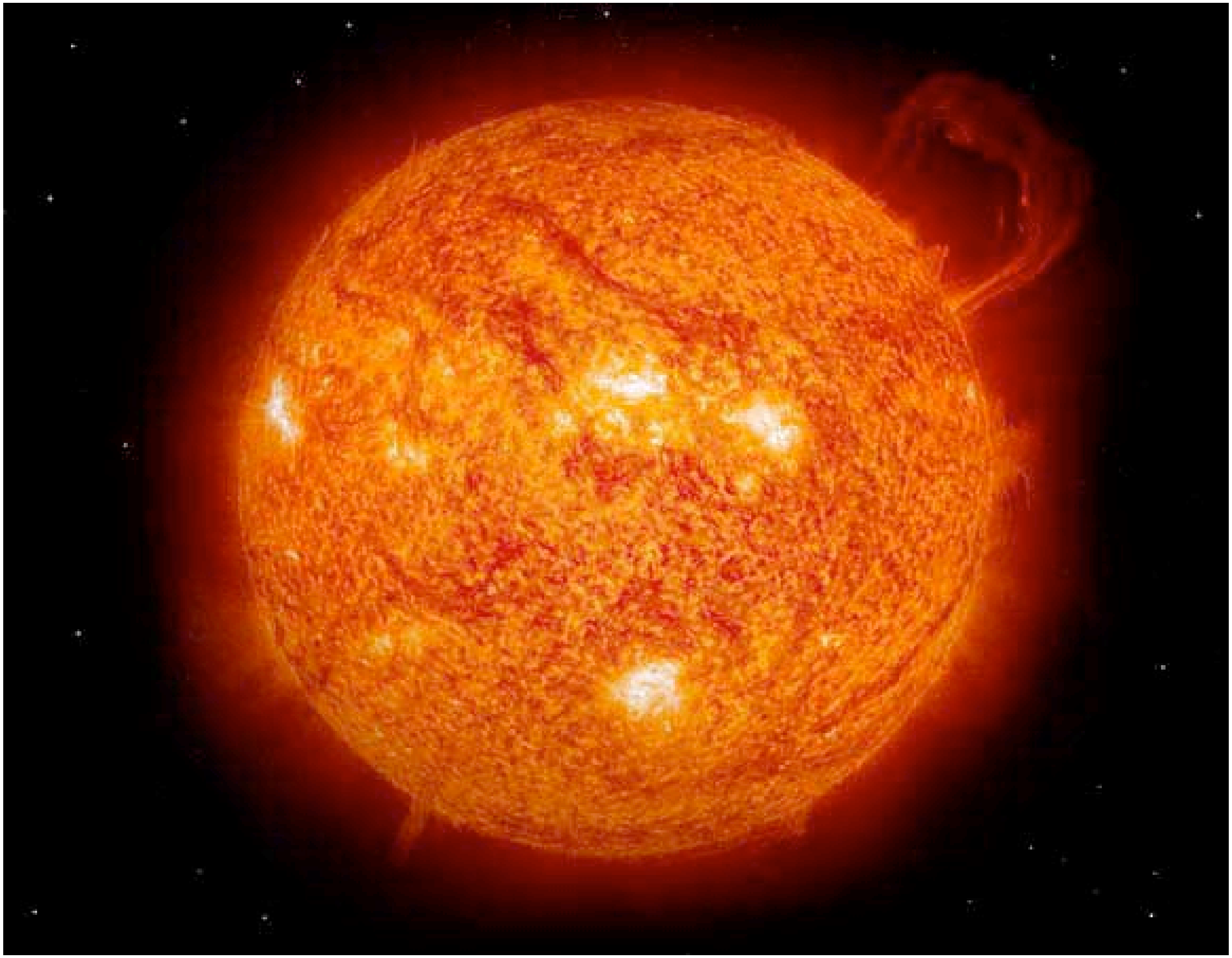
The Sun



The Sun, vital statistics:

Average distance to earth: 1AU (=1.5 x 10^8 km)

Average angular diameter: 0.5 degrees

Period of rotation: 25 days (at the equator)

Radius: 7 x 10^5 km (= 109 $R_{\oplus}$)

Mass: 2 x 10^{30} kg (= 333,000 $M_{\oplus}$)

Surface temperature: 5800K

Core temperature: 15 million K

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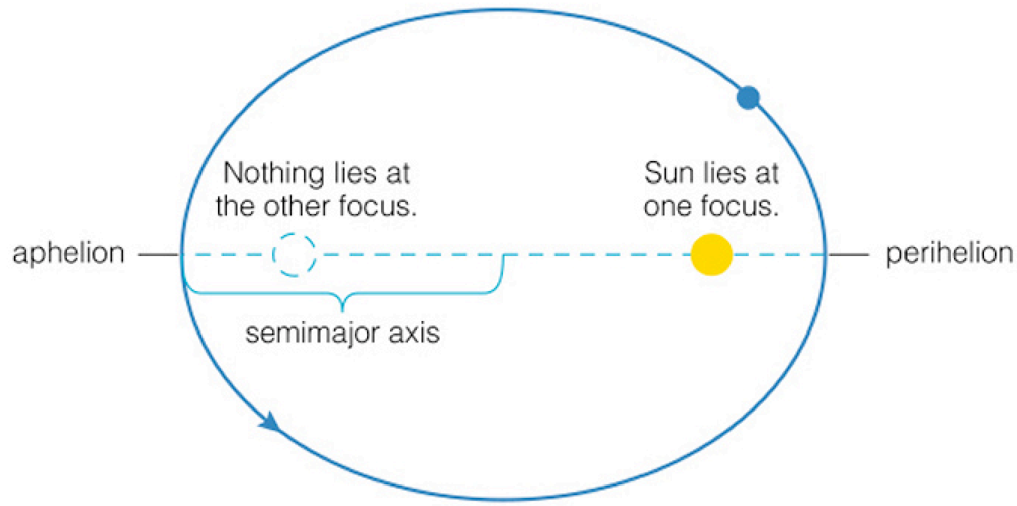
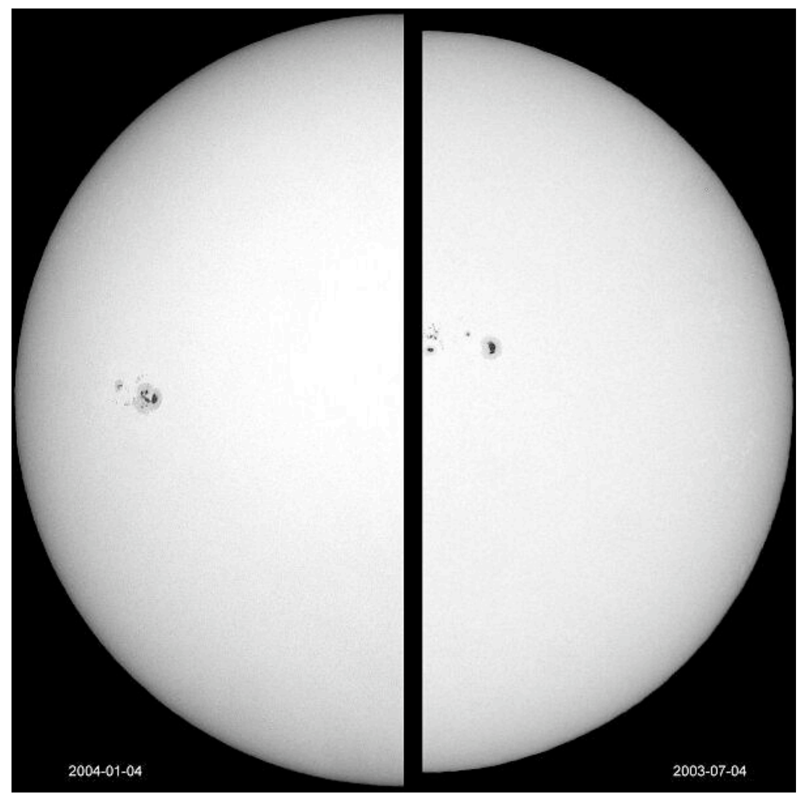
1 AU is the average distance between the sun and the earth. The actual distance varies because the orbit is elliptical. Earth's closest approach to the sun is called perihelion and its most distant point is called aphelion, although we barely notice the difference in the sun's apparent size.





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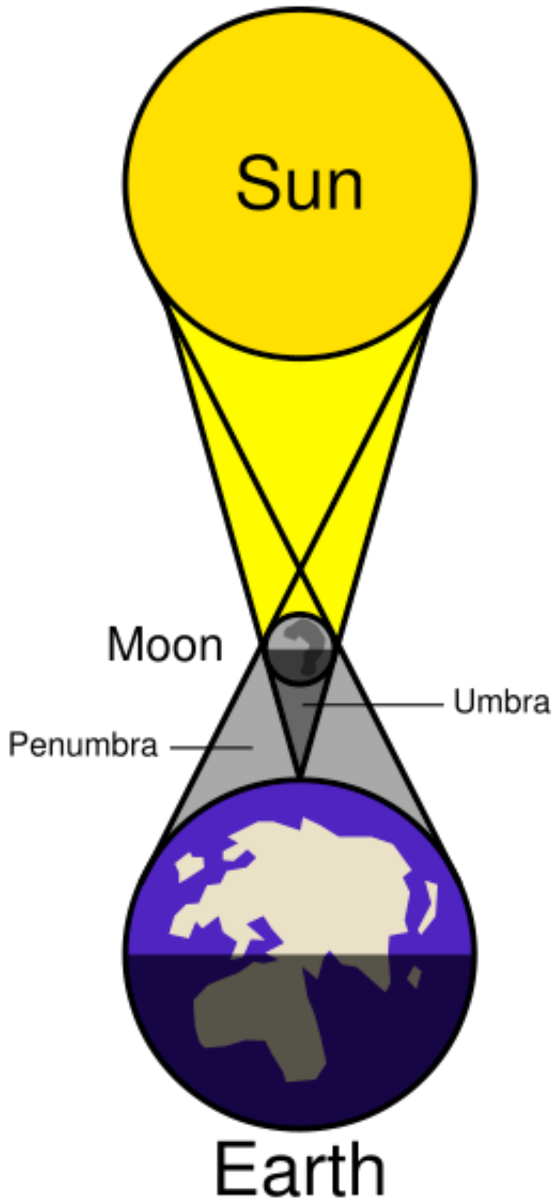
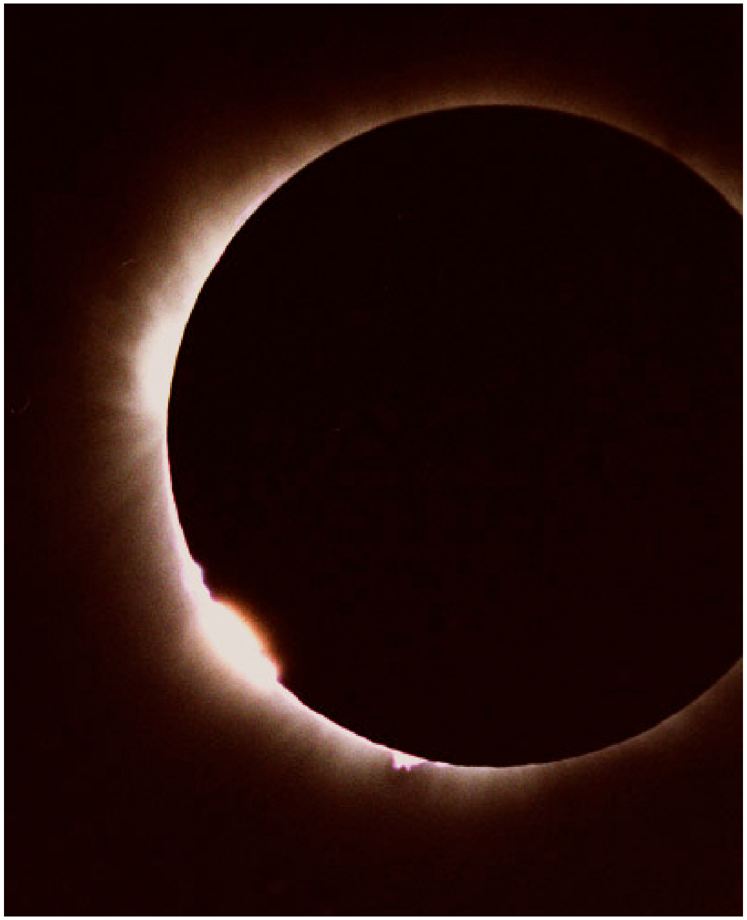
The sun and the moon have almost exactly the same angular diameter, which allows us to observe total solar eclipses.





