Lives of the Stars Lecture 4: The Sun

– a typical star

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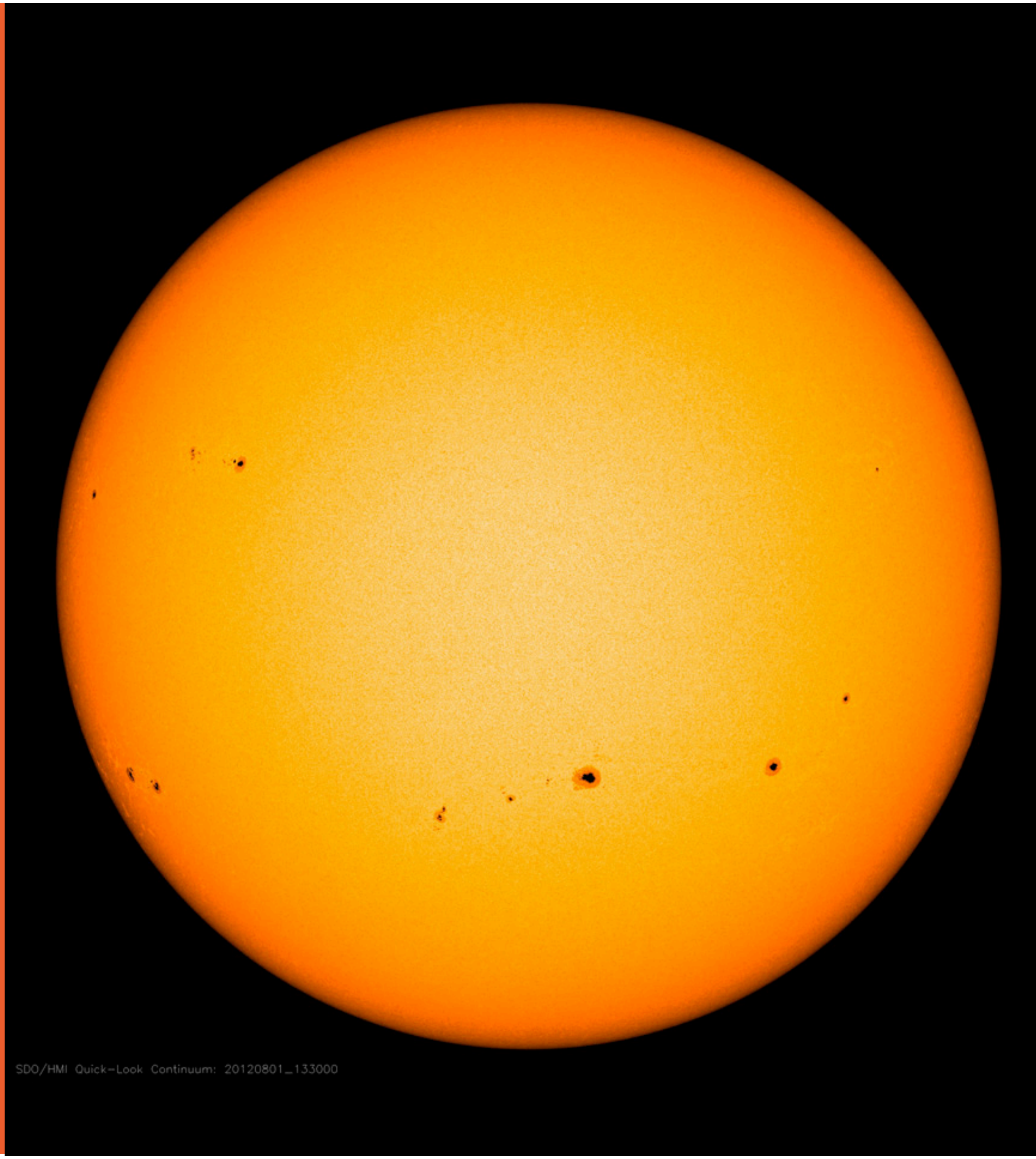
THE UNIVERSITY OF SYDNEY

