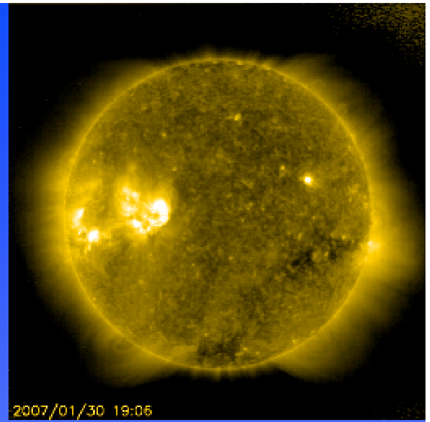
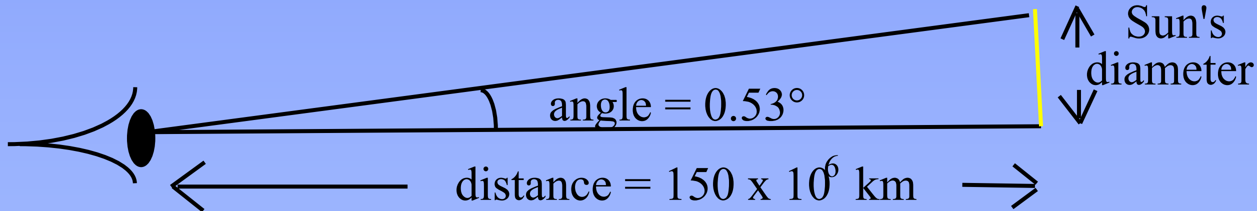
The Sun

Distance & diameter



↑ 2 weeks of
Sun in extreme UV

- Tiny parallax (about 8.8" arc)
- Kepler's laws give only relative sizes in solar system. Scale by radar reflection from planets. Average distance from Sun 150×10^6 km
- Diameter calculated from our simple triangle



Small angles:

diameter = tan (angle) x distance

$= 1.39 \times 10^6$ km

Sun's Mass from Kepler's Law

- Newton deduced Kepler's 3rd law in the form:

$$(M + m)P^2 = ka^3$$

M, m are masses of 2 objects

P is period of rotation

a is average dist between objects

k is a constant depending on units used

$(= 4\pi^2/G$, where G is grav. constant$)$

- in this form the law can be used to compare different orbiting systems, e.g. Sun - Earth system and the Earth - Moon system

Applying Kepler's 3rd Law

$$(M_{Sun} + m_{Earth})P_{Earth}^2 = ka_{Earth}^3$$
$$(M_{Earth} + m_{Moon})P_{Moon}^2 = ka_{Moon}^3$$

- take the ratio of these relationships
- ignore *m* terms (i.e. $M + m \rightarrow M$) and rearrange:

$$M_{Sun} = \frac{a_{Earth}^3}{a_{Moon}^3} \times \frac{P_{Moon}^2}{P_{Earth}^2} \times M_{Earth}$$
$$= 389^3 \times 0.0748^2 \times M_{Earth}$$
$$= 330000 \times M_{Earth}$$
$$\approx 1.97 \times 10^{30}\, kg$$

Solar Radiation

- **Luminosity** of a star is its total radiant energy output per second (in **watts**)
- Radiant energy reaching Earth is 1380 Wm^{-2}
  - area of sphere of radius 150×10^6 km is:

$$\text{area} = 4\pi r^2 = 2.83\times10^{23}\ \text{m}^2$$

  - Sun's power output = 1380 × area = 3.9×10^{26} W
    - notice that the same power output is spread over an area that increases as the square of the distance from the Sun. Hence the radiation received per m^2 falls off as the inverse square of the distance from the Sun

More Deductions about the Sun

- The surface area of the Sun is $4\pi r^2 = 6.07 \times 10^{18}$ m^2
- Hence the power per m^2 = luminosity/surface area

  = 64.3 MW m^{-2}
  - enough power to volatilise any material we know of
- Stefan-Boltzmann radiation law links power m^{-2} (E) and surface temperature (T): $E = \sigma T^4$
  - hence surface temperature of the Sun is ~5800 K

Source of Sun's Energy

- Chemical energy quite insufficient
  - "*The Earth was created in the year 4004 BC*" Bishop James Ussher (1581 – 1656)
- Energy released in bringing mass *m* of a star into a ball of radius *r* is $\frac{3}{5} G \frac{m^2}{r}$.
  - to produce its observed radiant energy the Sun needs to shrink at only 36 m per year
    - it could do this for a few hundred million years
- To produce radiation for ~4.6 billion years (the Sun's life so far) needs nuclear power
  - the Sun is a nuclear fusion reactor

Mass to Energy

- Energy conversion from mass to radiation is governed by Einstein's famous equation

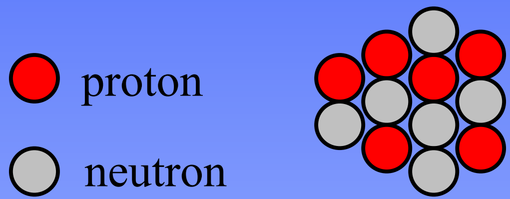
$$E = mc^2$$

  - mass required to fuel Sun is $E/c^2 = 4.3 \times 10^9$ kg s^{-1}

- Sun's mass could last up to 15,000 billion years if all were dispersed in radiation. This doesn't happen. **Nuclear fusion** builds heavier elements from lighter ones, the products having a little less mass than the constituents. This lost mass is what appears as energy

Nuclear Concepts

The nucleus



nucleus $^{12}_{6}C$

- 12: number of protons + neutrons
- C: name of element
- 6: number of protons

The players

$^{1}_{1}H$ – a *proton*

e^{+} – a *positron*

γ – *radiation*

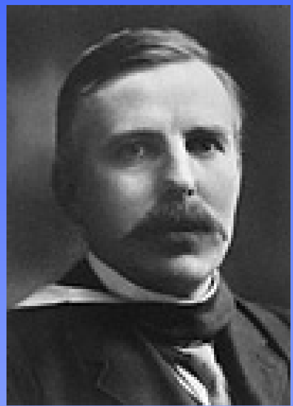
$^{3}_{2}He$ – *helium* 3

$^{2}_{1}H$ – *deuterium*, an isotope of hydrogen with 1 proton and 1 neutron

ν – a *neutrino*

$^{4}_{2}He$ – *helium* 4

Nobel Prize Winners



Ernest Rutherford
(1871 – 1937)
Radioactivity: 1908

Frederick Soddy
(1877 – 1956)
Isotopes: 1921

James Chadwick
(1891 – 1974)
Neutron: 1935

Enrico Fermi
(1901 – 1954)
Neutron irradiation:
1938

Wolfgang Pauli
(1900 – 1958)
Exclusion principle: 1945

Fred Hoyle

- Fred Hoyle in his famous 1946 paper, "The Synthesis of the Elements from Hydrogen" laid the foundations of our ideas on how stars work
  - he followed this up with a series of papers over the next 12 years describing how stellar evolution is predictable from nuclear physics
  - his popular books on Astronomy inspired many youngsters to become scientists
  - his Sci Fi novels like *The Black Cloud*, *A for Andromeda* and *October the First is Too Late* are still great stories

