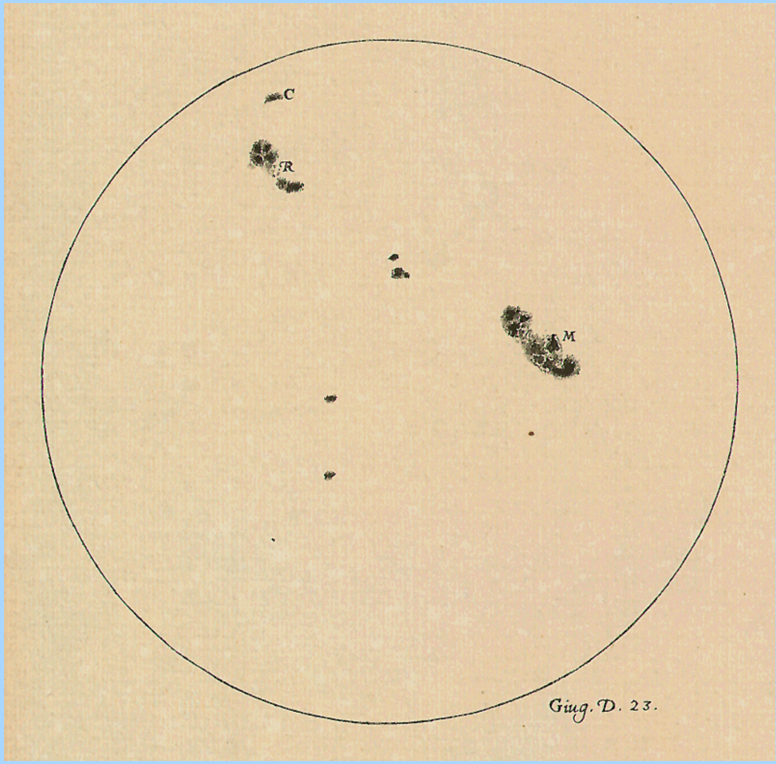
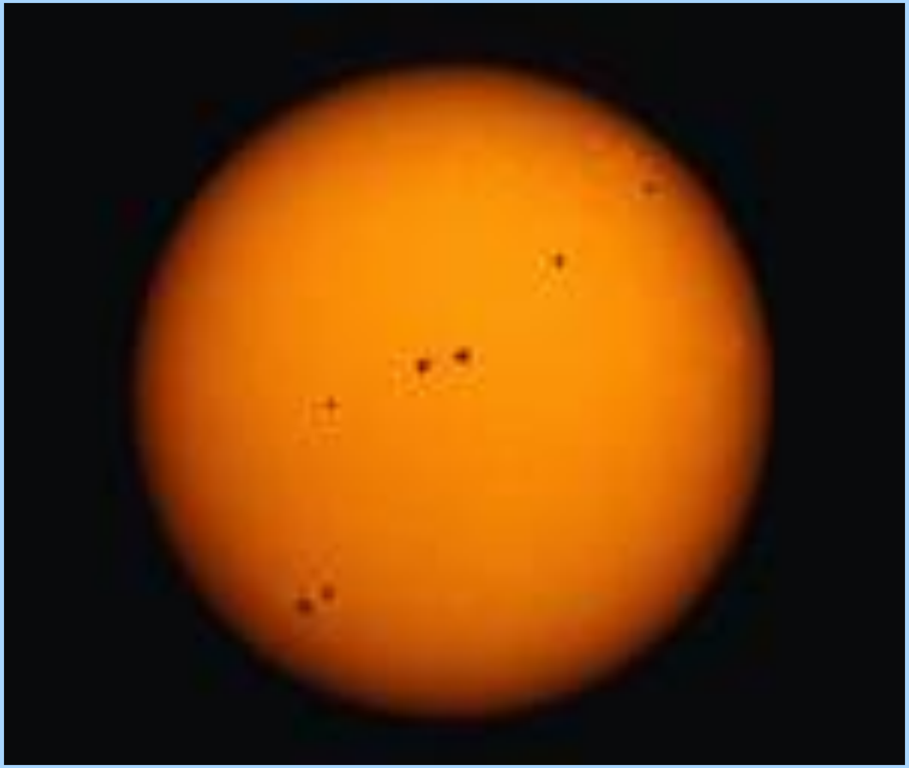
The Sun





Data for Sun

Mass = 2 X 10^{30} kg = 2 X 10^{33} g

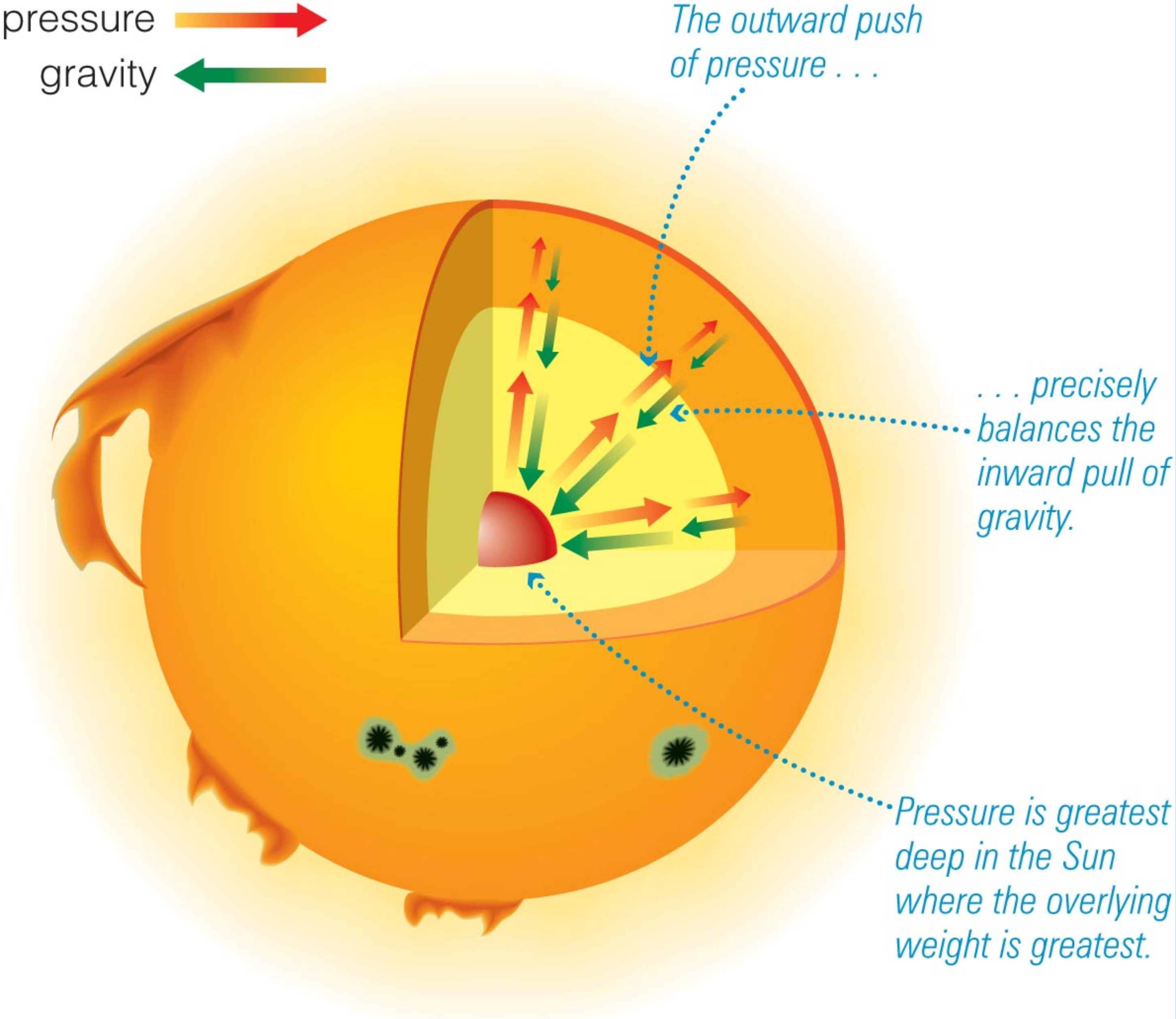
Radius = 6.96 X 10^{5} km = 6.96 X 10^{8} m

