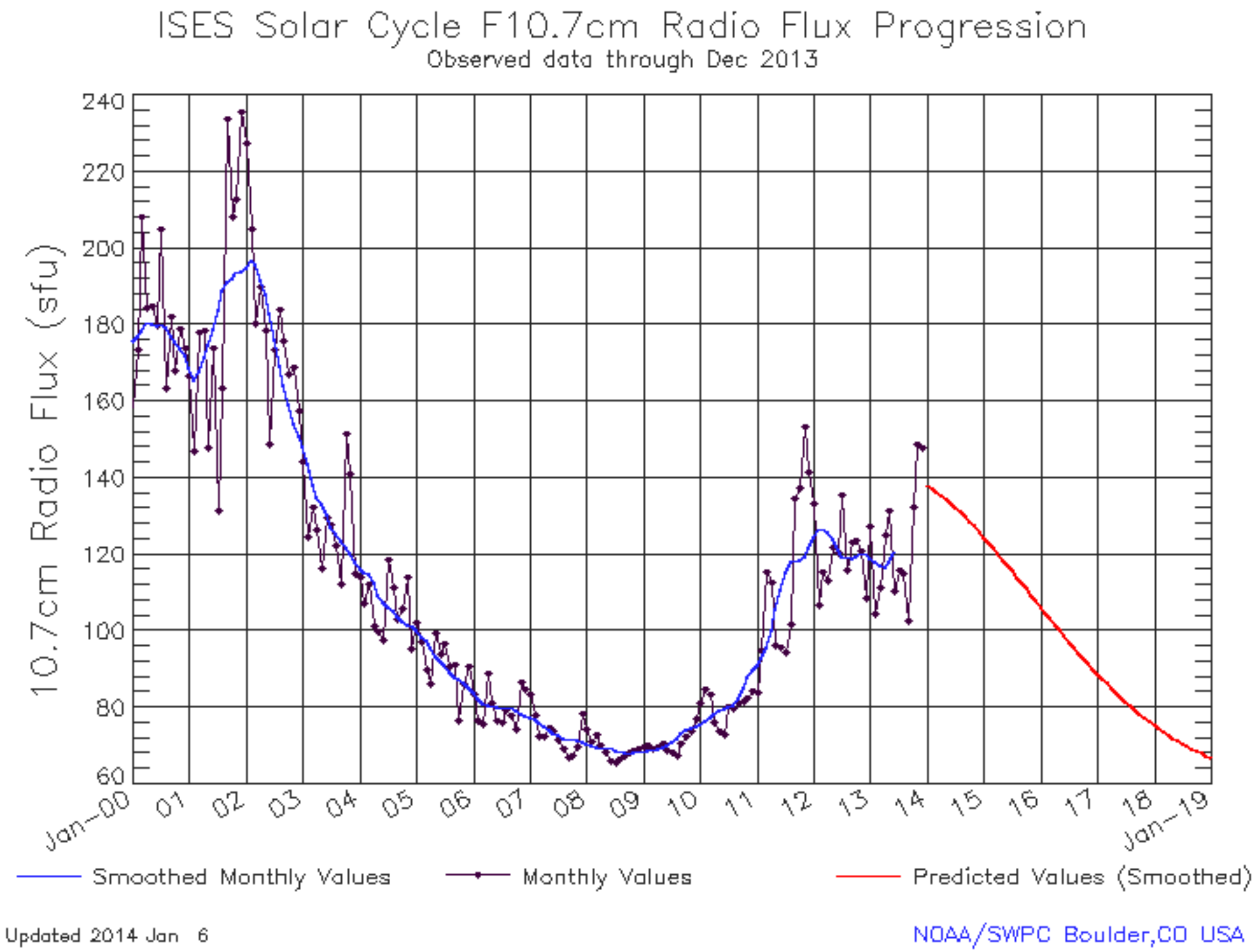
Current Solar Cycle (Jan 2014)



ISES = International Space Environment Service
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NOAA Space Weather Prediction Center
http://www.swpc.noaa.gov/SolarCycle/

The Effect of the Solar Cycle

The intensity of the Sun varies along with the 11-year sunspot cycle.

- When sunspots are numerous the solar constant is high (~1367 W/m^2). When sunspots are scarce the value is low (~1365 W/m^2). This is due to increased emission from the plages and faculae.
- Eleven years isn't the only cycle. The solar constant can fluctuate by ~0.1% over days and weeks as sunspots grow and dissipate.
- The solar constant also drifts by 0.2% to 0.6% over many centuries.

These small changes can affect Earth in a big way. For example, between 1645 and 1715 (a period astronomers call the "Maunder Minimum") the sunspot cycle stopped; the face of the Sun was nearly blank for 70 years. At the same time Europe was hit by an extraordinary cold spell: the Thames River in London froze, glaciers advanced in the Alps, and northern sea ice increased.