Links in the Proton – Proton Chain

- 2 protons make a deuterium nucleus

$$ {}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + e^{+} + \nu \rightarrow {}^{2}_{1}H + 2\gamma + \nu $$

  - this reaction is very hard to get going

- A deuterium and a proton make helium-3

$$ {}^{2}_{1}H + {}^{1}_{1}H \rightarrow {}^{3}_{2}He + \gamma $$

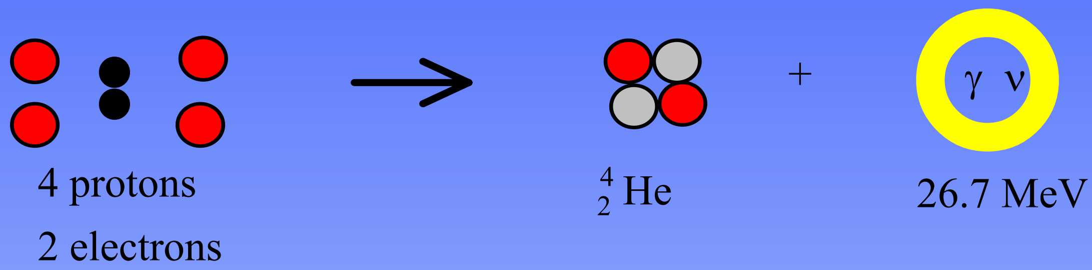
- 2 helium-3 make helium-4 and 2 protons

$$ {}^{3}_{2}He + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + 2\,{}^{1}_{1}H $$

  - and so ${}^{4}_{2}He$ is built from H, with a surplus of energy

Nuclear Energy

- Proton - proton chain reaction results:

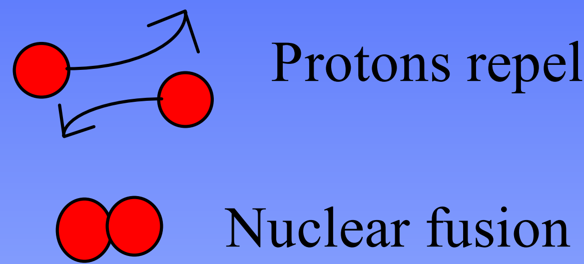


4 protons + 2 electrons → helium + 6 γ + 2 ν

- Loss of mass is about 0.7% (26.7 MeV per reaction)
  - using $E = mc^2$, energy available for 1 kg of hydrogen converted is 6.3×10^{14} J.
  - Sun uses 6×10^{11} kg s^{-1} hydrogen to sustain energy o/p

Nuclear Reactions

- Two (positively charged) protons tend to repel each other
  - to make a nuclear reaction 'go', the protons have to be forced together against the inverse square law of repulsion (*another inverse square law*)
  - this needs high temperatures and pressures, found only deep within the Sun and other stars



- About 7% of H $\rightarrow$ He conversion in the Sun is achieved through the carbon cycle, using $^{12}_{6}C$

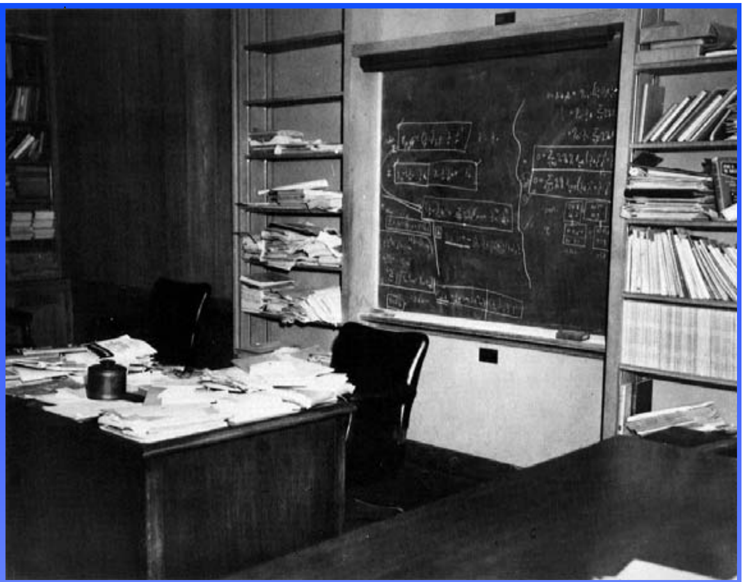
A Digression

- *“There is not the slightest indication that energy will ever be obtainable from the atom”*

  Albert Einstein

- *“Atomic energy might be as good as our present day explosives, but it is unlikely to produce anything very much more dangerous.”*

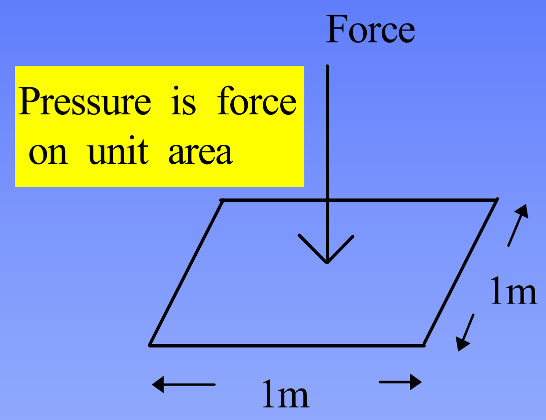
  Winston Churchill in 1939



Einstein’s last blackboard, at Princeton (1956)

Inside the Sun

- **Pressure** increases with depth into the Sun, because of the weight of material above
- **Temperature** therefore also increases: $PV \propto T$



- Fusion takes place in the core of the Sun out to $0.1 \times$ radius
- The Sun is in **hydrostatic equilibrium**
  - the weight of overlying gas is balanced by the pressure of the hot gas within