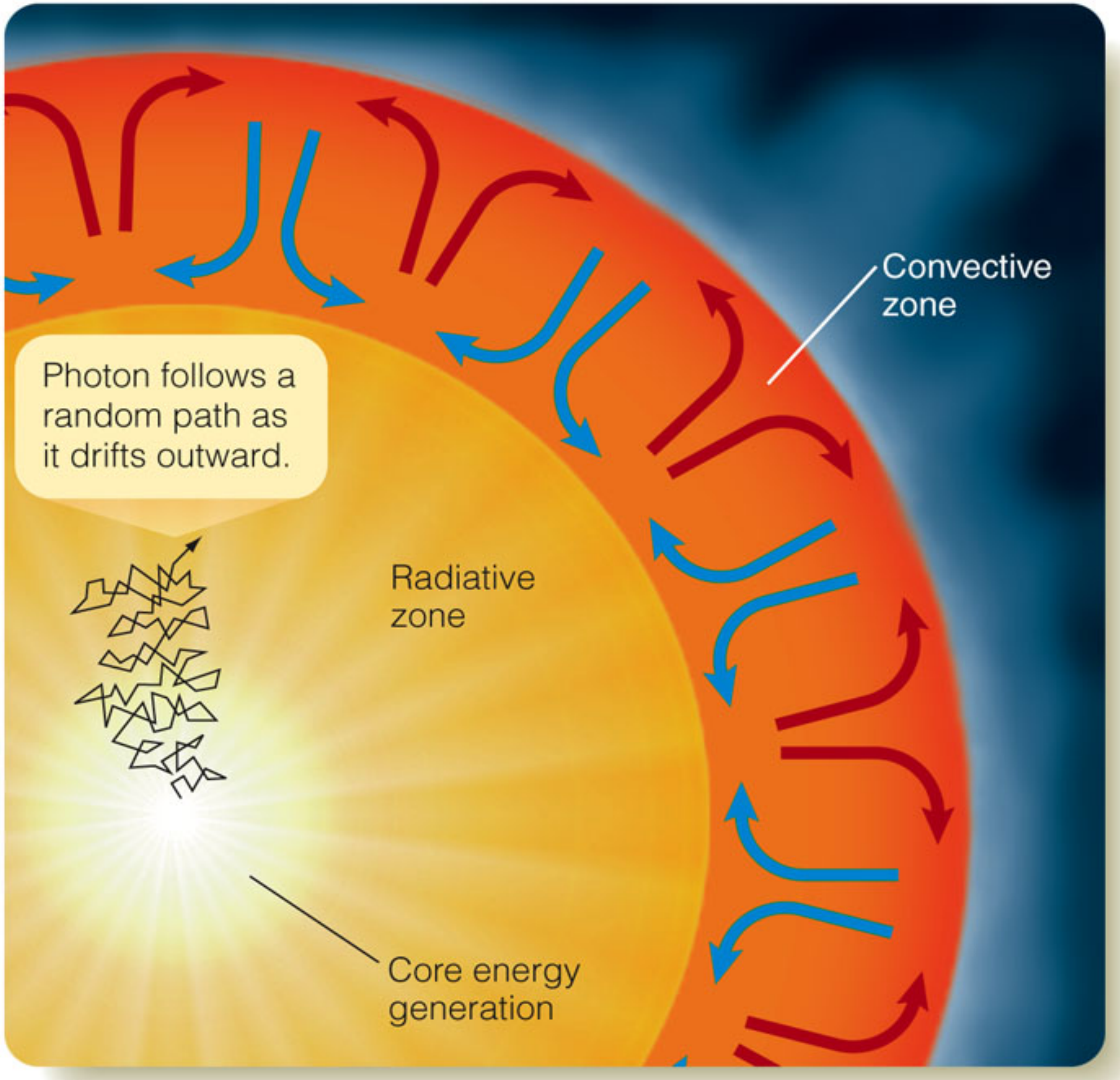
Luminosity = 3.8 X 10^{26} J/sec = 3.8 X 10^{33} erg/sec

Spectral type = G2 V

An example of gravitational equilibrium.

Without equilibrium this stack would collapse.

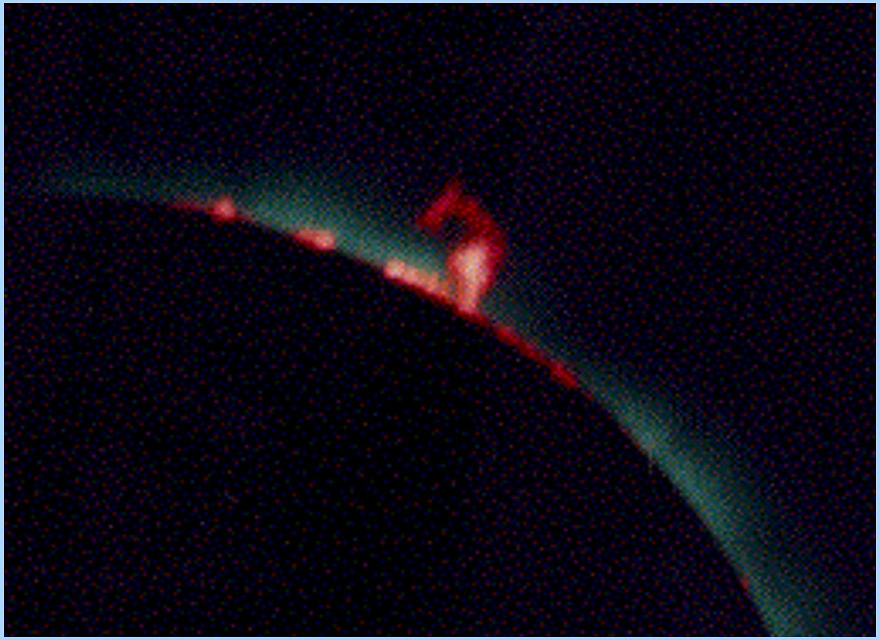

pressure
gravity
The outward push of pressure . . .
. . . precisely balances the inward pull of gravity.
Pressure is greatest deep in the Sun where the overlying weight is greatest.