The Effect of the Solar Cycle

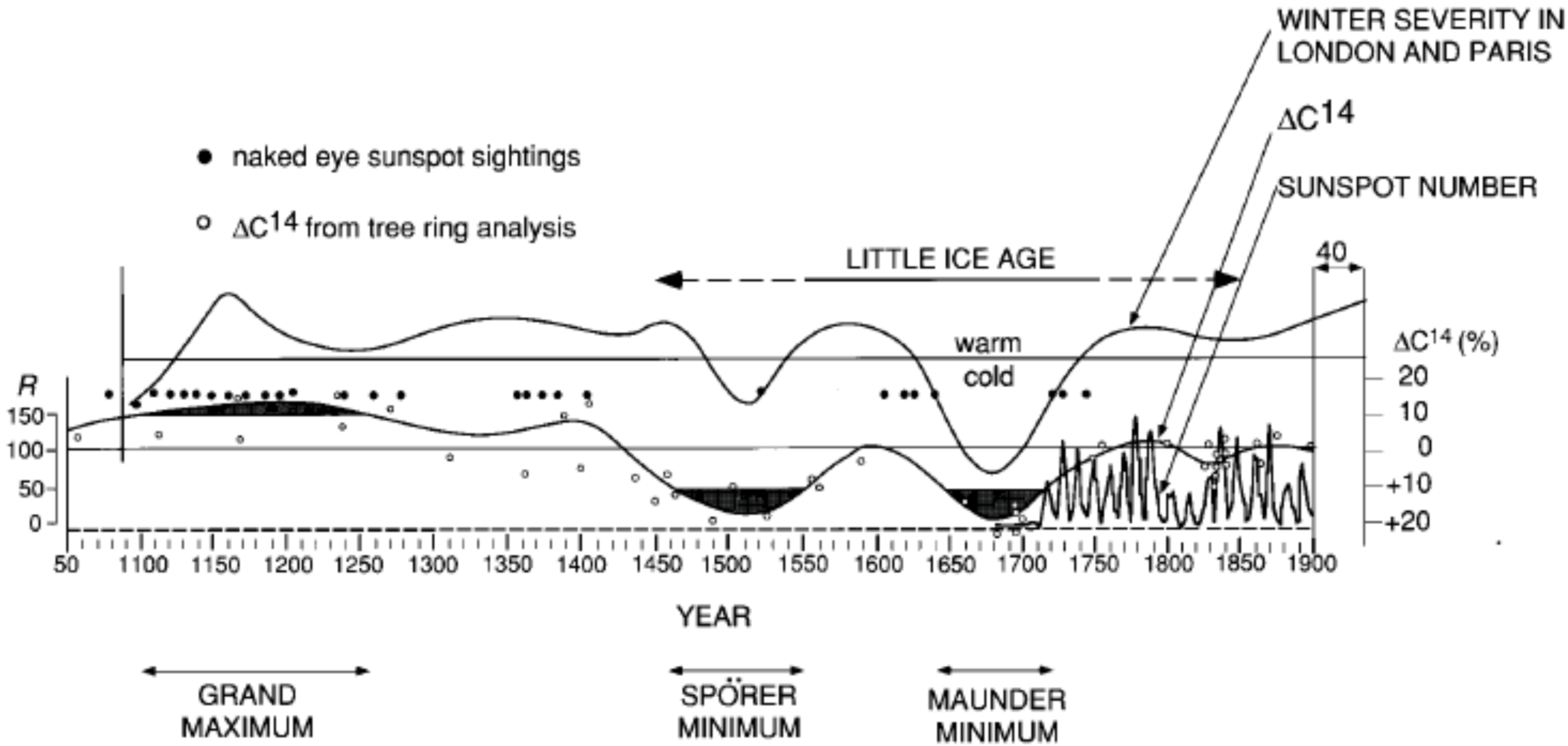

FIG. 15. Shown is the relationship between winter severity in Paris and London (top curve) and long-term solar activity variations (bottom curve). The shaded portions of this curve denote the times of the Spörer and Maunder minima in sunspot activity. The dark circles indicate naked-eye sunspot observations. Details of the solar activity variation since 1700 are indicated in the bottom curve by the sunspot number data. The winter severity index has been shifted 40 yr to the right to allow for cosmic ray-produced ^{14}C assimilation into tree rings. From Eddy (1976, 1977).

[From Lean & Rind, J. Climate, 1998]

The Effect of the Solar Cycle

The total energy coming from the Sun only varies by about 0.1% over each 11-year cycle. For a long time scientists didn't notice this, which is why the Sun's intensity is called, ironically, the “solar constant”.