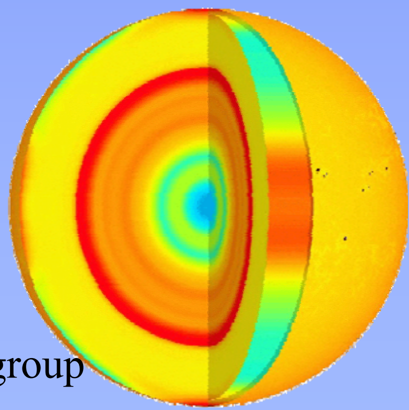
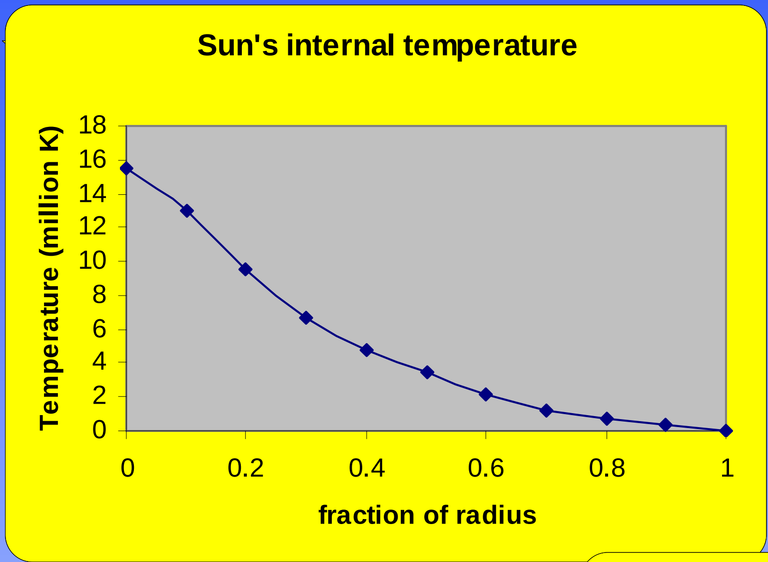
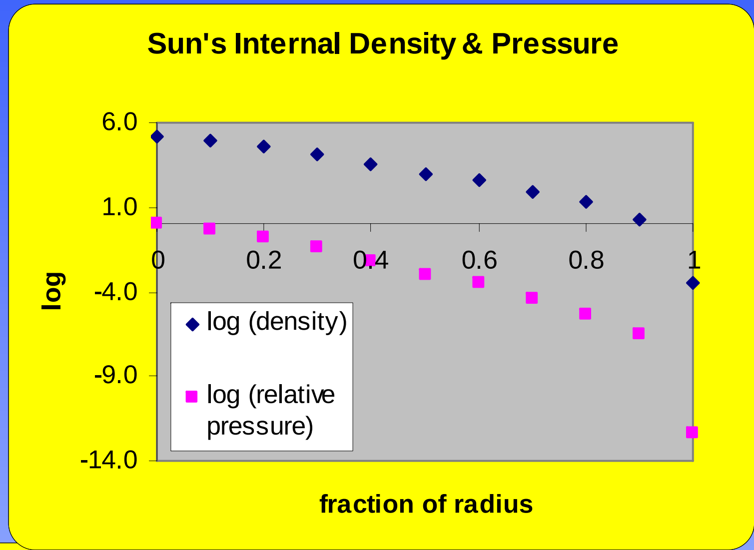


Diagram courtesy: SOHO group

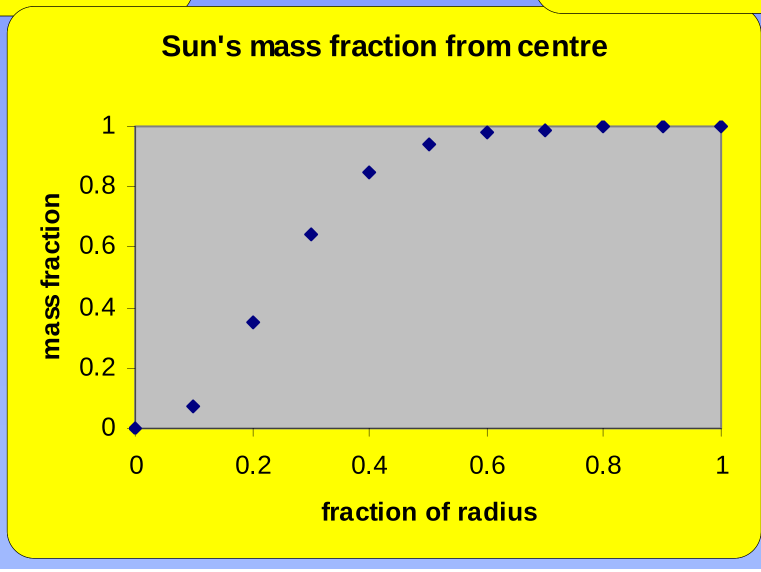
Standard Model of the Sun



↑ Central temperature reaches >15×10⁶ K



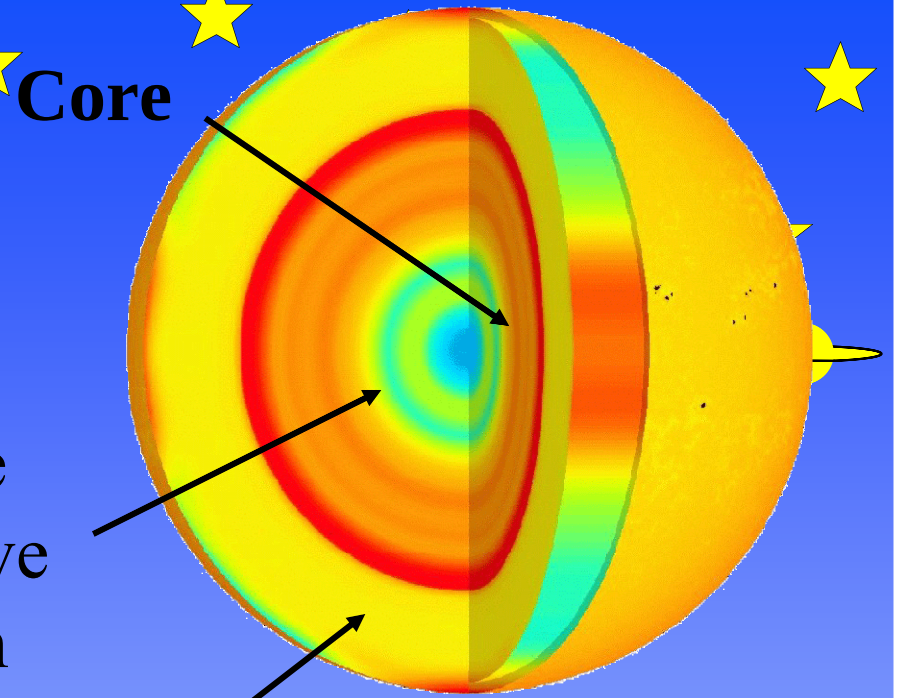
↑ Both pressure and density increase by many powers of ten towards the Sun's centre



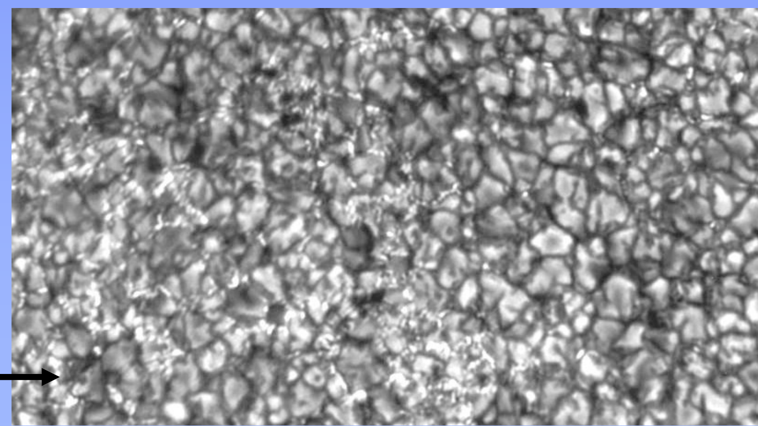
Most of mass is in inner half of the Sun →

Heat Transfer Outwards

- **Radiation** through a dense medium involves successive absorption and re-radiation
  - radiation from the centre of the Sun takes ~10^6 years to escape
- **Convection** transports heat the last 150,000 km to the surface
  - the convection cells can be seen on the surface
    - the **photosphere** is well stirred