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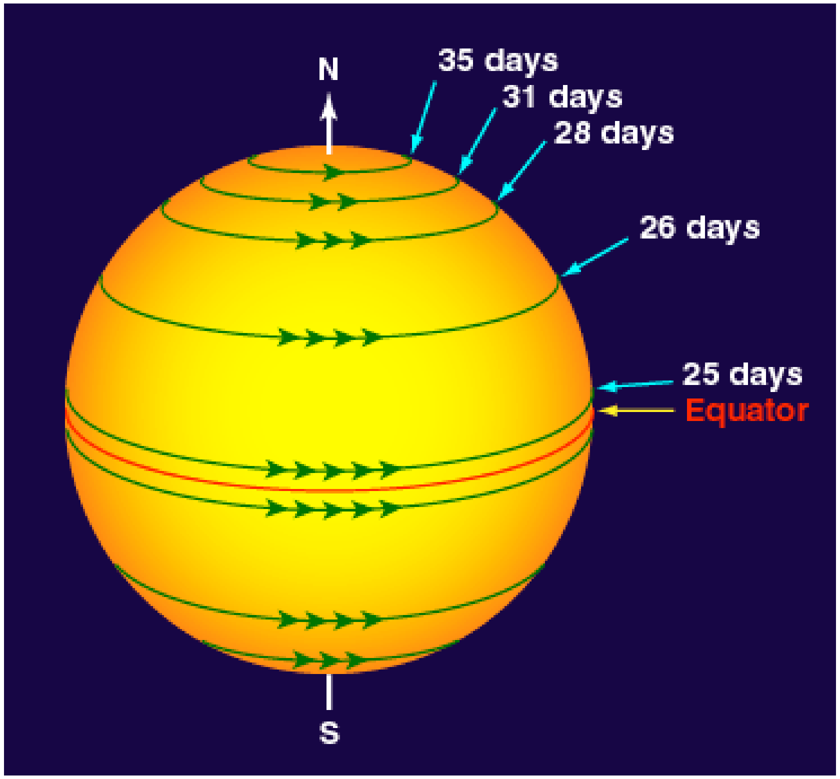
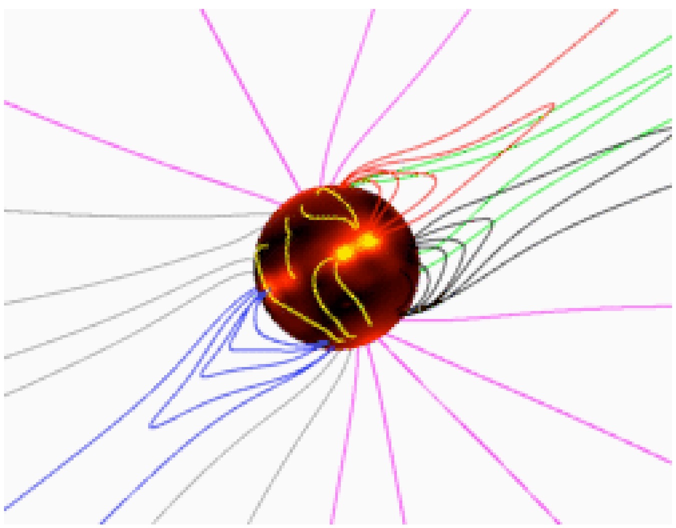
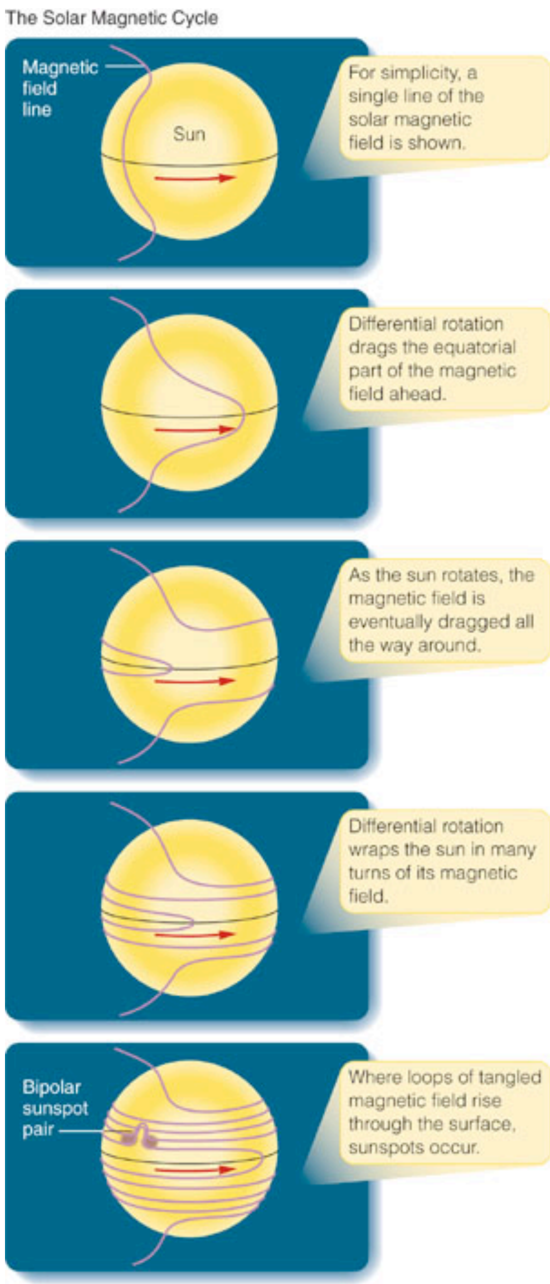
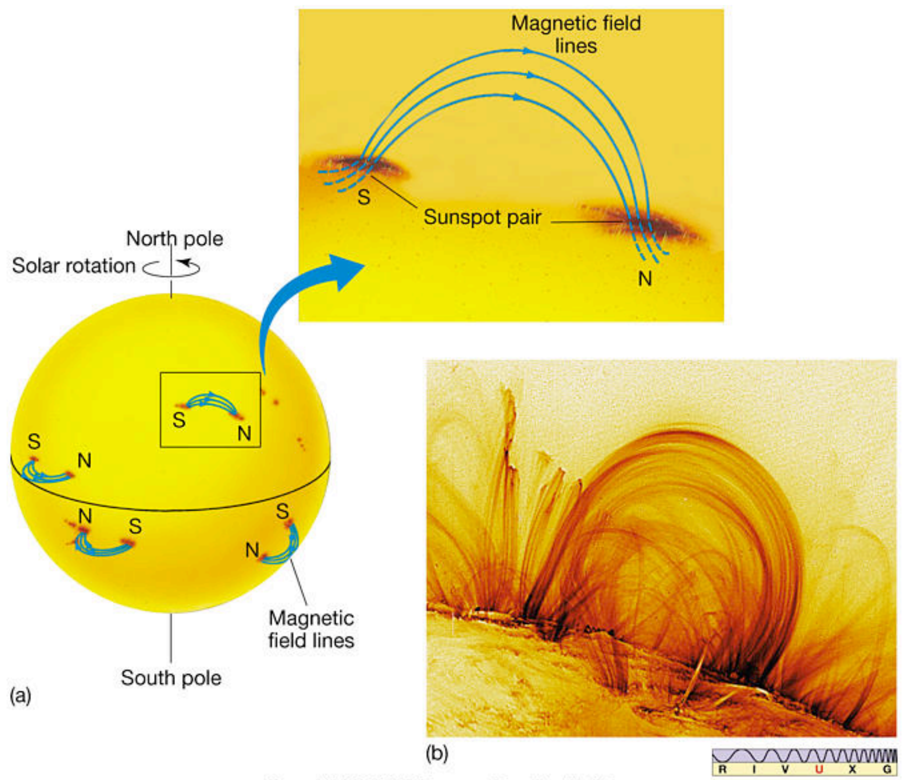


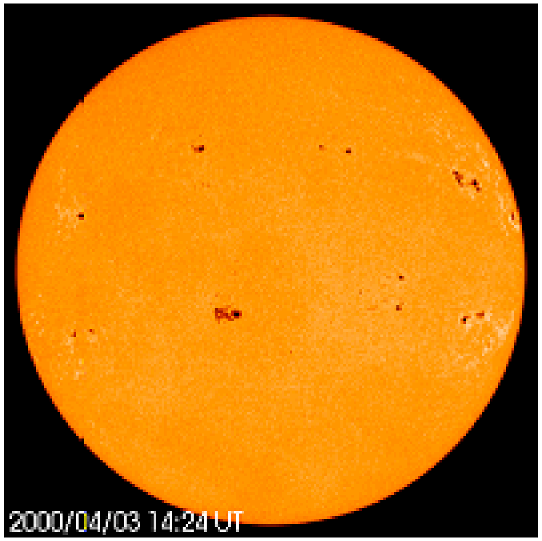


The sun undergoes differential rotation, that is the orbital period is longer at the poles than at the equator. The sun’s rotation stirs up the ionized plasma from which it is made, the motion of which forms a dynamo and creates a magnetic field

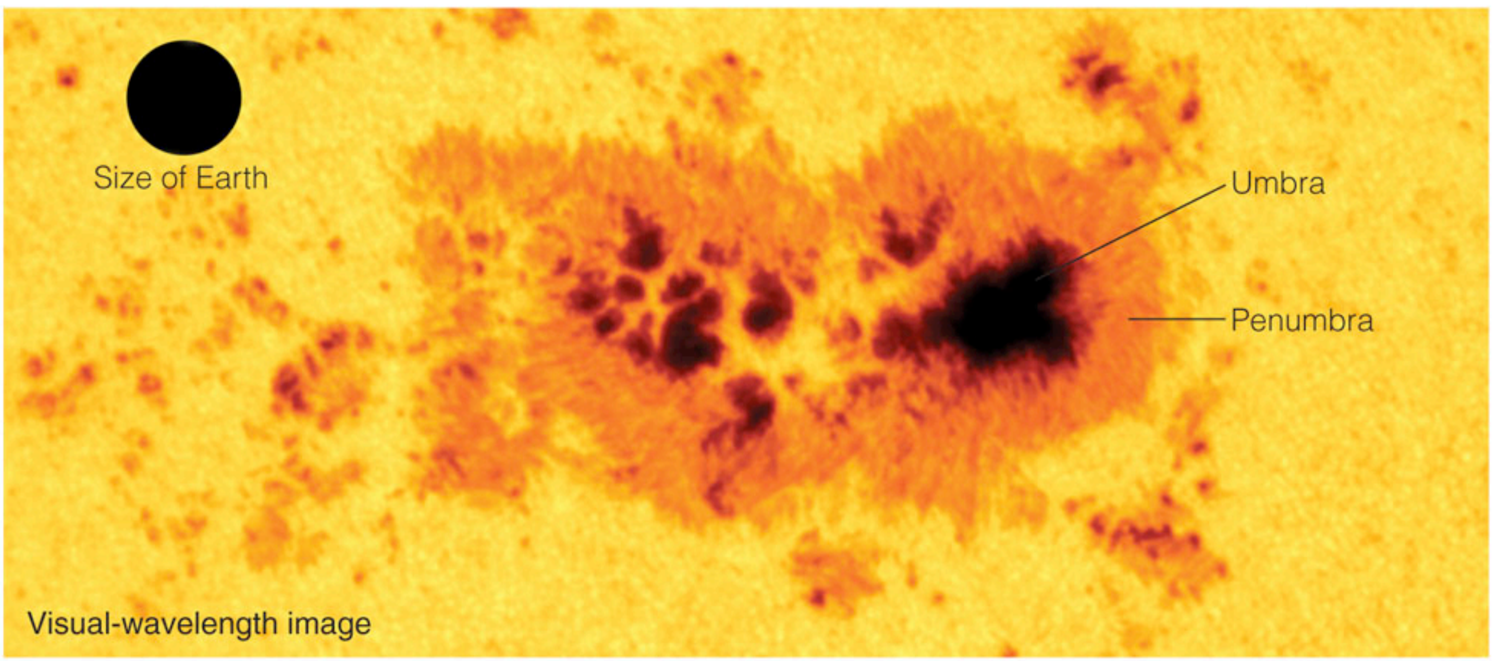


Differential rotation causes complex knots and loops to develop in the magnetic field. Localized pairs of magnetic poles can form, showing up as darker patches called sunspots.