The core of the Sun extends to about 0.2 of the Sun's radius.

Energy is transported outwards in two ways: radiation and convection.

The pale yellow layer of the Sun that we see every sunny day is called the **photosphere**. Its temperature is about 5800 K. Above that is the **chromosphere**, so named because we see colored loops of gas there during a total solar eclipse. This layer's temperature ranges from 4500 K to 10,000 K at the top.



The hottest region of the Sun's atmosphere is the **corona**. It also has the lowest density. We observe the corona during a total solar eclipse, or using a special telescope called a coronograph.

The most important thing to know about the Sun is that nuclear **fusion** takes place in its core. Hydrogen nuclei (protons) are converted into helium nuclei.

Consider the following masses:

$$
\begin{array}{lrl}
 & \text{4 hydrogen nuclei} & = 6.691 \text{ X } 10^{-27} \text{ kg} \\
- & \text{1 helium nucleus} & = 6.644 \text{ X } 10^{-27} \text{ kg} \\
 & & \\
 & \text{difference} & = 0.047 \text{ X } 10^{-27} \text{ kg}
\end{array}
$$

The fraction of mass that is converted into energy is 0.047 / 6.691 = 0.0070.

Let us assume naively that the Sun started out with a composition of 100 percent hydrogen and it all can be converted into helium. How long would that take?

0.007 of Sun's mass = $0.007 \times 2 \times 10^{30} = 1.4 \times 10^{28}$ kg. If converted into energy, how much energy would you get?

$E = m c^2 = 1.4 \times 10^{28} (3 \times 10^8)^2 = 1.26 \times 10^{45}$ Joules

Since the Sun gives off 3.8×10^{26} J each second, it could keep this up for 1.26×10^{45} J / (3.8×10^{26} J/sec) = 3.3×10^{18} sec. Since one year contains 3.156×10^{7} sec, this time scale is 1.05×10^{11} years = 105 billion years!

No wonder controlled nuclear fusion would be the answer to all our energy problems!

However, our naïve calculation is too simple for two reasons. The original composition of the Sun was about 75 percent hydrogen, 23 percent helium and 2 percent everything else. Also, it turns out that once 10 to 15 percent of the hydrogen is converted into helium, the Sun becomes a red giant star.

In the present stage of its life, converting hydrogen into helium, the Sun will last about 10 billion years.

H. Bethe (1906-2005)

In 1938 the German-American physicist Hans Bethe determined how the sequence of nucleus reactions in the Sun works.

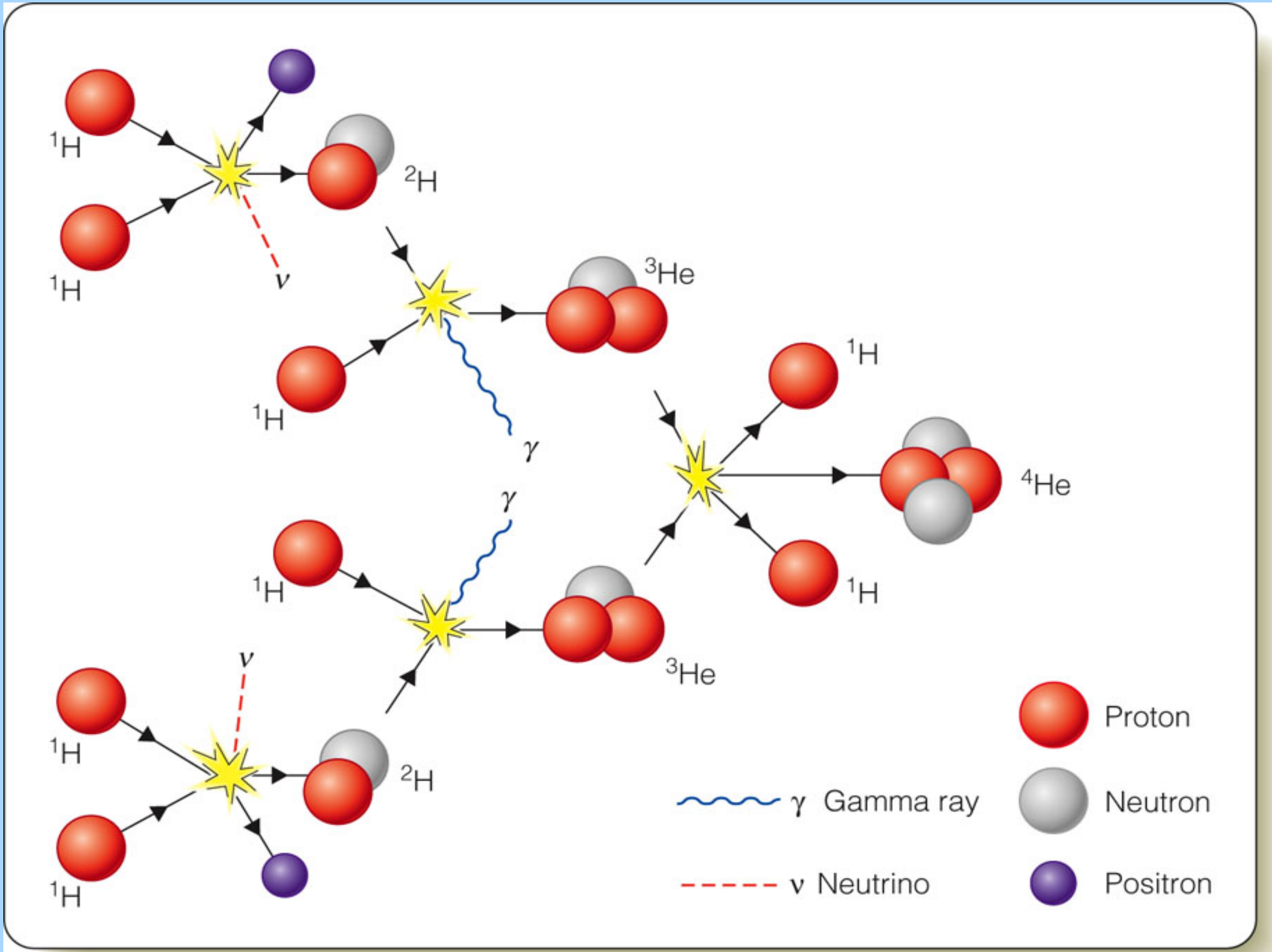
The sequence of three nuclear reactions is called the **proton-proton cycle**.