Activate diagram for simulation

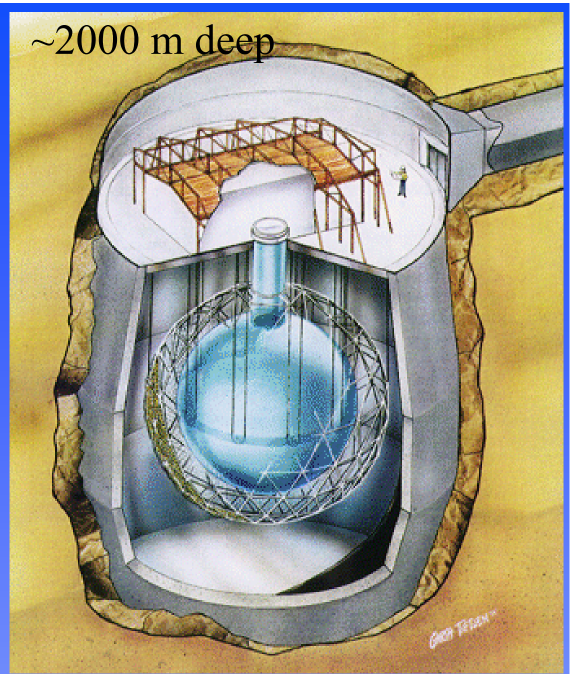


Granules, courtesy: NASA

Sun's Composition

- 78% of mass of photosphere is hydrogen, 20% helium and 2% are remaining 60 elements. The composition is measured spectroscopically
  - the big bang produced about 25% helium by mass and 75% hydrogen 13.7 billion years ago
  - the Sun at about 5 billion years old is considered a 3rd generation star

SNO →



The Great Neutrino Puzzle - Solved

- The *standard solar model* describing the Sun's interior predicts about 6.6×10^{14} neutrinos $m^{-2}\,s^{-1}$ at the distance of the Earth
- Careful experiments detect barely half of this flux
- What is wrong with our understanding?
  - do solar neutrinos decay into other neutrinos in flight?
  - yes! This implies neutrinos have a very small mass (~0.1eV)

Sun's Outer Reaches

- **Chromosphere** 2000 - 3000 km thick, optically thin, red light showing bright spectral lines particularly of hydrogen
  - seething ferment of rising *spicules* of gas getting hotter the further out it goes
  - flares send hot gases outward very far and fast
- **Corona** - very extensive, irregular, temperature rises to over 10^6 degrees, emits x-rays, strongly magnetic
  - **solar wind** appears to come from coronal holes

Solar Wind

- Plasma mainly of protons, He ions and electrons, with trapped magnetic field
- ~10^6 particles m^{-3} reach Earth at ~400 km s^{-1}
- Solar flares greatly increase solar wind
  - solar wind blows out comets' tails
  - influences upper atmosphere
  - interacts strongly with Earth's magnetic field, one consequence of which is to produce aurora
  - can affect radio communication around Earth

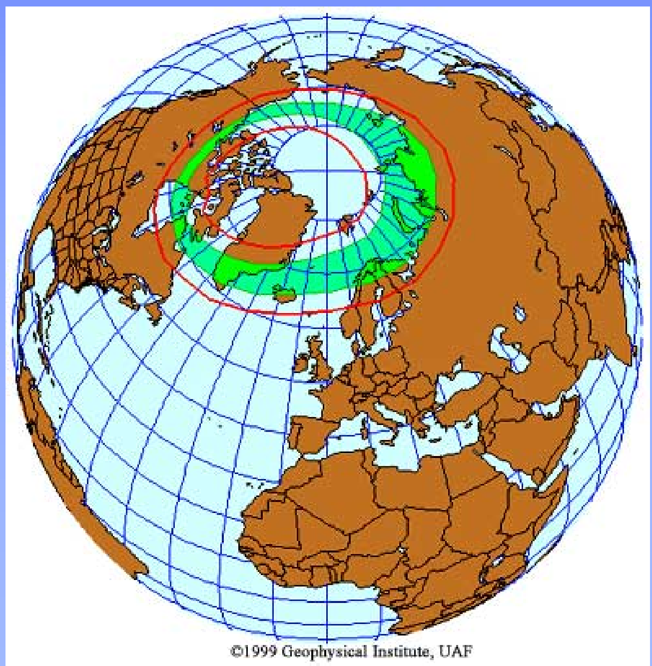
The Aurora

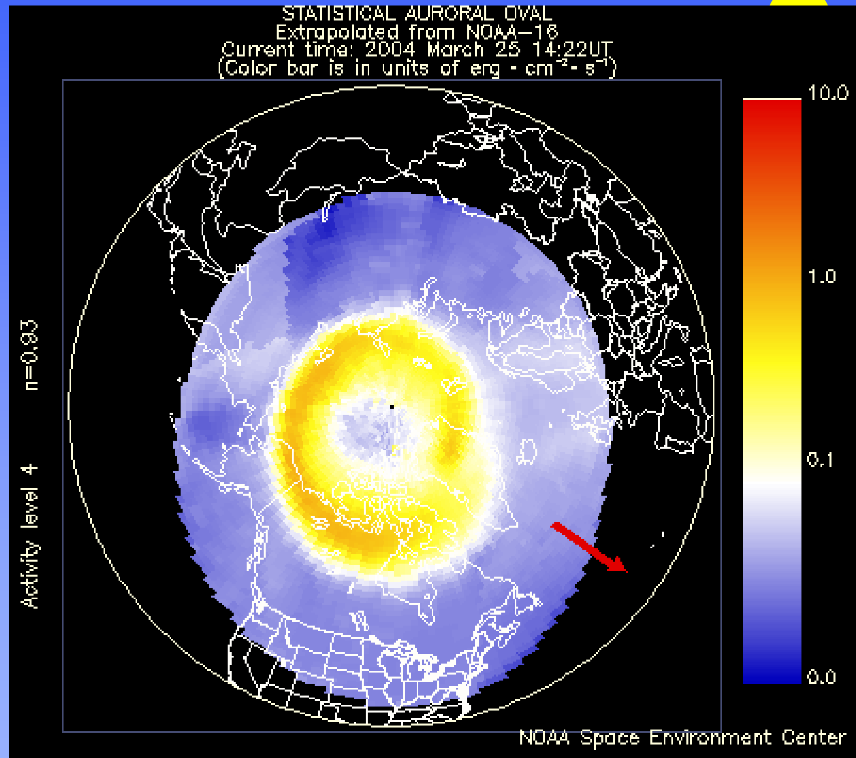
← Alaskan aurora courtesy Jan Curtis

Aurora from the Space shuttle ↓

Current Auroral Oval

- Image from NOAA – 16 **P**olar-orbiting **O**perational **E**nvironmental **S**atellite →