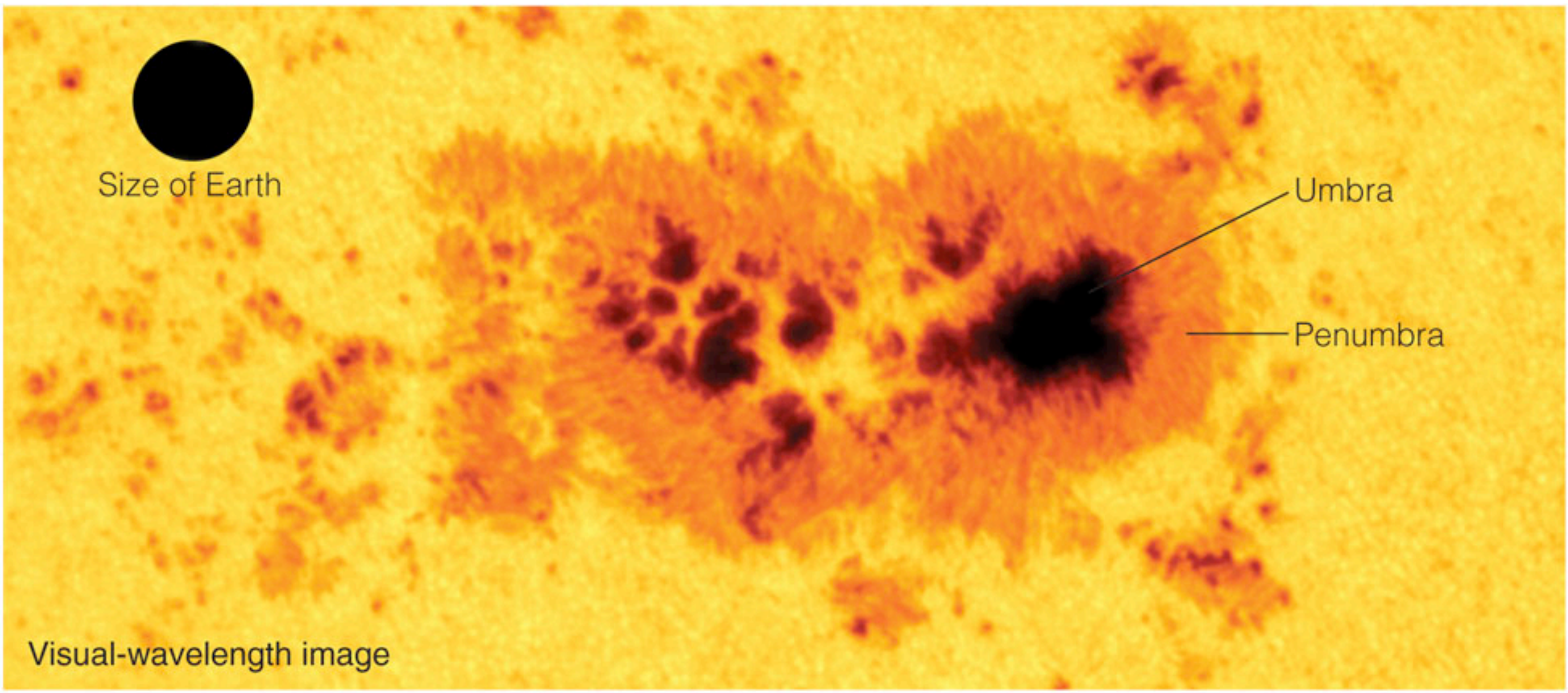




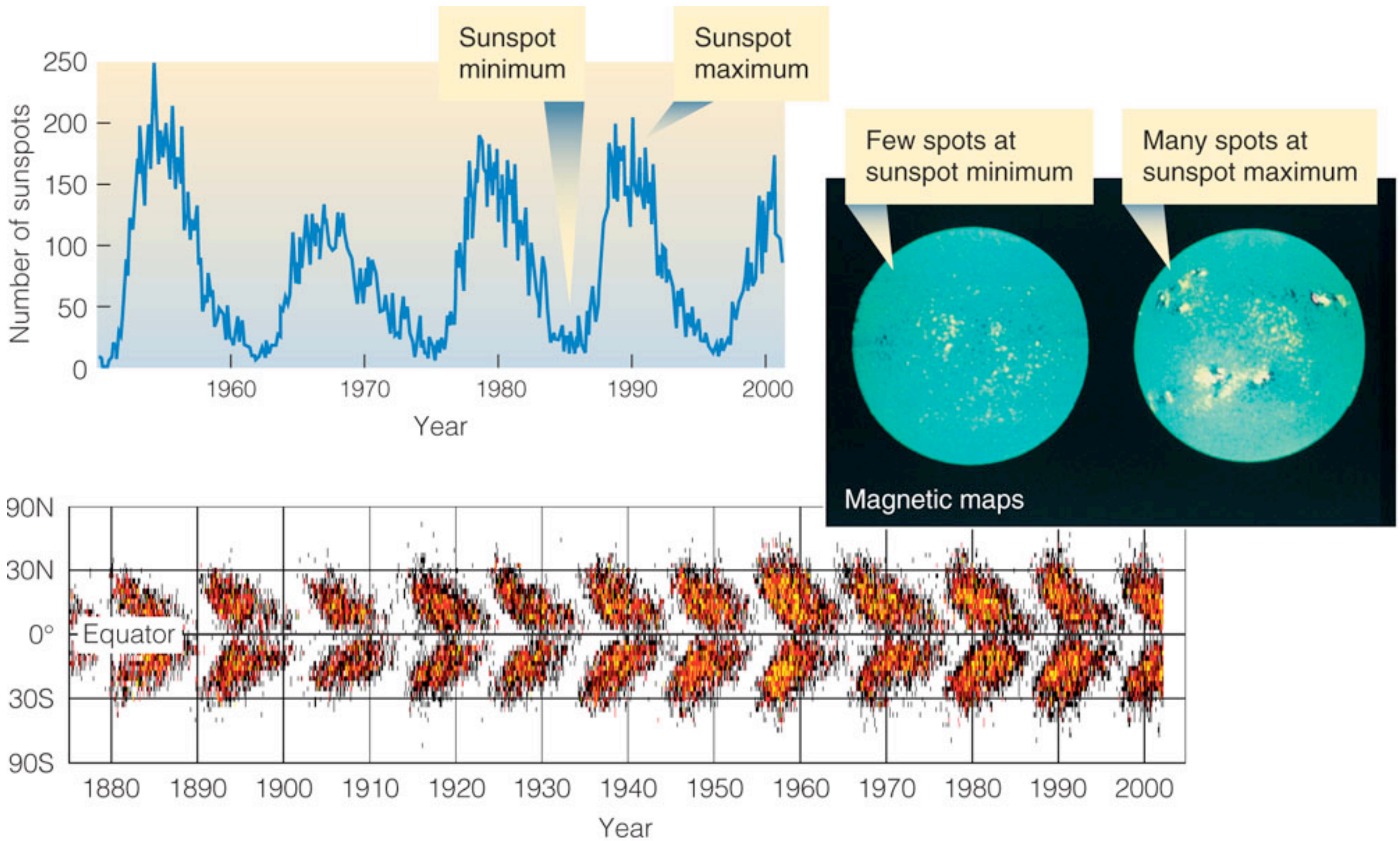
Sunspots are easily seen by projecting the image of the sun onto a screen and are about 1500K cooler than the rest of the surface of the sun. Although they look small, sunspots are about the size of the Earth (or larger) and last a few weeks up to a month or two.



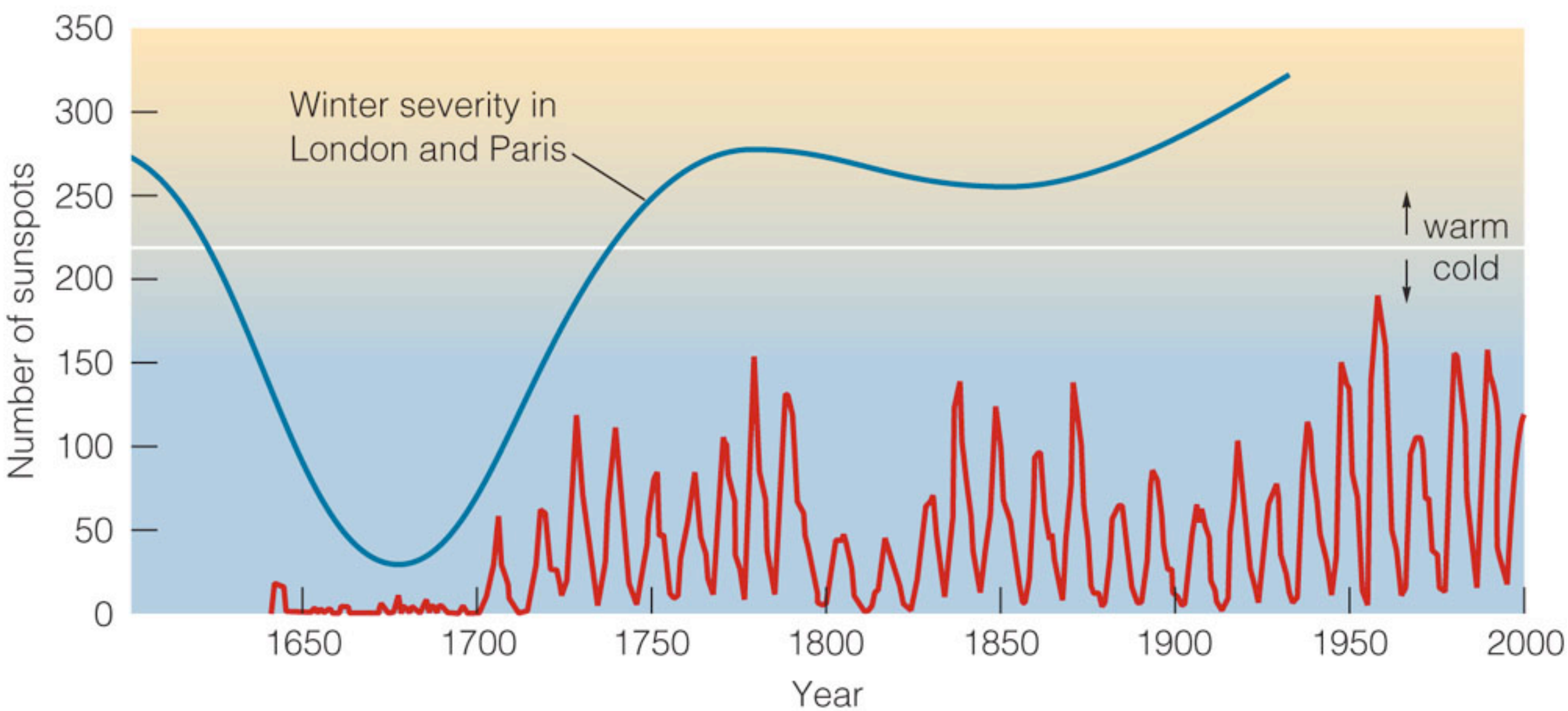
The centre of a sunspot is darker and called the umbra, whilst the outer region is called the penumbra. Because of differential rotation, sunspots near the sun's equator will have a shorter orbital period than sunspots near the poles.