$^{1}\mathrm{H} + {}^{1}\mathrm{H} \text{ --> } {}^{2}\mathrm{H} + e^{+} + \text{neutrino}$

$^{2}\mathrm{H} + {}^{1}\mathrm{H} \text{ --> } {}^{3}\mathrm{He} + \text{gamma ray}$

$^{3}\mathrm{He} + {}^{3}\mathrm{He} \text{ --> } {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{1}\mathrm{H}$

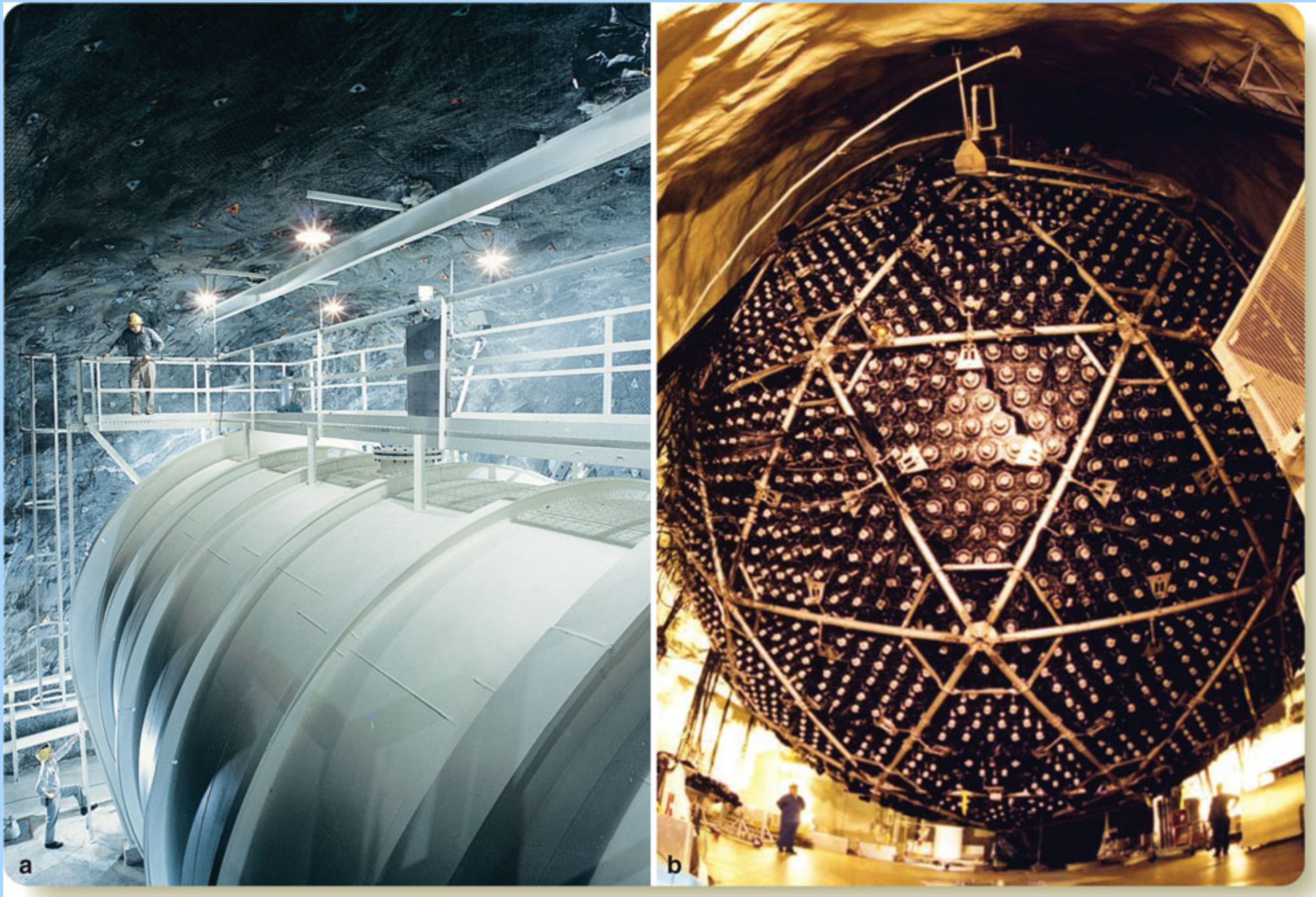
A hydrogen nucleus containing one proton and one neutron (^{2}H) is called **deuterium**. A particle with the mass of an electron but having a positive charge is called a **positron**. A **neutrino** is a very light sub-atomic particle. A nucleus containing two protons and two neutrons is a stable helium nucleus.



¹H
¹H
²H
ν
³He
¹H
γ
¹H
⁴He
¹H
γ
¹H
³He
ν
¹H
²H
¹H
Proton
Neutron
Positron
γ Gamma ray
ν Neutrino

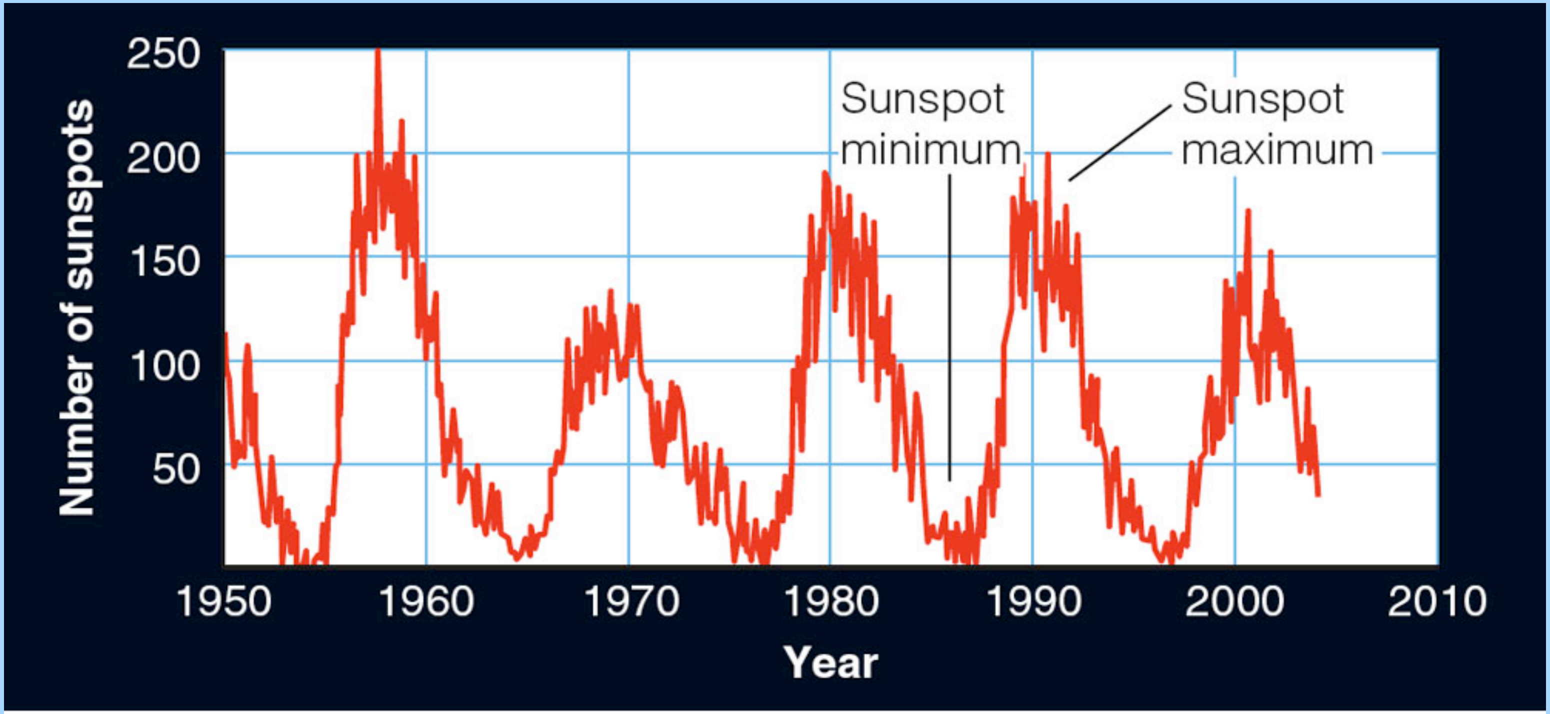
As the gamma rays produced by the nuclear fusion in the Sun's core work their way out of the Sun, they are absorbed many times and are reradiated as a larger number of *lower energy* photons. The total amount of energy is conserved. Finally, by the time the photons leave the solar photosphere, they have been converted into a very large number of ultraviolet, visual, and near-infrared photons.