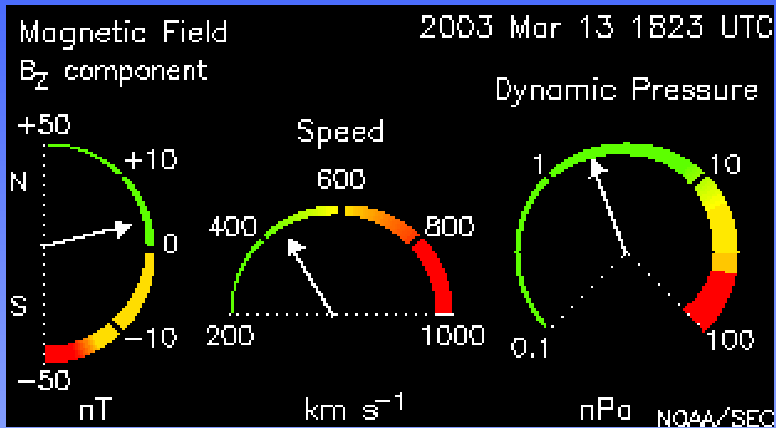




http://sec.noaa.gov/pmap/pmapN.html

http://www.gi.alaska.edu/aurora_predict/map4/0.html

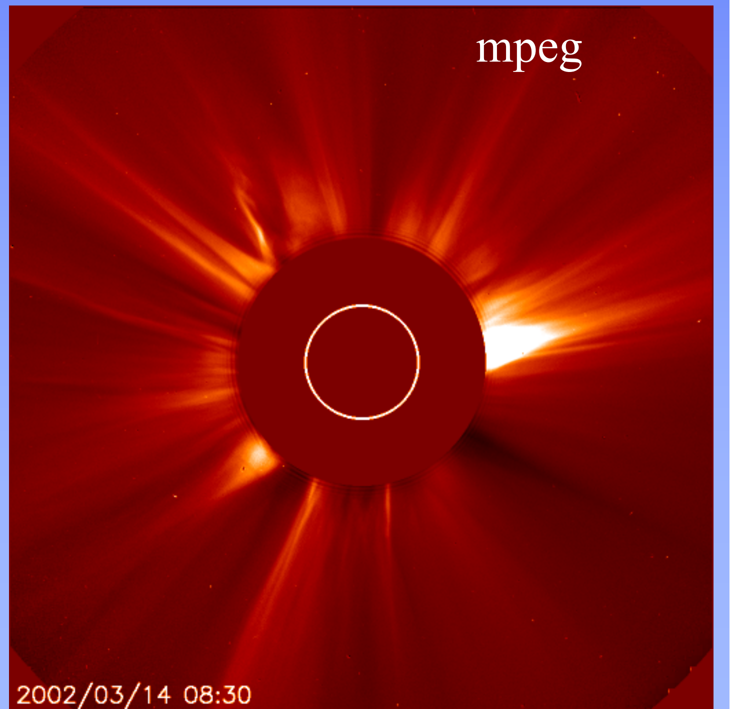
Space Weather



← Space weather dials

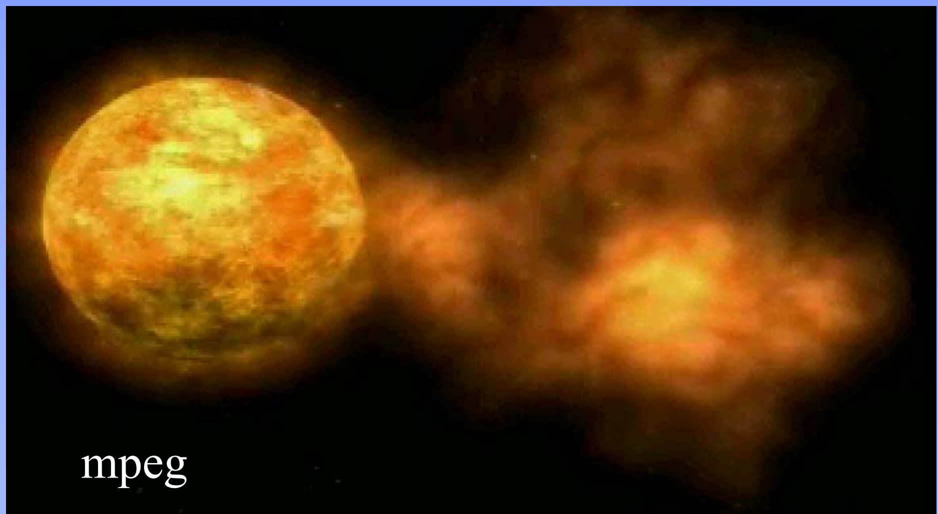
Coronal view

from SOHO ↓



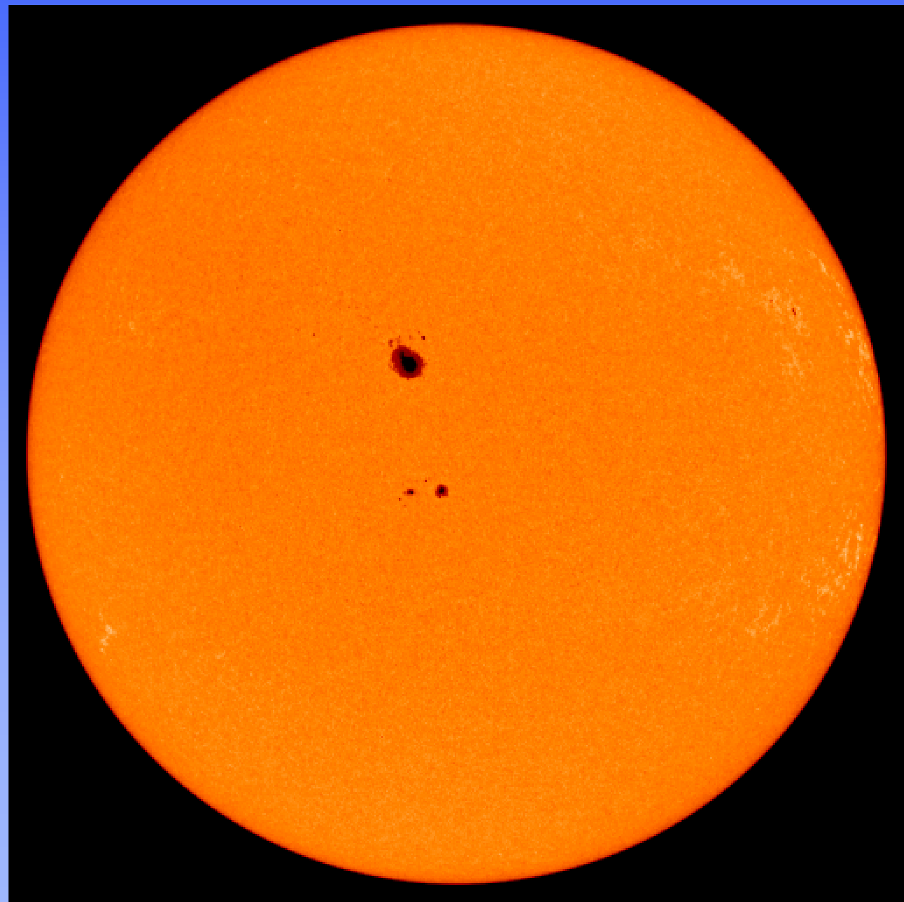
Coronal mass

↓ ejection



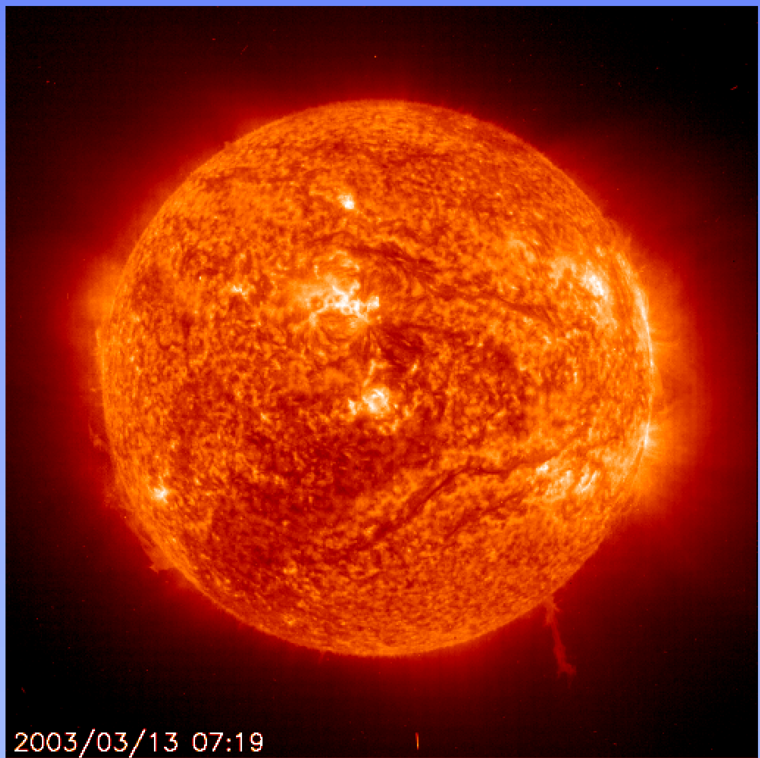
Monitoring the Sun - 1

The Sun in H_α light →



The Sun in extreme UV

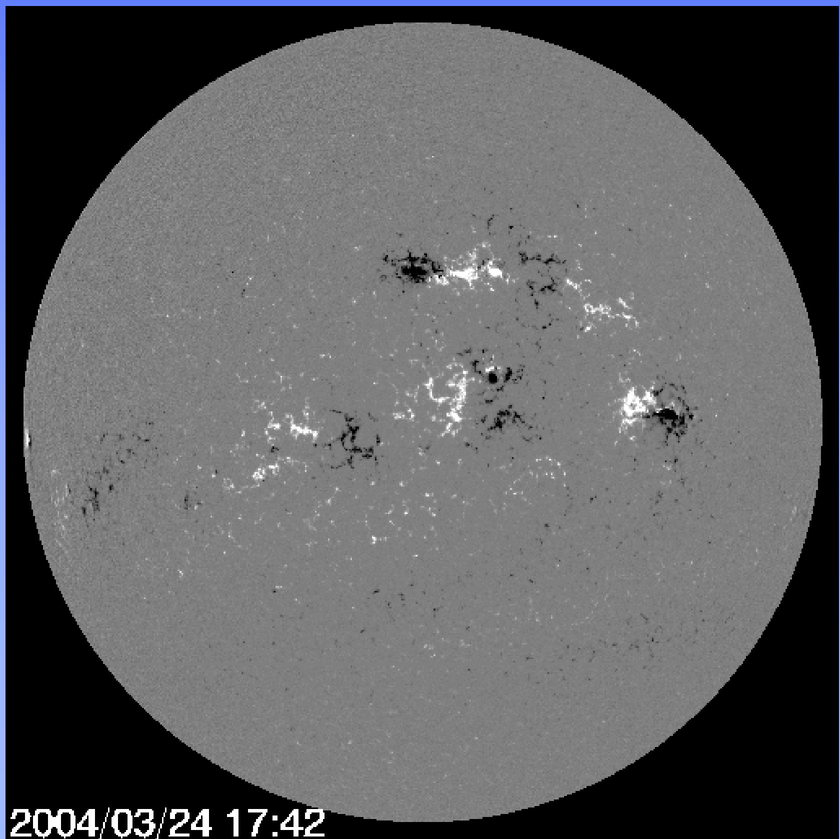
in false colour (SOHO) ↓



Monitoring the Sun - 2

Sunspots 24 - Mar - 2004 →