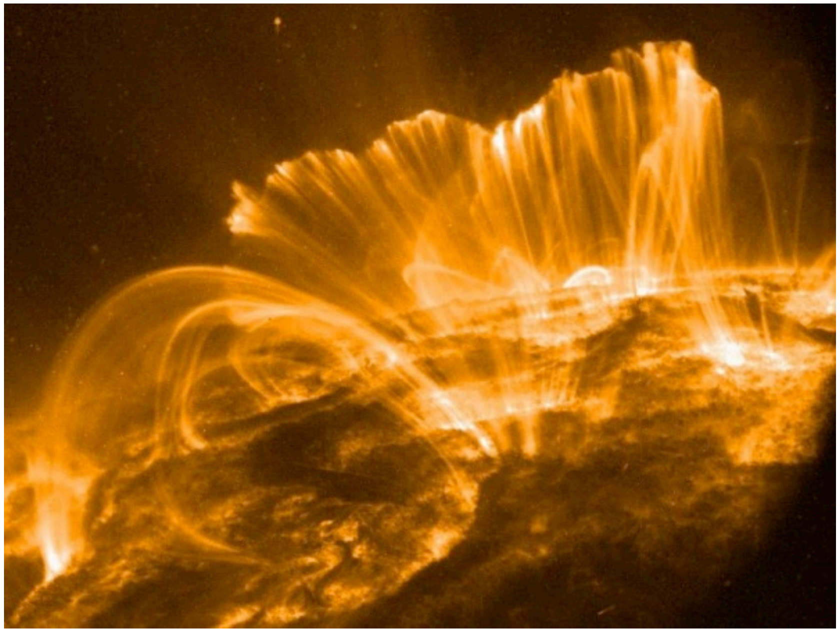


The number of sunspots is not constant, but varies in an 11 year cycle. Near sunspot minimum, most sunspots are near the equator, migrating to higher latitudes towards the maximum. This is represented in a "butterfly" diagram.



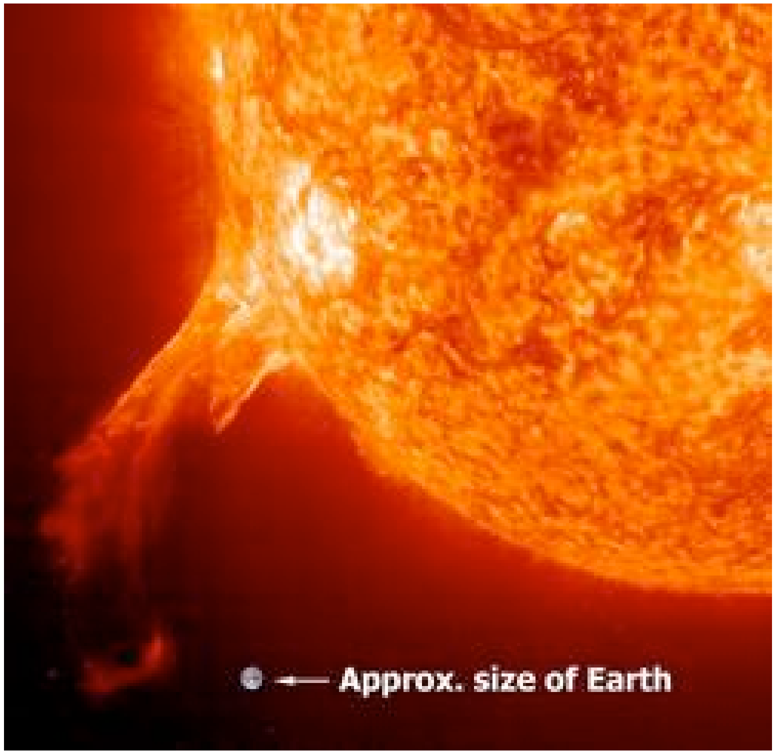
At some periods in history the sun spot cycle has apparently broken down. For example, between 1645 - 1715 there were very few sunspots observed and very cold winters were experienced. This period is called the Maunder minimum. Periods of ‘quiet sun’ mean reduction in other magnetically driven events, such as flares and prominences.

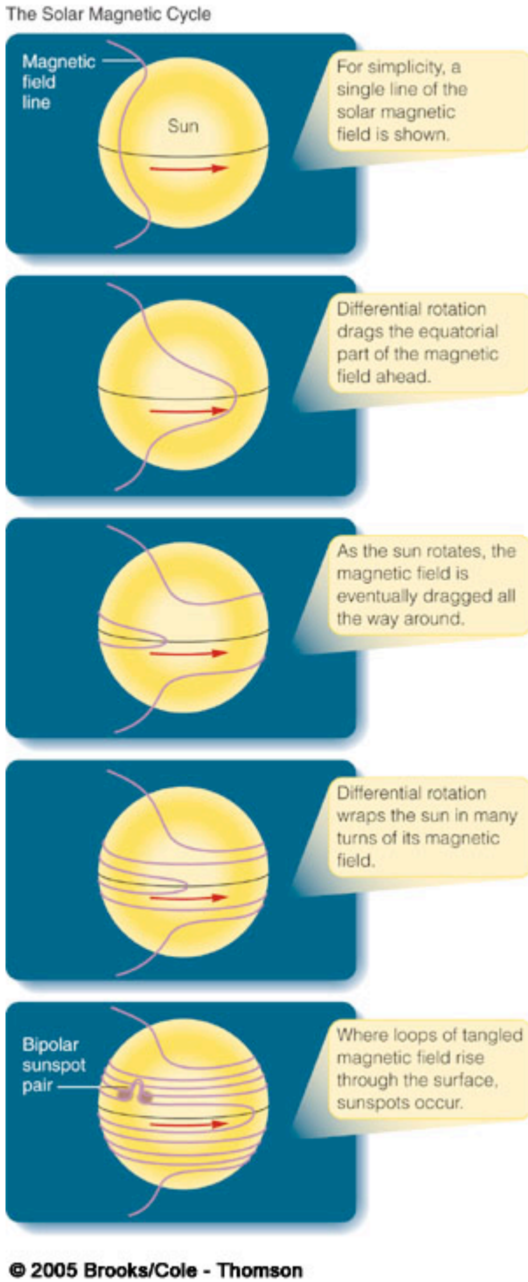




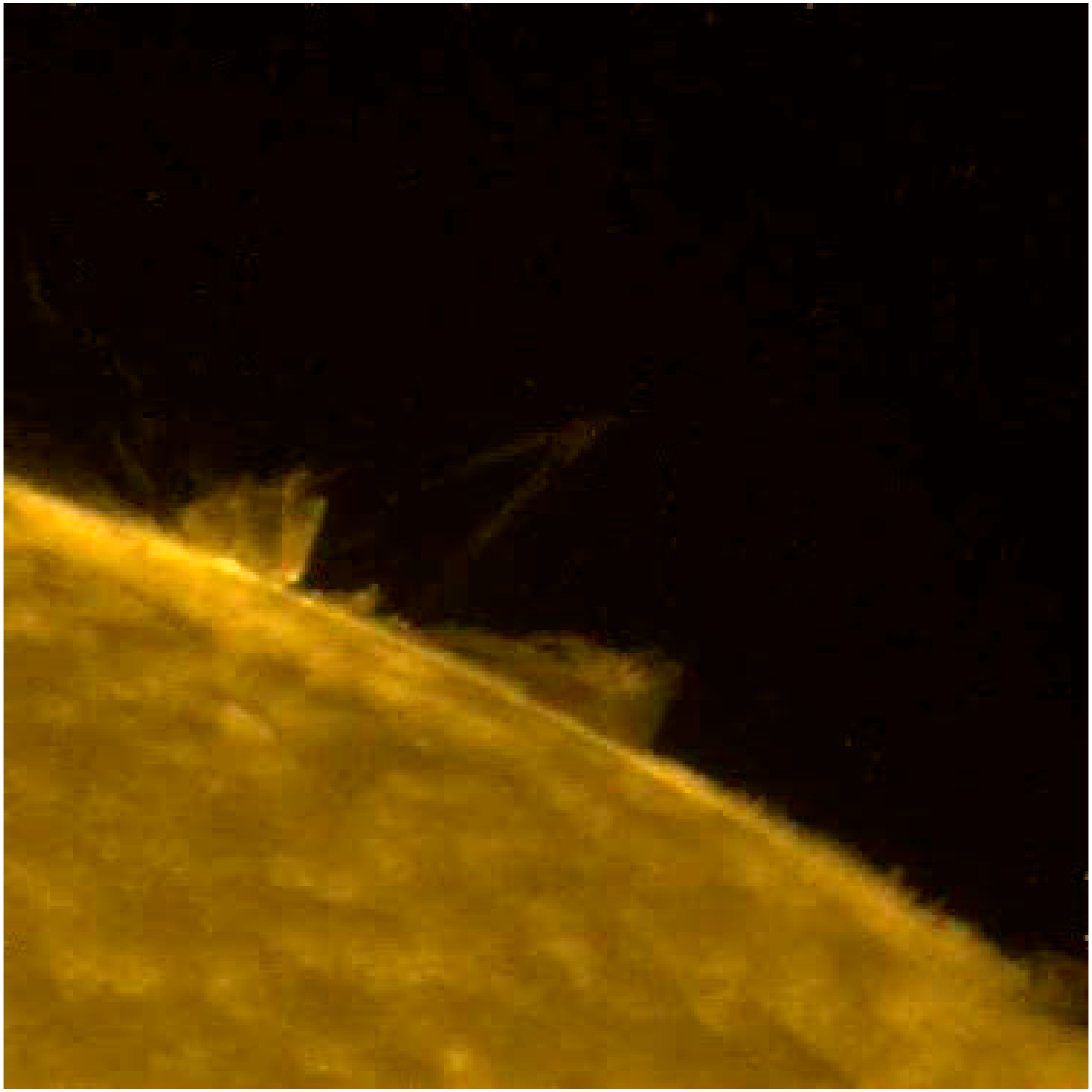
Solar prominences can be seen where ionized material is flowing along the magnetic field lines that connect sunspots.

When magnetic field lines reconnect (a localized north pole comes close to a local south pole) huge amounts of energy can be released in solar flares.