For many years the *observed* numbers of neutrinos did not match what the theoreticians said the neutrino flux should be. Was the data bad, or was the theory wrong?

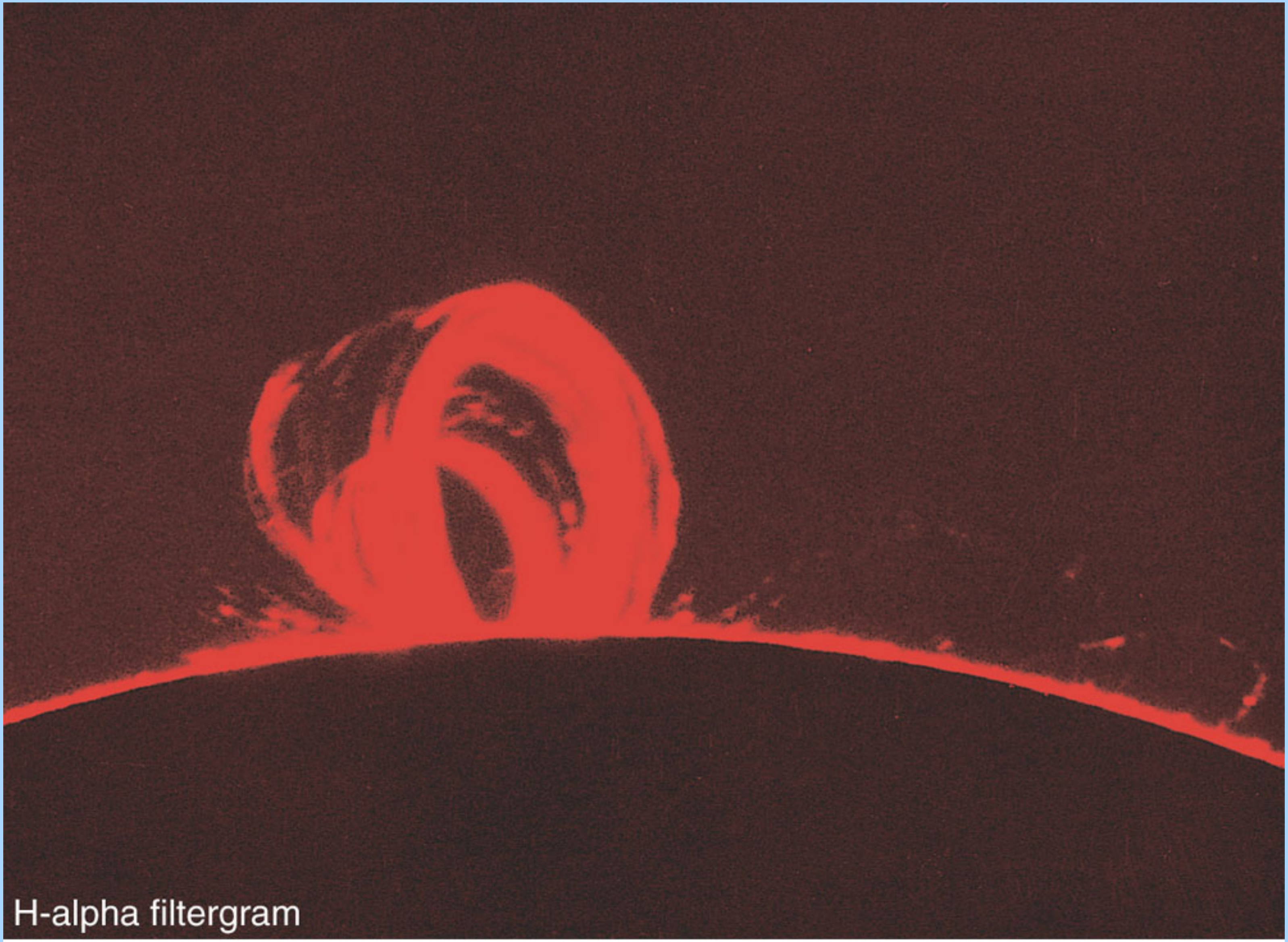

a
b

There are three types of neutrinos: electron neutrinos, muon neutrinos, and tau neutrinos. The Davis tank of C_2Cl_4 was only sensitive to electron neutrinos, and it was proven that some of the electron neutrinos produced in the Sun were permuting themselves into muon and tau neutrinos. The theory of nuclear fusion in the Sun was basically OK. What we needed was a new theory of what neutrinos are.

The key thing to know about **sunspots** is that they are regions of very strong **magnetic fields**. Also, the number of spots increases and decreases with an 11 year period.



When the Sun is experiencing a *solar maximum*, there are lots of spots, strong magnetic storms, and a strong **solar wind**. When this wind hits the Earth's atmosphere, radio transmission can be disrupted. And one can observe the northern lights (*aurora borealis*).


H-alpha filtergram

Even if there are no storms of magnetic activity on the Sun, the solar wind varies in intensity over the course of the solar cycle. This causes a variation of a kind of low level aurora (*air glow*). Both the air glow and the aurora borealis are due to reactions in the upper atmosphere.