Magnetogram 24th March 2004 ↓



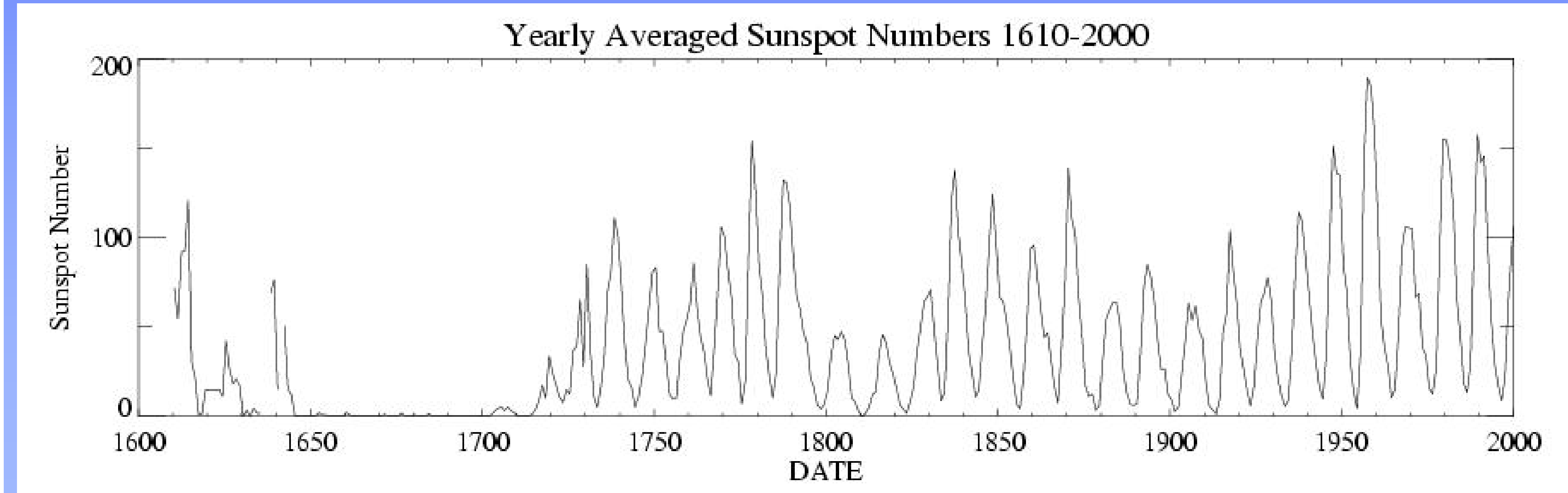
← http://sohowww.estec.esa.nl/

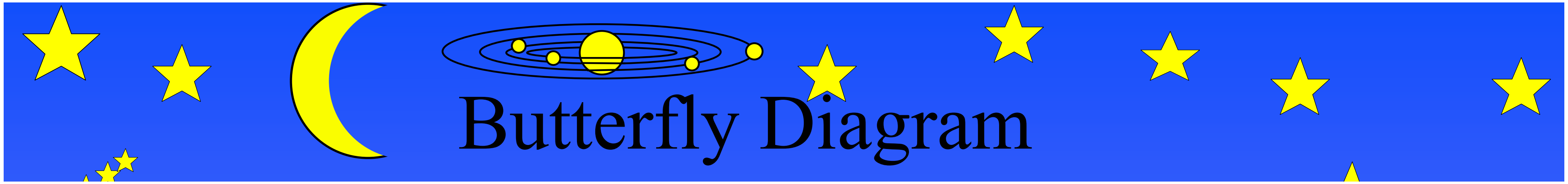
Sunspots

- Cooler (4800°C), slightly depressed regions with relatively dark centre
  - strong magnetic field (×5000 Earth's) that inhibits convection
  - occur in pairs, last from a few days to a few months
- 22 year cycle with minima and maxima every 11 years
  - increase in flares and hence strong solar wind; ^{14}C abundance correlates inversely with solar wind
  - increase in radiation flux - influence on climate