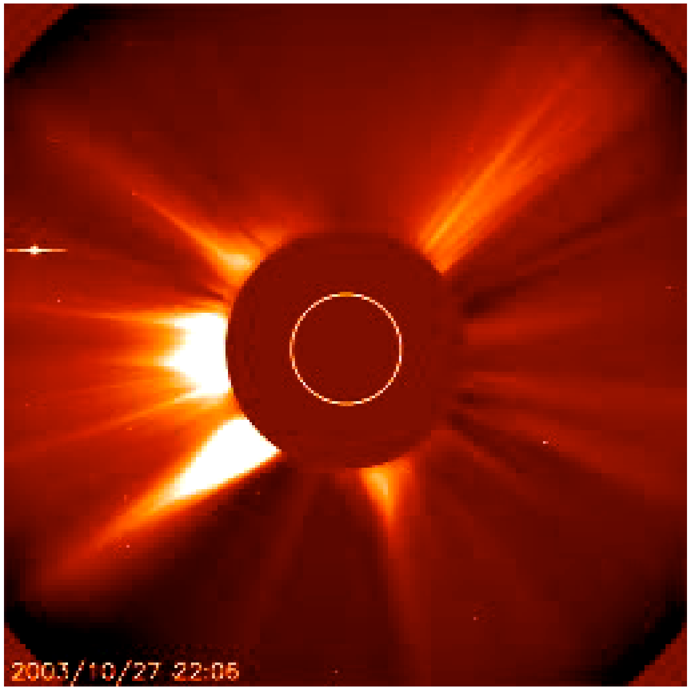


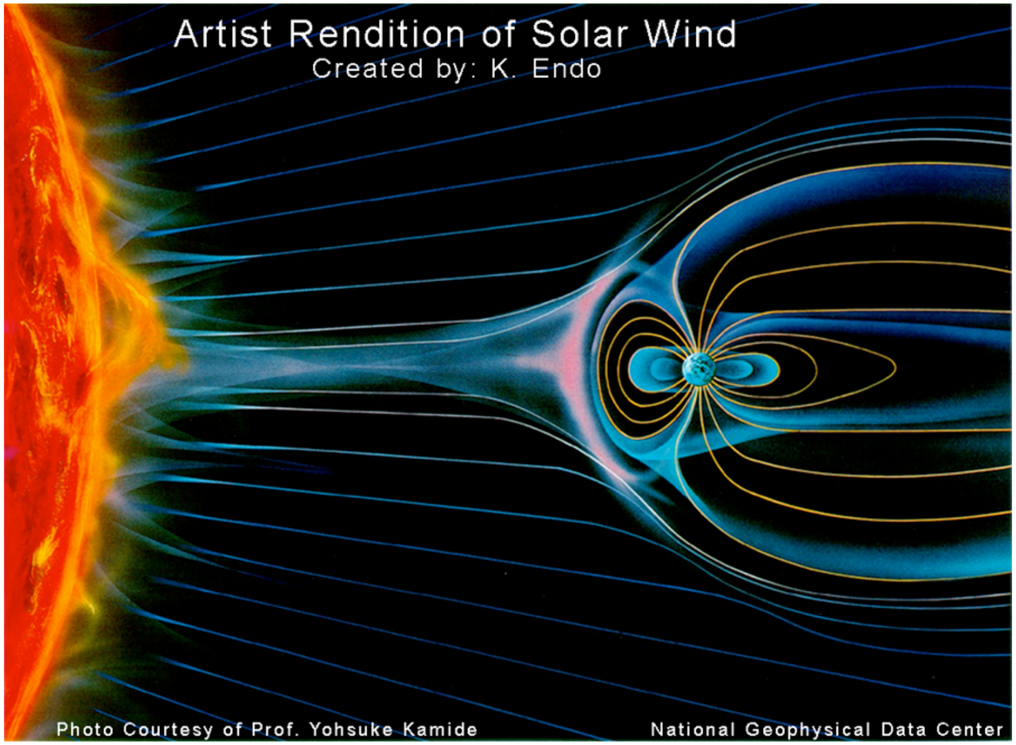


As the magnetic field lines become more and more tangled as more sunspots form close to the solar maximum, the sun actually reverses its poles! So, every 11 years or so, the north and south pole of the sun change places to 'iron out' the tangled field lines.

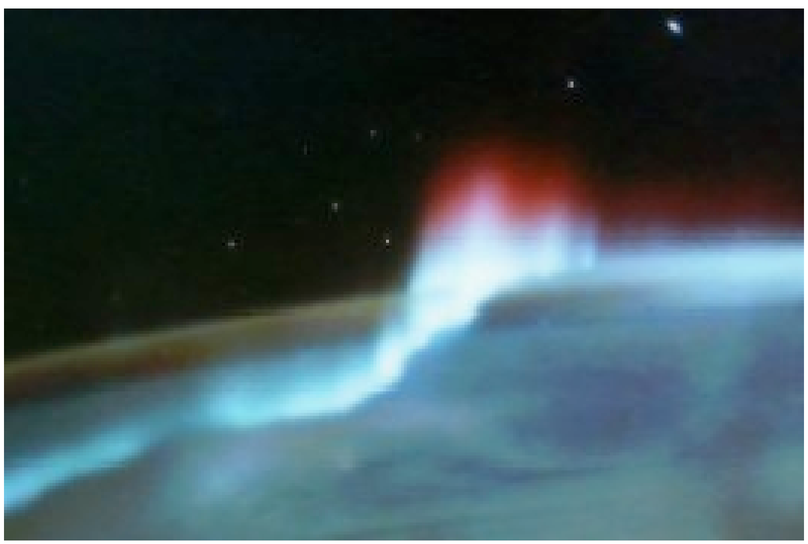


Flares are often associated with coronal mass ejections where large amounts of material are belched out into the solar wind. There is always a low level solar wind, which is a steady stream of ionized particles being lost from the sun. CMEs and flares cause the wind to intensify, which can result in auroras on Earth.





The earth is mostly protected from the solar wind's barrage of particles by its magnetic field. However, some particles get caught in the field and channeled towards the poles, ionizing gas atoms in the atmosphere and creating aurora.



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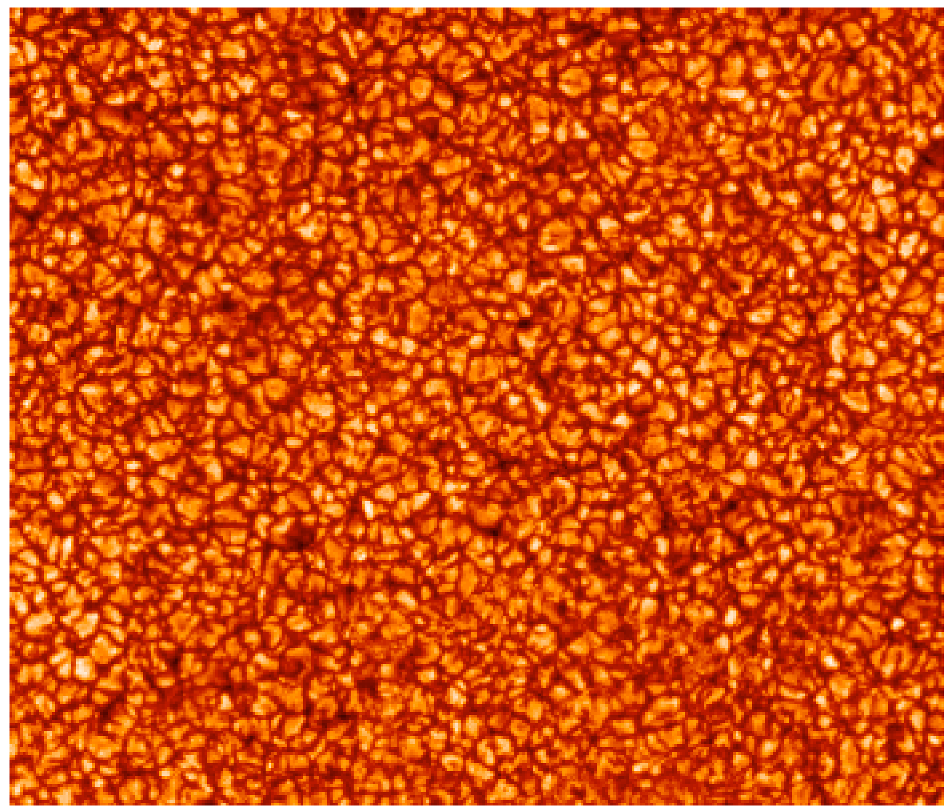
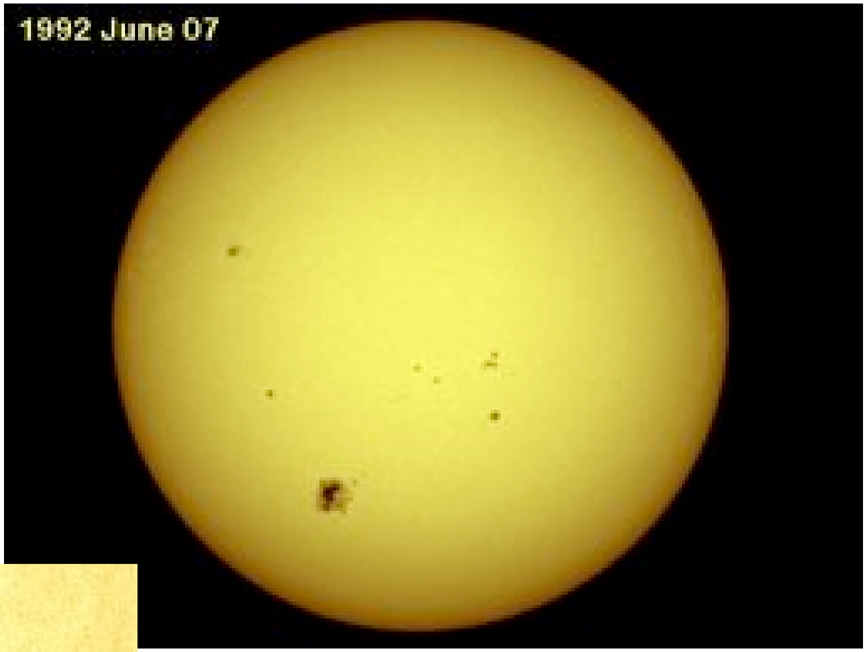
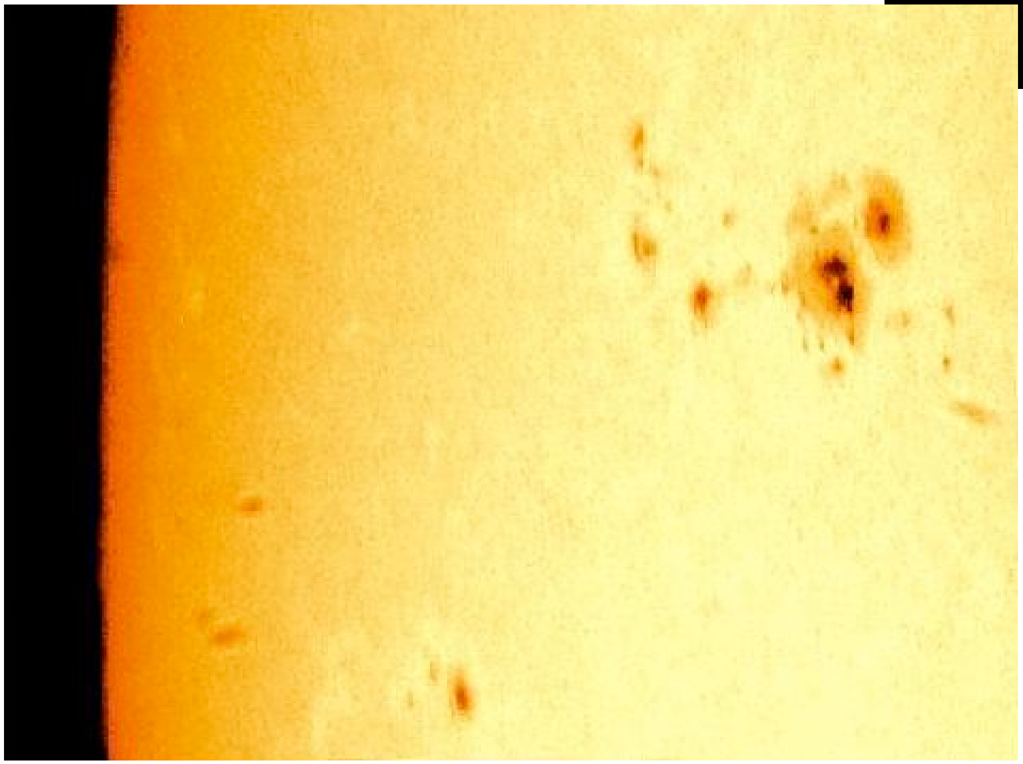
When we look at the sun, we are only seeing photons from its outer layer, called the photosphere. This is a thin layer, going only 500km deep. We can't see deep than this because there is a large amount of negative hydrogen ions (H^-) where a hydrogen atom has captured a free electron. This ion is easily destroyed by photons, but the process "uses" up the photons. This means that photons don't get very far through the sun's atmosphere!