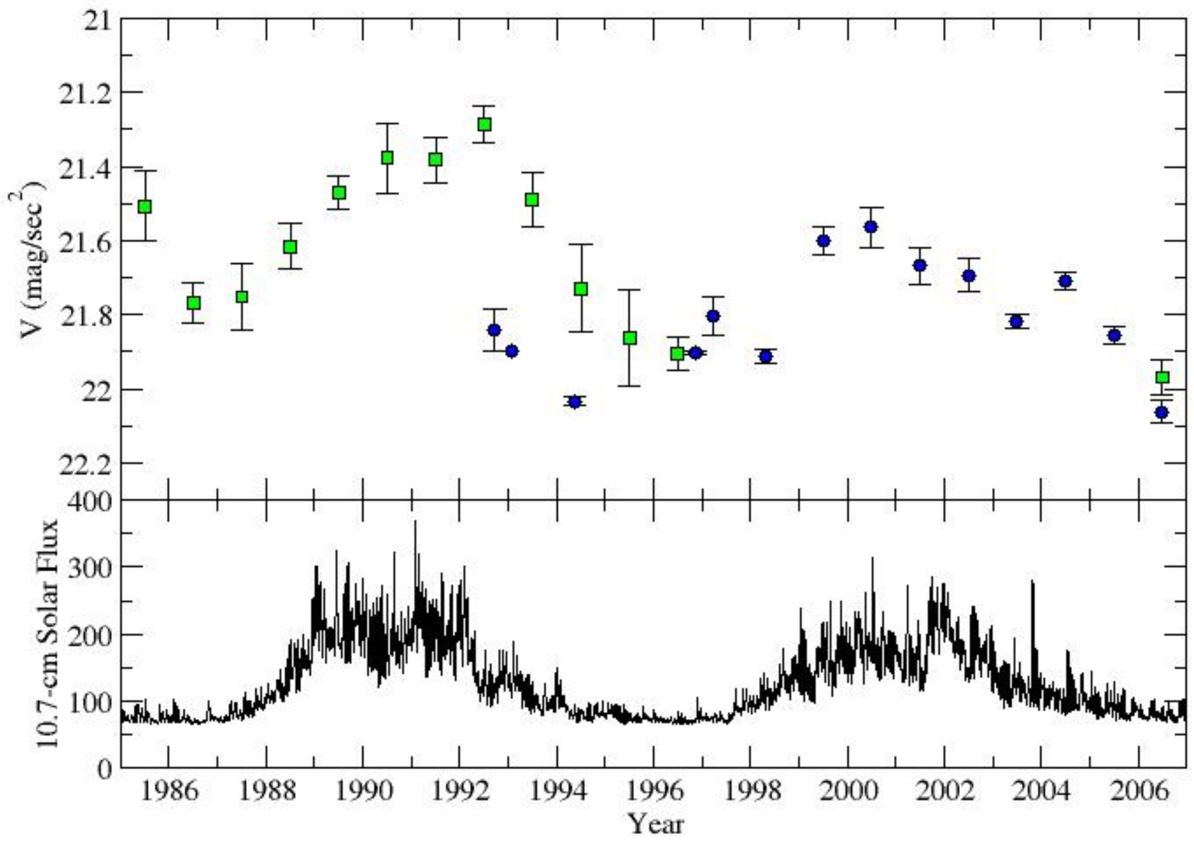
One of the consequences of the solar cycle is that the Earth's atmosphere is *larger* at the time of solar maximum and smaller at the time of solar minimum.

And one consequence of a larger atmosphere is more drag on orbiting satellites. Some fall back to Earth!

The Earth’s airglow, as viewed from outer space.

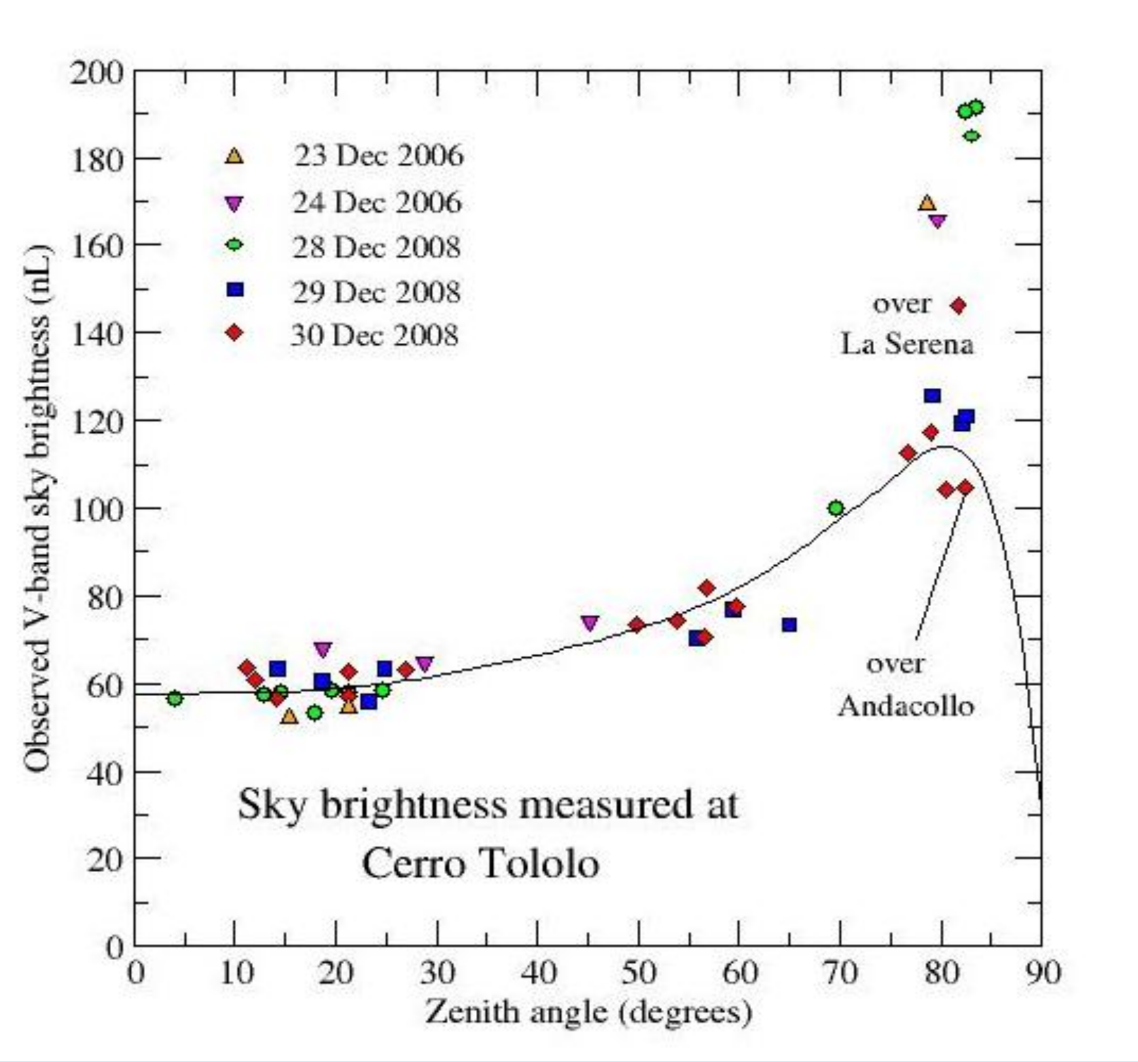
Skylab was launched on May 14, 1973. It fell back to Earth on July 11, 1979, mostly because it was solar maximum and that caused the Earth's atmosphere to swell, producing more drag on the satellite.

Mauna Kea and CTIO data show that the sky brightness is a function of the phase of the solar cycle.