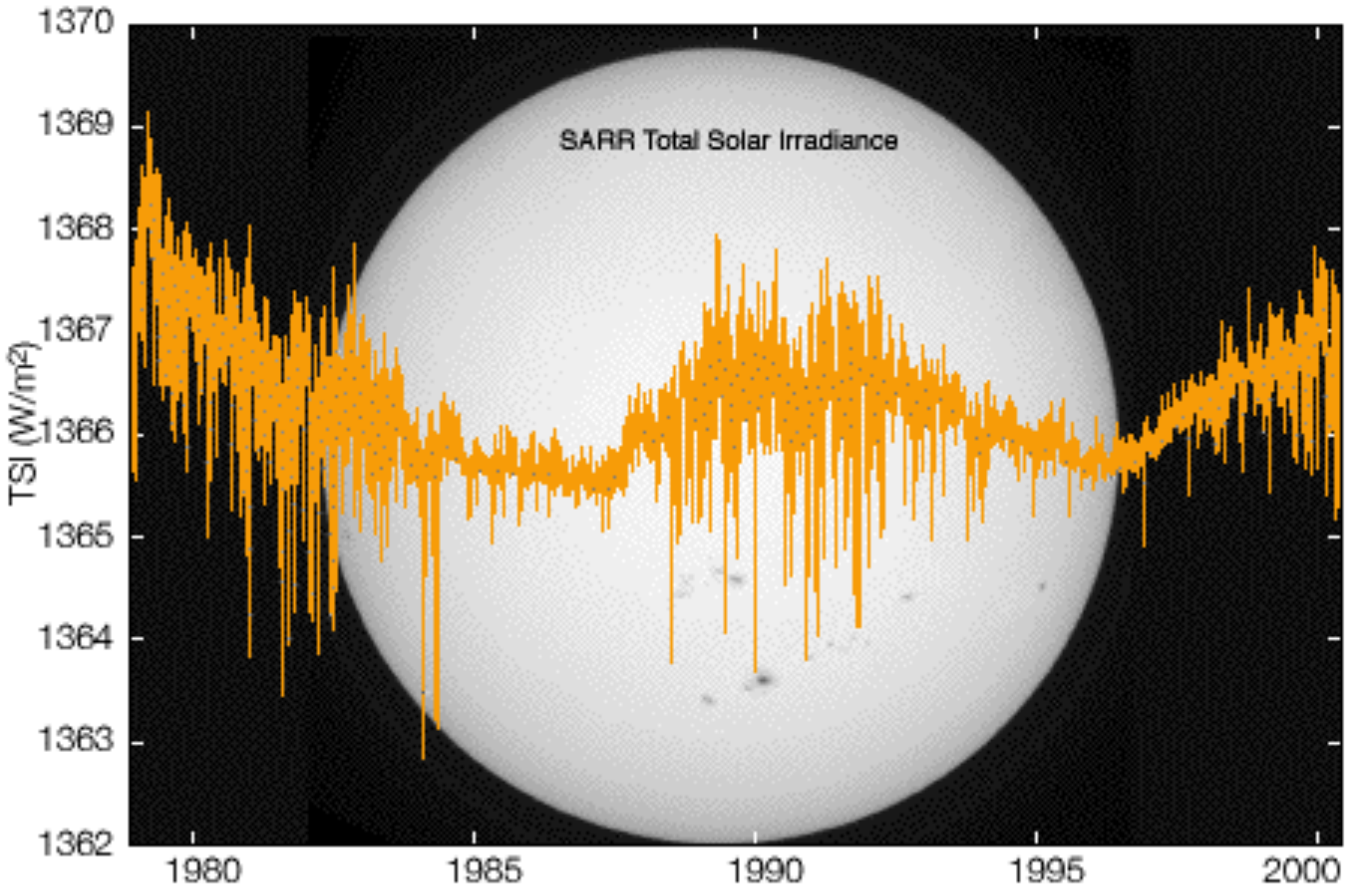

Image credit: Catania Astrophysical Laboratory.

How sensitive is the Earth's climate to changes in solar radiation?

- Sensitivity of climate to solar radiation changes is not well known.
  - A conservative estimate is that a 0.1% change in solar total radiation will bring about a temperature response of 0.06 to 0.2 °C, providing the change persists long enough for the climate system to adjust. This could take 10 to 100 years.
- The Sun plays a critical role in the Earth's climate system, with both changing continually, over all time scales.
- Physical connections that link the variations seen in one with the variability in the other remain poorly understand.
- We only have continuous monitoring of direct solar radiation since 1979 - a very short period in the life of the Sun.
- Reconstructed data suggests solar radiation changes may
  - have been the dominant climate forcing in the 1600s &1700s
  - contribute to about half of the 0.55°C surface warming since 1900
  - be responsible for <1/3 of surface warming since 1970