Remember, the entire sun is made of a gas, and this gas is constantly in motion. We see granulation on the sun's surface where convection cells are churning up the photosphere. These granules can be a significant fraction of the earth's size!



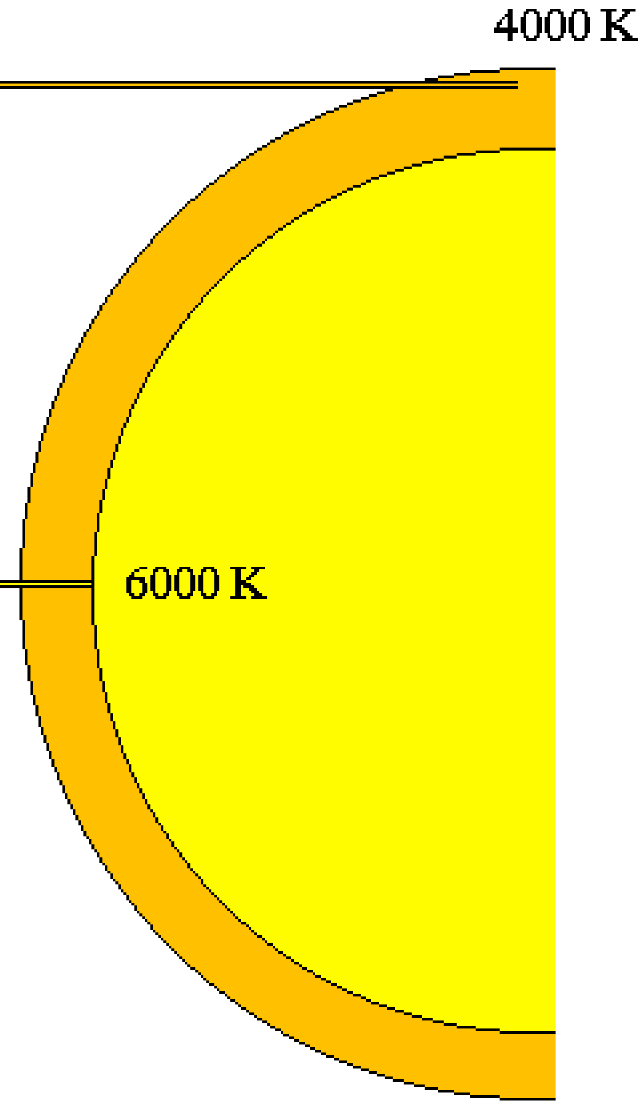
Notice that an image of the sun appears darker at the edges than in the centre, this effect is called limb darkening.





This effect can be explained by the different layers of the sun we are able to see at different locations across its face.

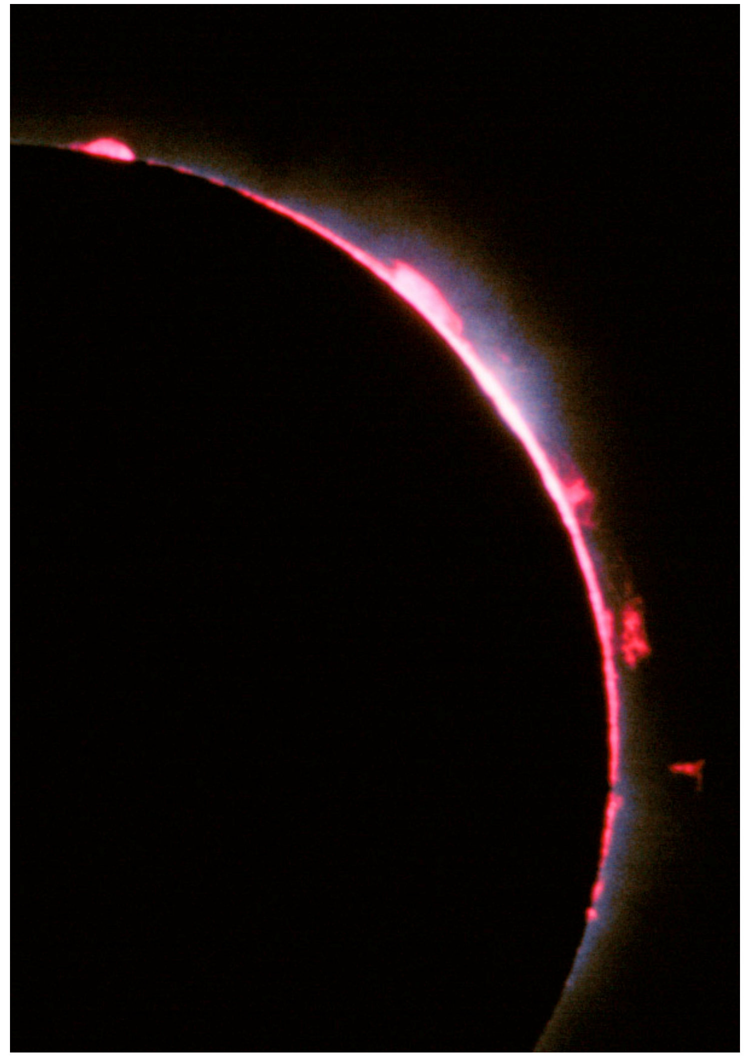
Limb Darkening



light observed near the limb of the Sun is emitted from cooler regions of the photosphere – from Planck's curve we know that this light will be dimmer than light emitted from the hotter regions

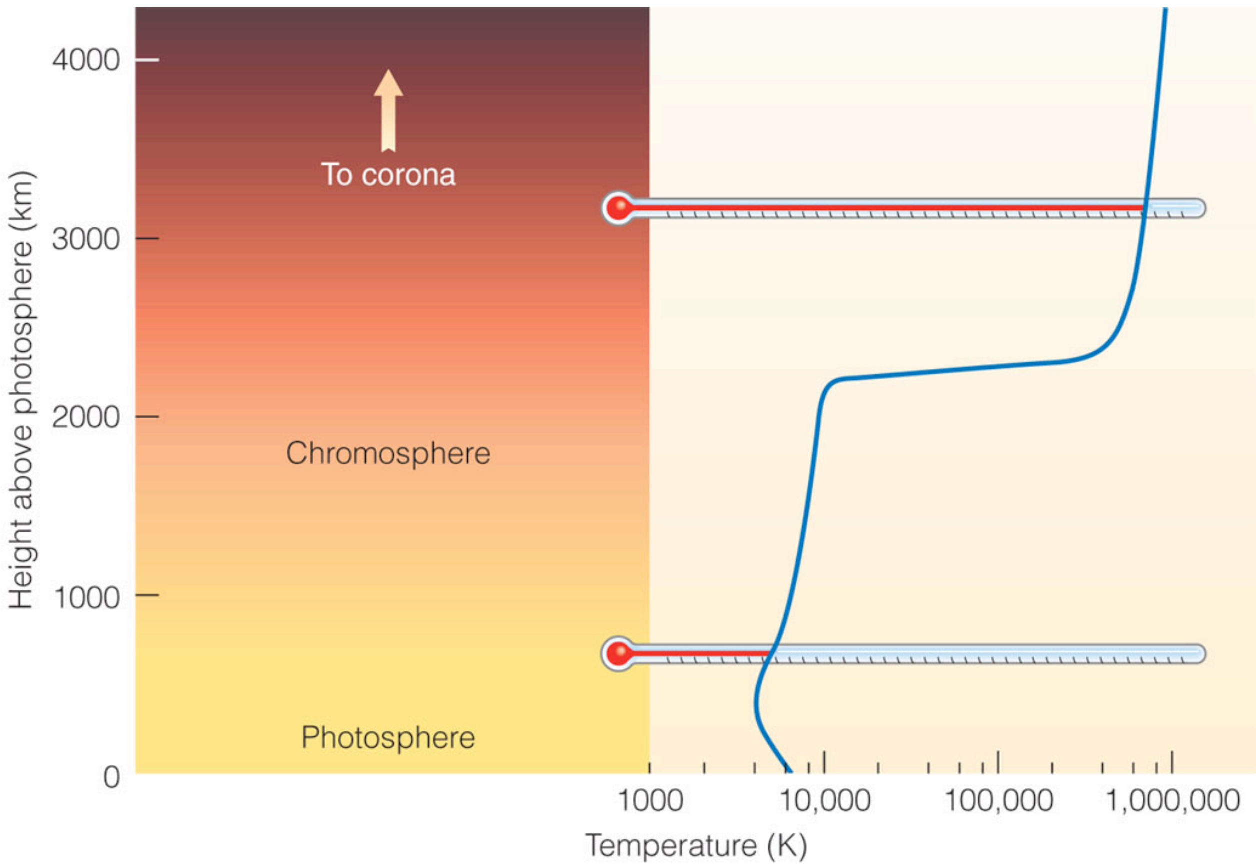
the final effect is that the Sun's limb looks darker than the middle regions

Above the photosphere is the chromosphere, a less dense layer that extends about half the size of the earth into the sun's atmosphere. We can only see this faint low density gas during a solar eclipse.