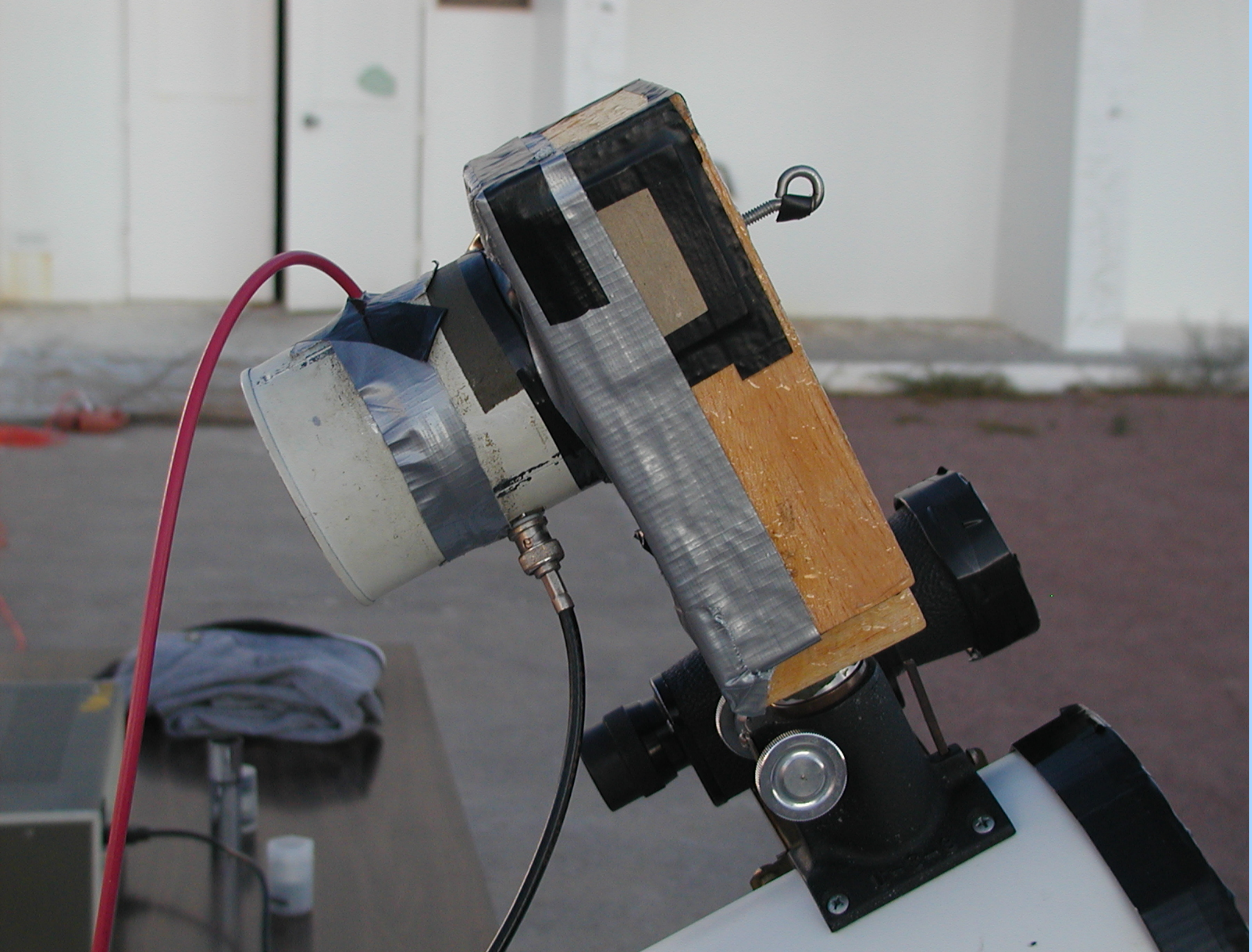


15 minute digital image towards La Serena/Coquimbo, Chile.

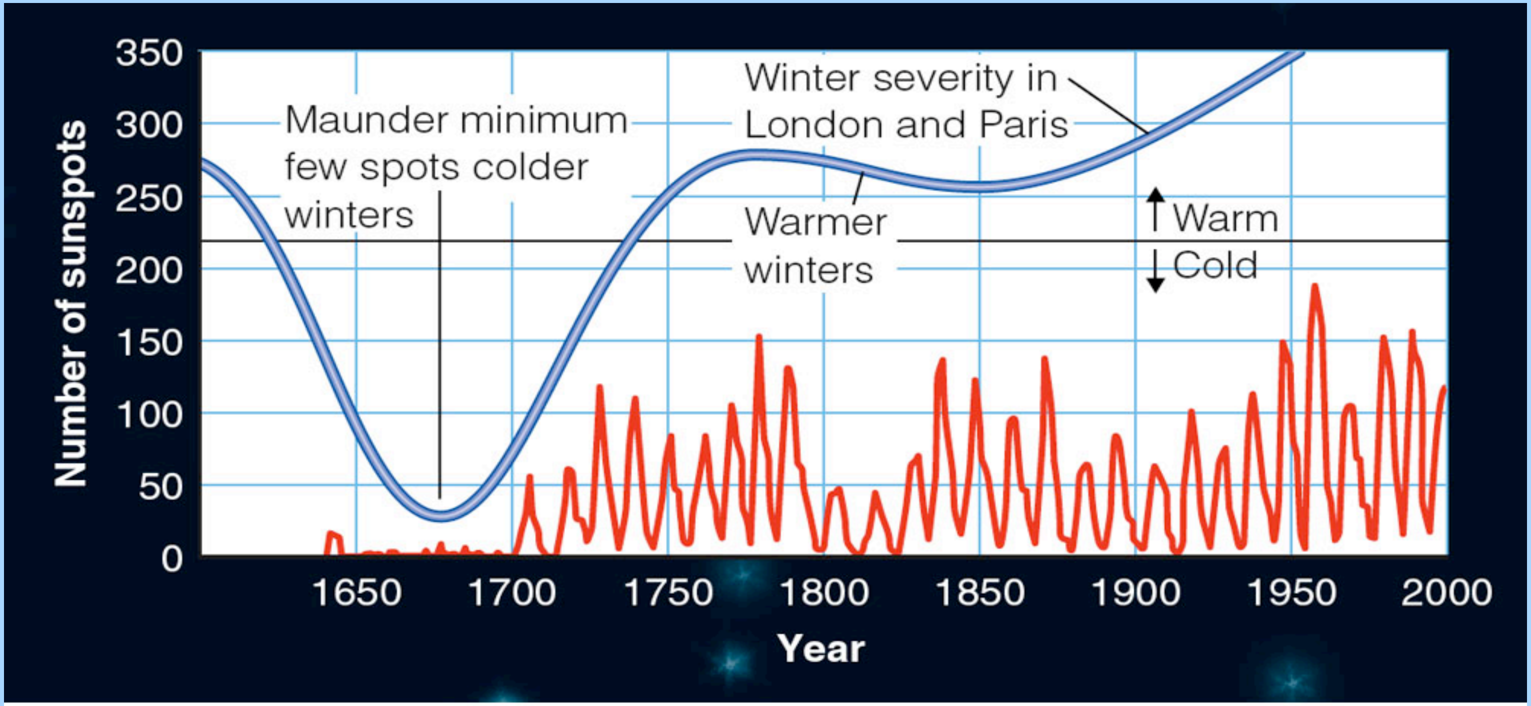
It's darker at Cerro Tololo when La Serena is covered by cloud.