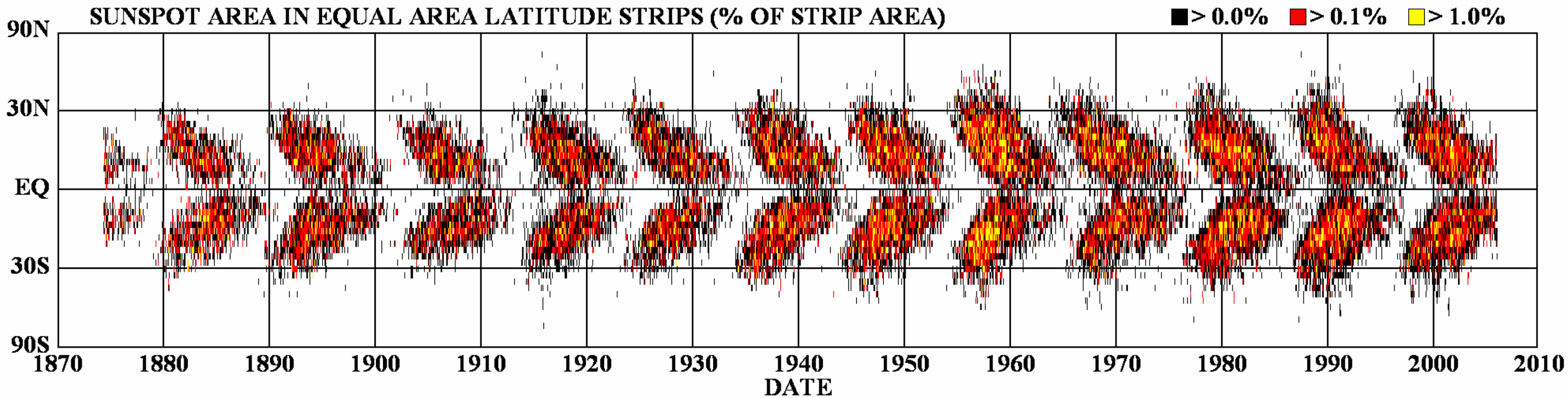
Longer term fluctuations

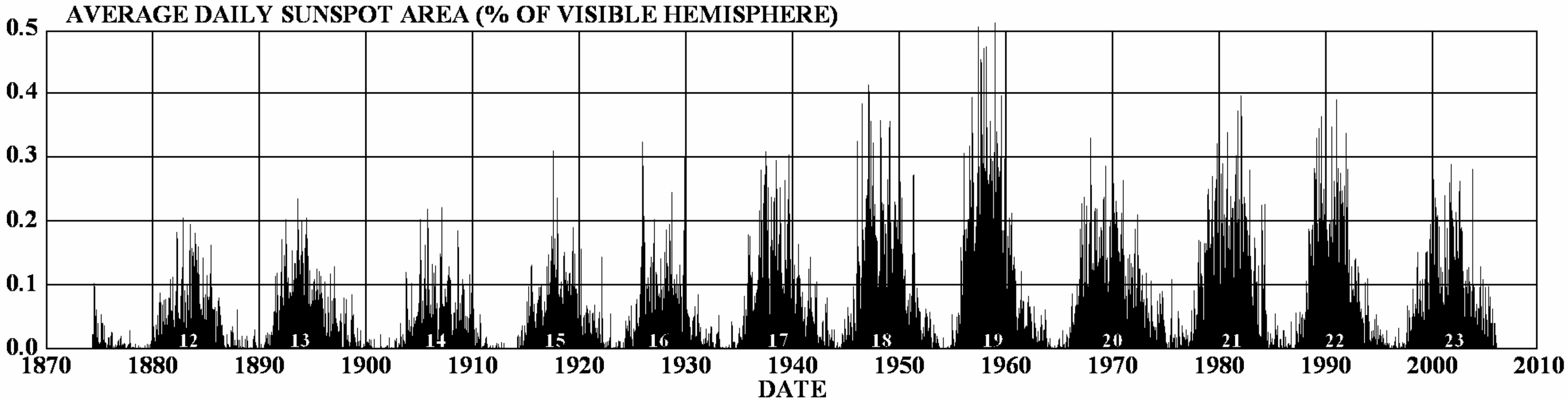
- Longer term cycles than 11.3 years (on average) are emerging, e.g. ~90 years found by Gleissberg
  - note the Maunder minimum, when sunspots disappeared





DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS



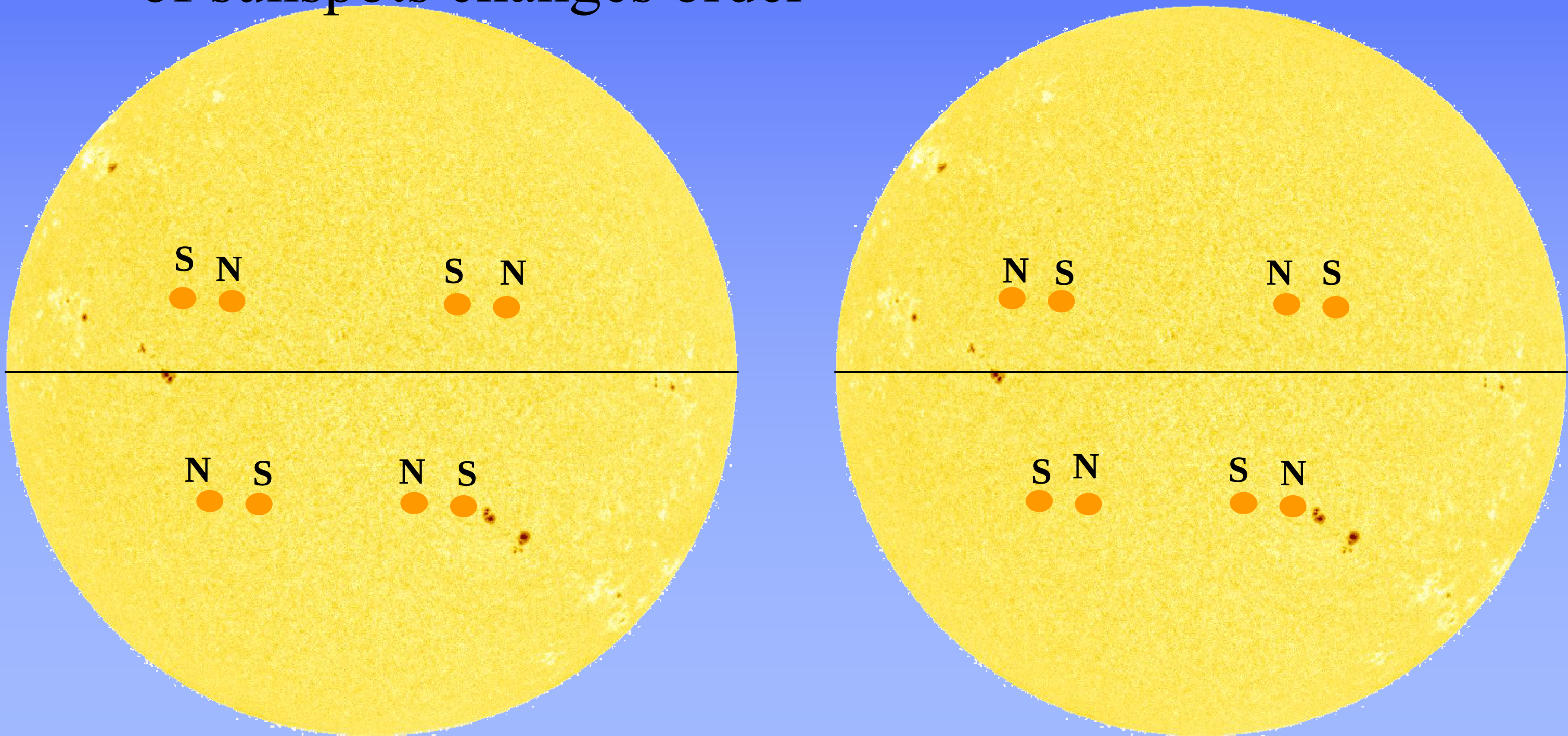


http://science.msfc.nasa.gov/ssl/pad/solar/images/bfly.gif

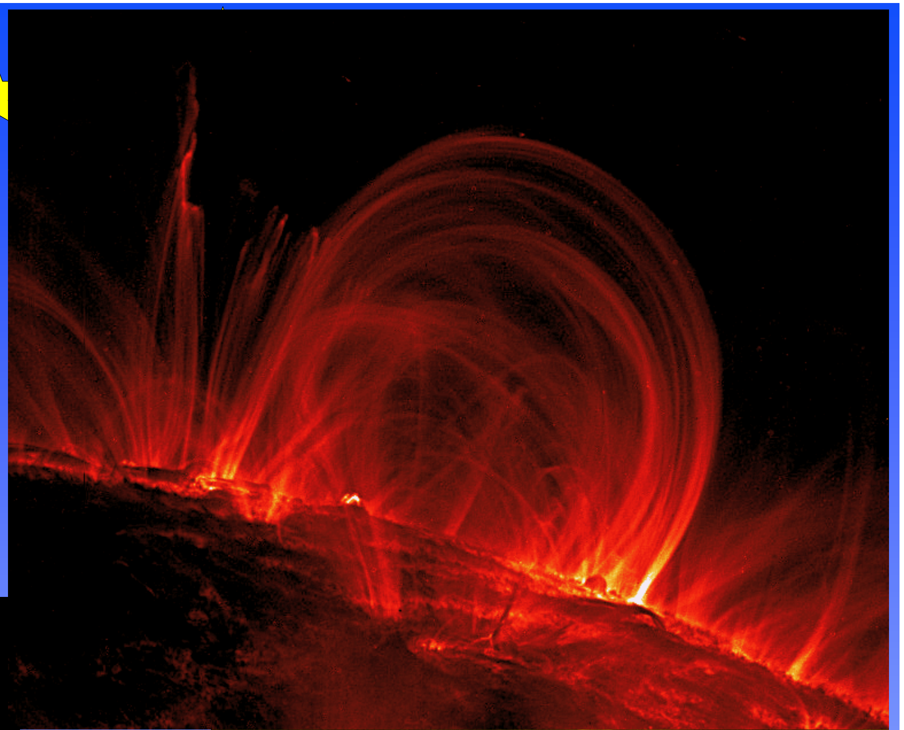
NASA/NSSTC/HATHAWAY 2006/03

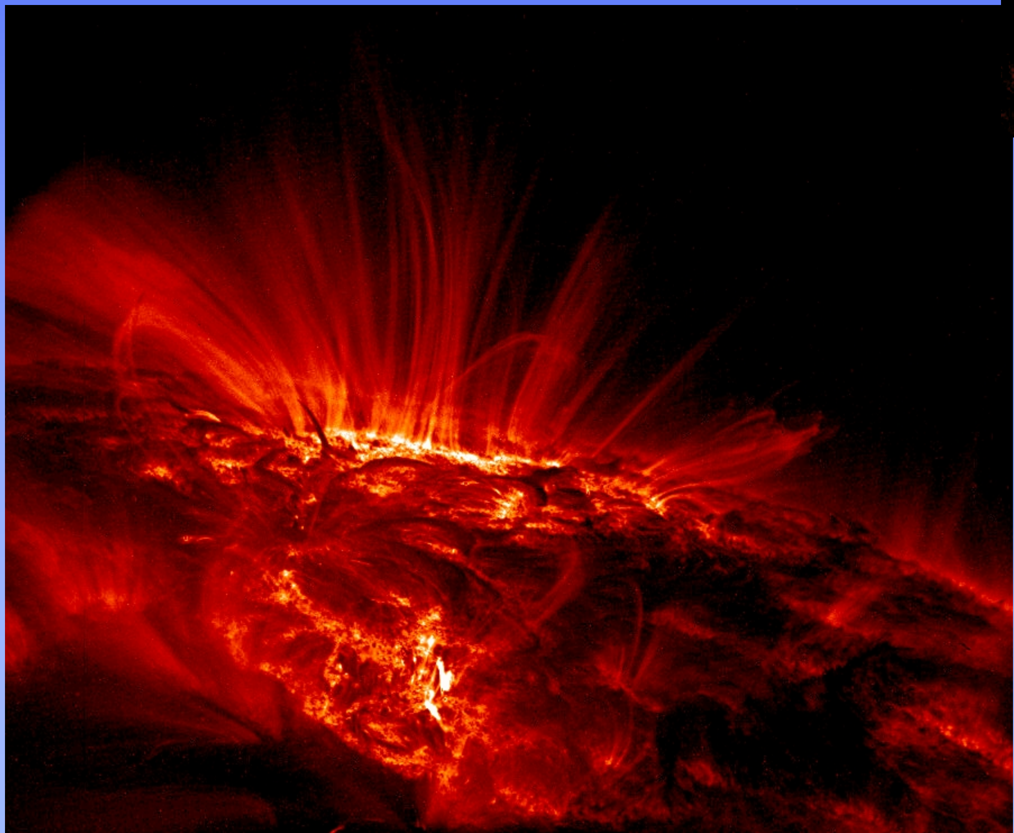
Sunspot Polarity Changes

- In successive 11 year cycles, the polarity of pairs of sunspots changes order



Hairy Ball Model of Sun's Magnetic Field





Pictures courtesy: Transition Region and Coronal Explorer program, TRACE