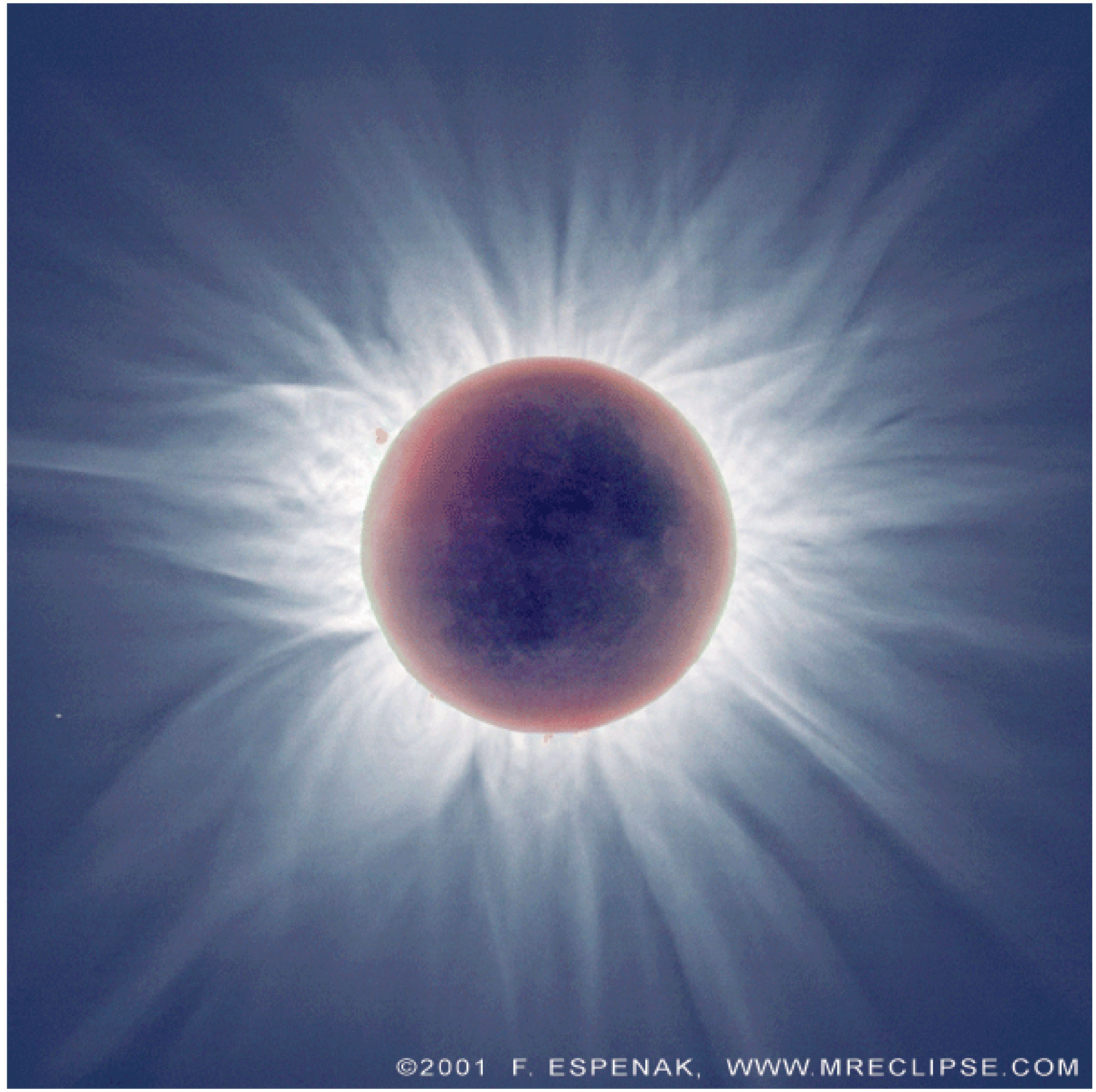


"Chromo" is Greek for colour, and indeed the hydrogen Balmer lines give this hot, diffuse, excited gas a pink colour.

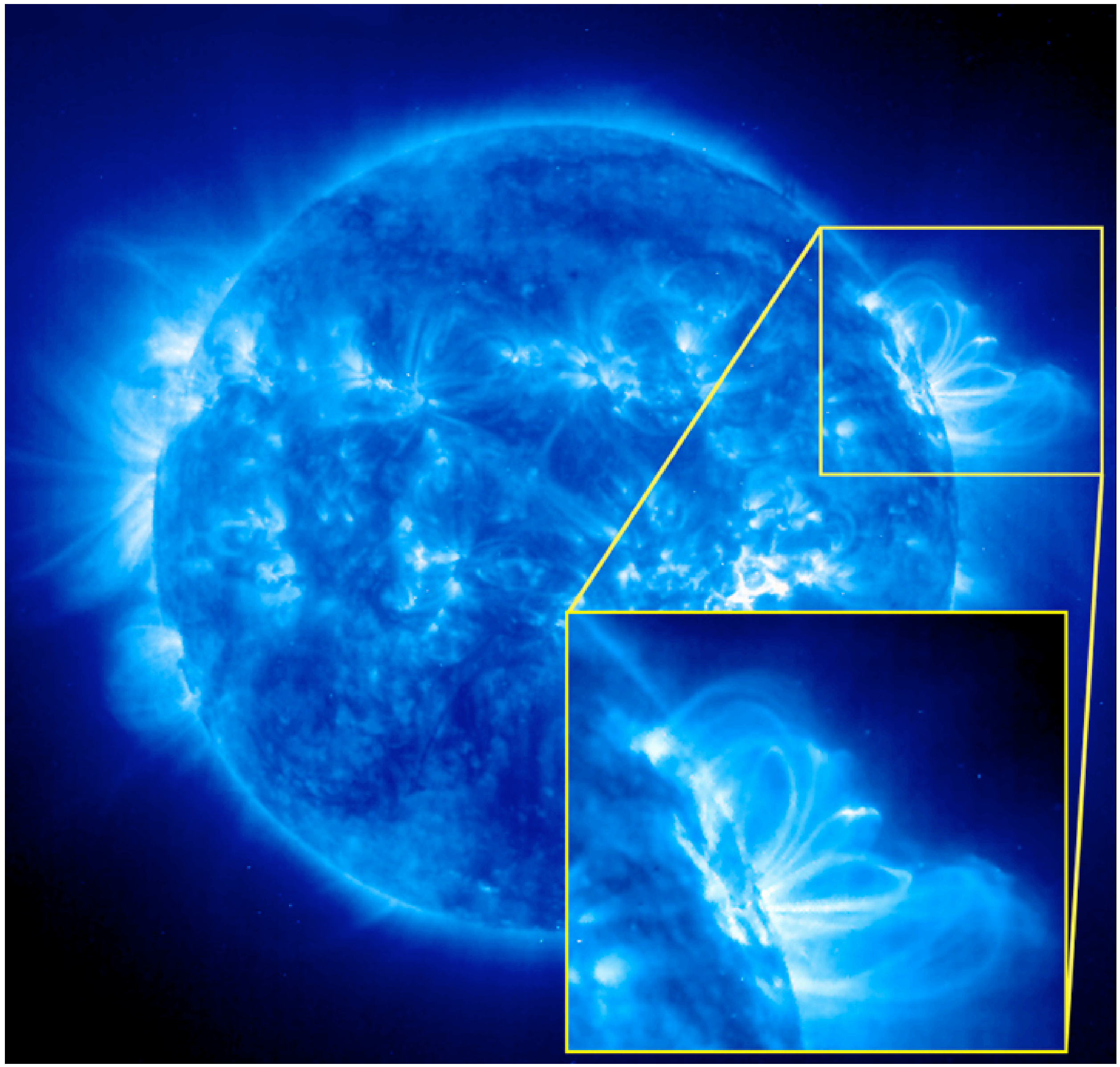
Almost immediately, the chromosphere gets hotter as you extend further into the sun's atmosphere. The corona is the outermost part of the atmosphere and also the hottest with a temperature of ~1 million degrees.



Just like the chromosphere, we only get a good view of the corona during solar eclipses. However, because the corona is so hot, it does not emit most of its light in the optical part of the electromagnetic spectrum.



This picture of the sun was taken in the far ultra-violet.



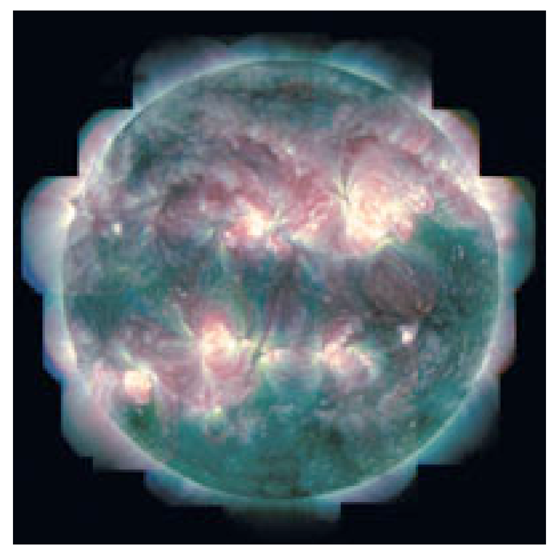
At what wavelength does the corona emit most of its light, if its temperature is 1 million degrees? Recall Wien's law:

$$\lambda_{max} = \frac{3000{,}000}{T}$$

So for T=1000,000 K:

$$\lambda_{max} = \frac{3000{,}000}{1000{,}000} = 3 \text{ nm}$$

This is in the X-ray part of the electromagnetic spectrum, even more energetic than the UV. Here is a picture of the sun taken in X-rays:



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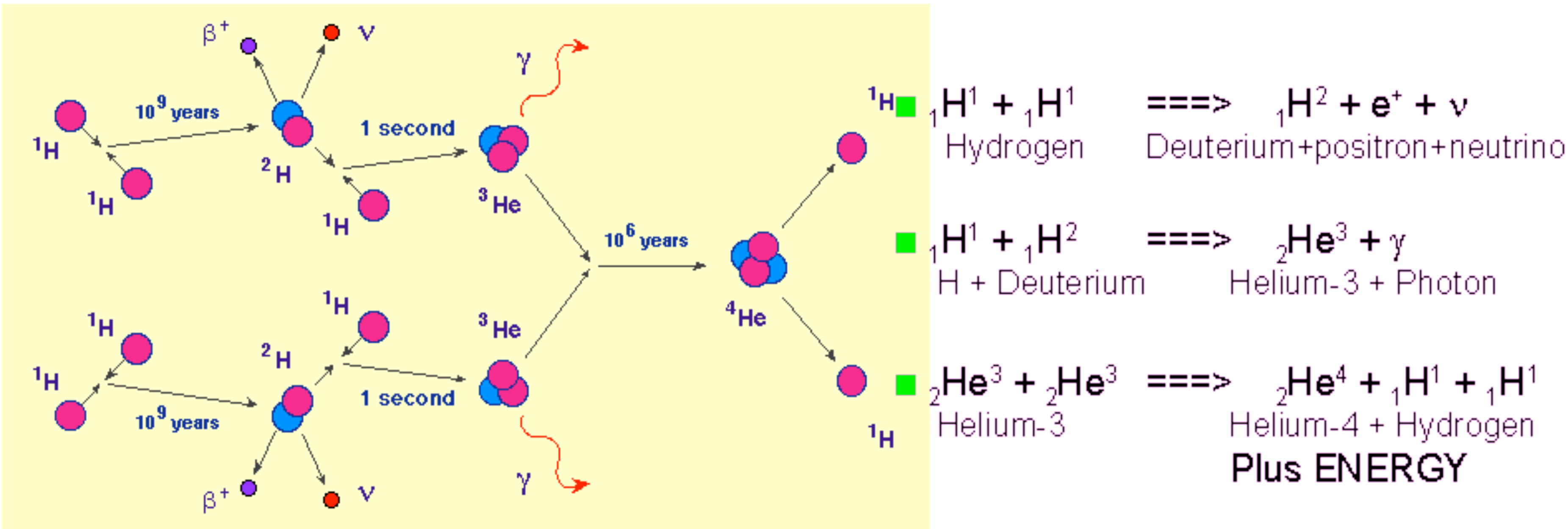
However, the hottest part of the sun is its core. This is where the nuclear fusion reactions that fuel the sun occur.



The basic reaction that occurs in the sun's core is called the proton-proton (or p-p) chain. It involves the conversion of hydrogen nuclei into a helium nucleus.

Energy From Fusion Reactions

But how does this reaction make energy? If we add up the mass of the 4 H nuclei that are used in the p-p chain to make He, we find some mass is missing.

4 H nuclei = 6.693×10^{-27} kg
1 He nucleus = 6.645×10^{-27} kg
difference = 0.048×10^{-27} kg

This difference in mass is called the mass defect. When nuclei undergo fusion, some of their mass is converted to energy. The same amount of energy is needed to break the nucleus apart. This energy is called the binding energy.