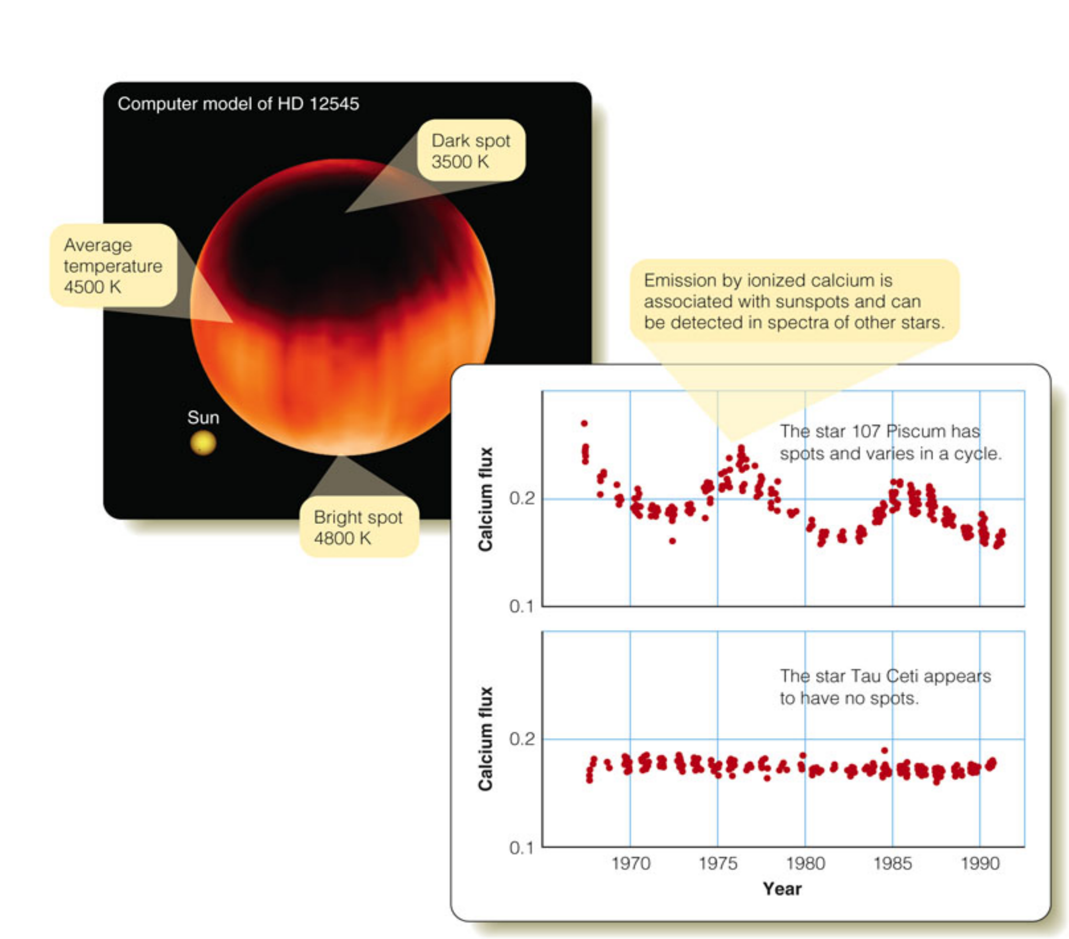
When La Serena is not covered by clouds, we can measure light pollution low in the sky in that direction.

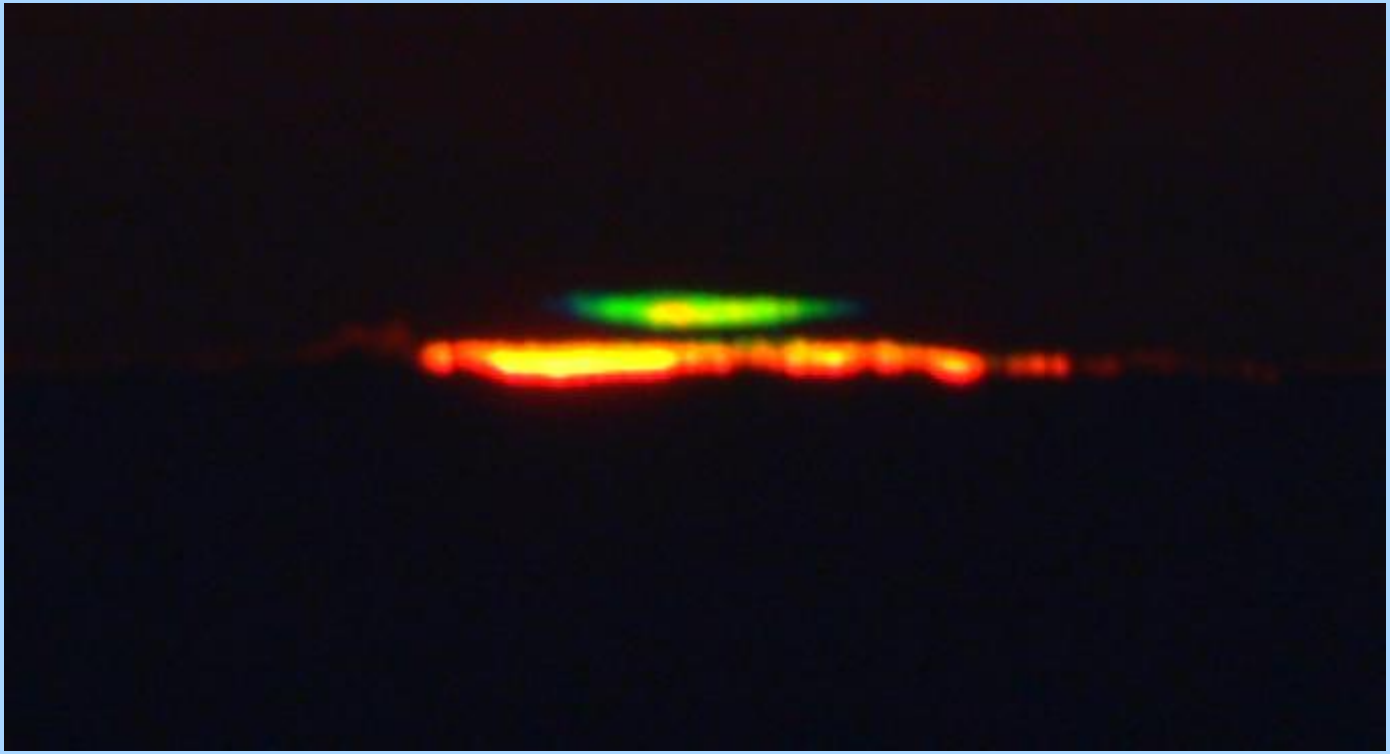


If there are very few spots on the Sun for a long time, the Earth's climate is much colder. It should not be that surprising that small changes in the Sun's activity have an effect on the Earth.



Stars other than the Sun are known to have spot cycles with periods of several years.





The green flash observed at Cerro Tololo, Chile (photo by T. Abbott).