Mass defect can also be expressed as a fraction. E.g. here it is 0.007

The equivalence of mass and energy was predicted by Einstein in his famous equation: $E=mc^2$. Here, E is the binding energy (i.e. the amount of energy created during fusion), mass is the mass defect and c is the speed of light.

Note that the units for this calculation are mass in kg, c in m/s and energy in J.

In the case of hydrogen fusion in the p-p chain (4H to 1 He), we saw that the mass defect is 0.048×10^{-27} kg. So the energy released from a single reaction is $0.048 \times 10^{-27} \times (3 \times 10^{8})^{2} = 0.43 \times 10^{-11}$ Joules.

This is a very small amount of energy so many reactions are needed in order to keep a star burning. In the sun, there are 10^{38} reactions per second!

Example: How much energy is produced when the sun converts 500 g of mass into energy?

Using $E=mc^2$, energy $= 0.5 \times (3 \times 10^{8})^{2} = 4.5 \times 10^{16}$ J.

How many megaton bombs is this equivalent to if a 1-megaton bomb produces 4×10^{15} J?

$4.5 \times 10^{16} / 4 \times 10^{15} = 11$ megaton bombs

Example: In a star, 100 kg of hydrogen is fused into helium. How much energy is liberated? How many kg of helium are produced?

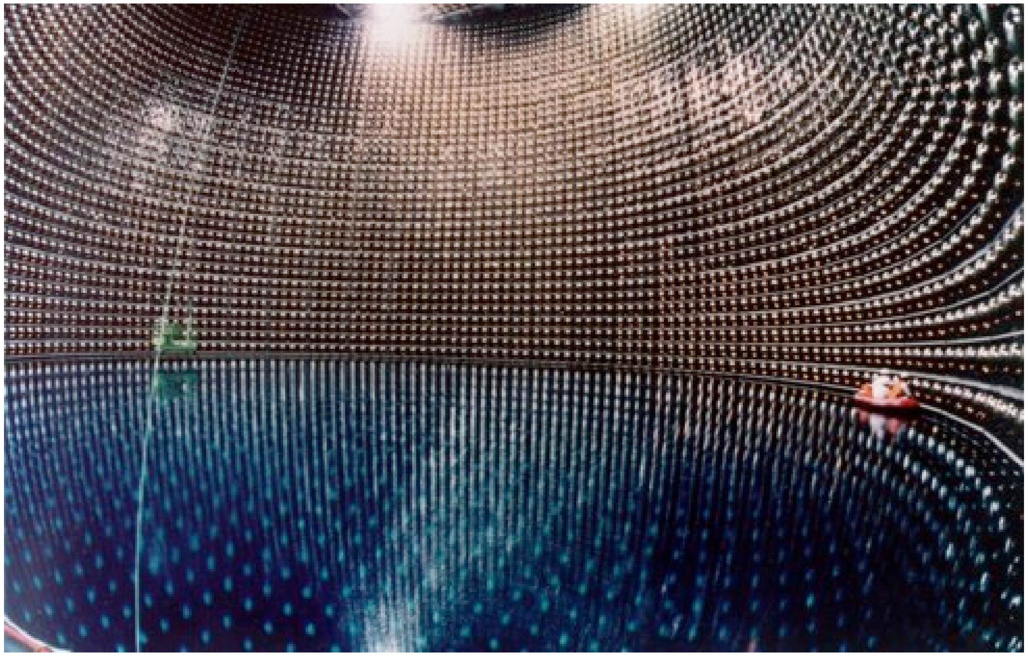
Here, the easiest thing to do is use the mass defect, i.e. the fraction of mass that is turned into energy. We saw that for H and He, this is 0.007.

Using $E=mc^2$, $E = 0.007 \times 100 \times 300000000^2 = 6.3\times10^{16}$ J.

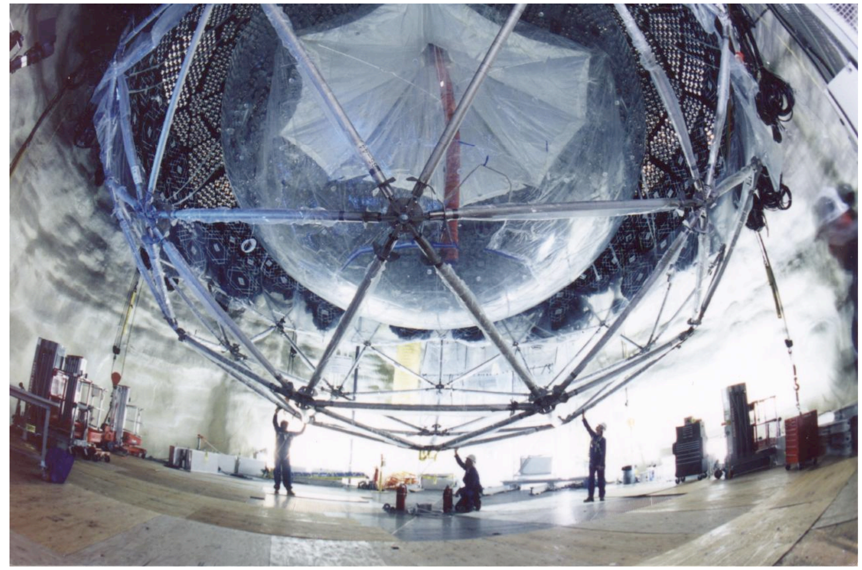
To calculate the amount of He produced, we again use the mass defect as a fraction. The mass defect tells us that 0.007 of the initial amount is converted to energy. That is 0.007 x 100 kg = 0.7 kg. This amount is therefore "missing", so 100-0.7=99.3 kg of He are produced

Based on the reactions we believed to occur in the core of the sun, we could predict how many neutrinos should be produced. The problem is, neutrinos could travel through several light years of lead without interacting with anything! Early neutrino observatories were built in old mine-shafts filled with cleaning fluid! Occasionally, a neutrino would interact with a chlorine atom and cause a detectable flash.

These experiments lead to the solar neutrino problem: we only detected 1/3 of the neutrinos that were predicted.

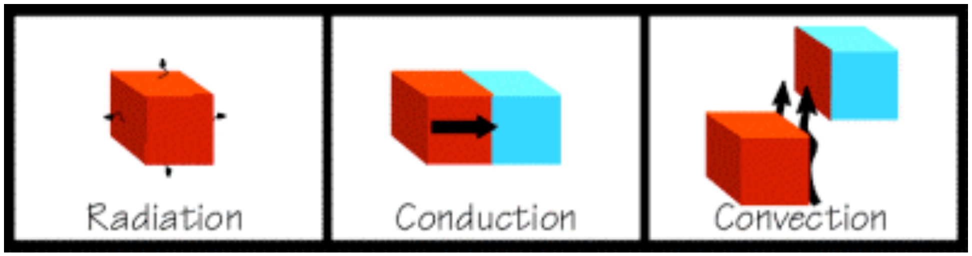


A Canadian facility (the Sudbury Neutrino Observatory) has helped to solve this problem. The answer lies in the fact that our theory predicts only electron neutrinos should be



produced in the sun (and those are the types of neutrinos detected by early experiments). However, we now know that neutrinos can change their flavour between one of 3 types: electron, muon and tau. So, early experiments missed the 2/3 of non-electron type neutrinos! New experiments like SNO are filled with pure water, rather than cleaning fluid and can detect all 3 types of neutrino.

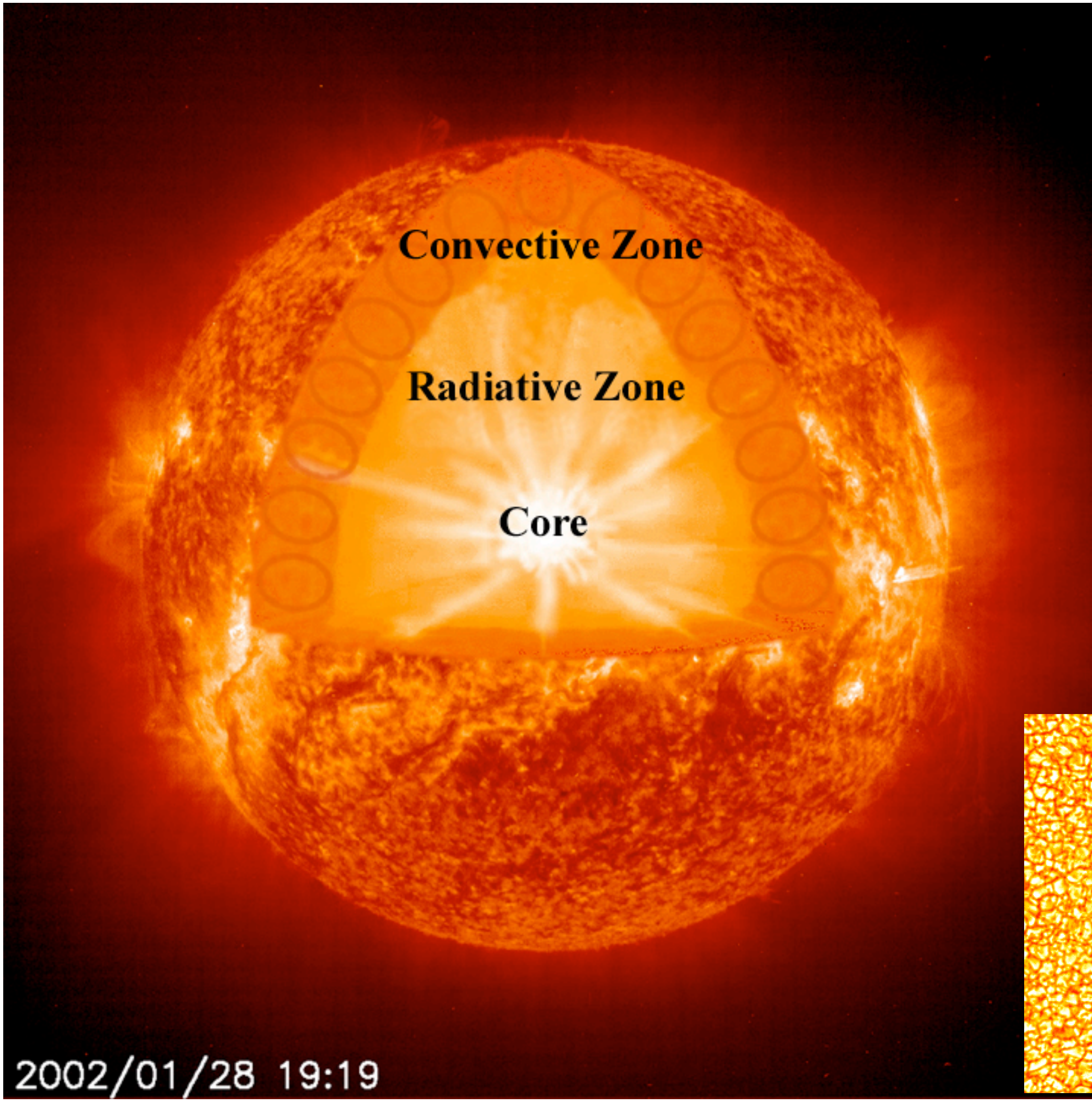
The thermal energy produced in star's core has to be transported to the surface. Thermal energy can be moved around via 3 processes: conduction, convection and radiation



Conduction: heat is transferred by the vibration of particles in close contact. E.g. heating along a metal bar.

Convection: heat is transferred by the movement of particles from a warm to a cold environment. E.g. air currents on a warm day

Radiation: heat is transferred by photons. E.g. sunlight. This is the only one that works in a vacuum.



Remember, it is those convection cells that cause granulation in the photosphere.