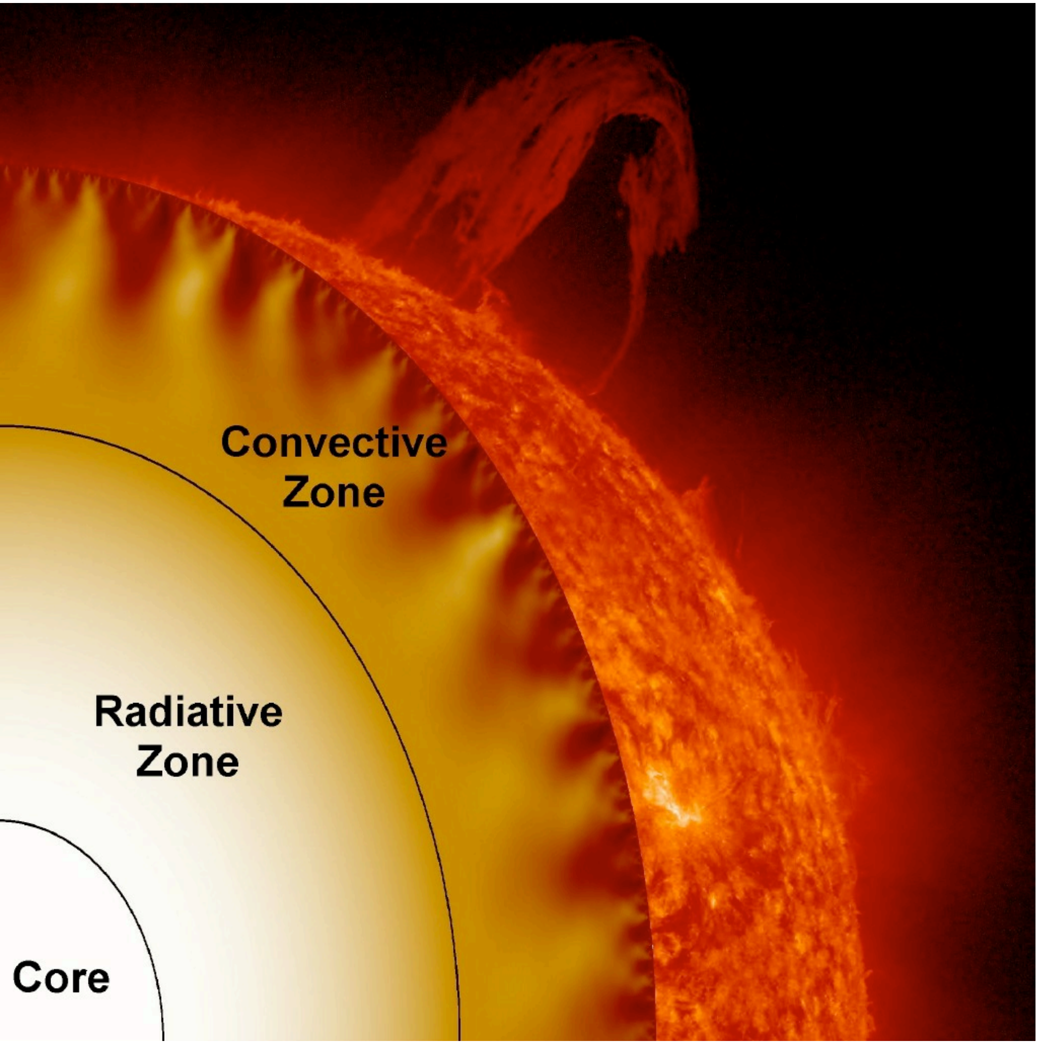


The Sun is a G2V main sequence star comprising about 99.86% of the total mass of the Solar System. Its mass is 330,000 times that of the Earth, and a diameter 109 times that of the Earth.

The Sun rotates once every 25.4 days at the equator, with the period of rotation increasing to about 36 days near the pole.

Its axis of rotation is inclined 8° to the ecliptic (the plane in which the planets orbit).

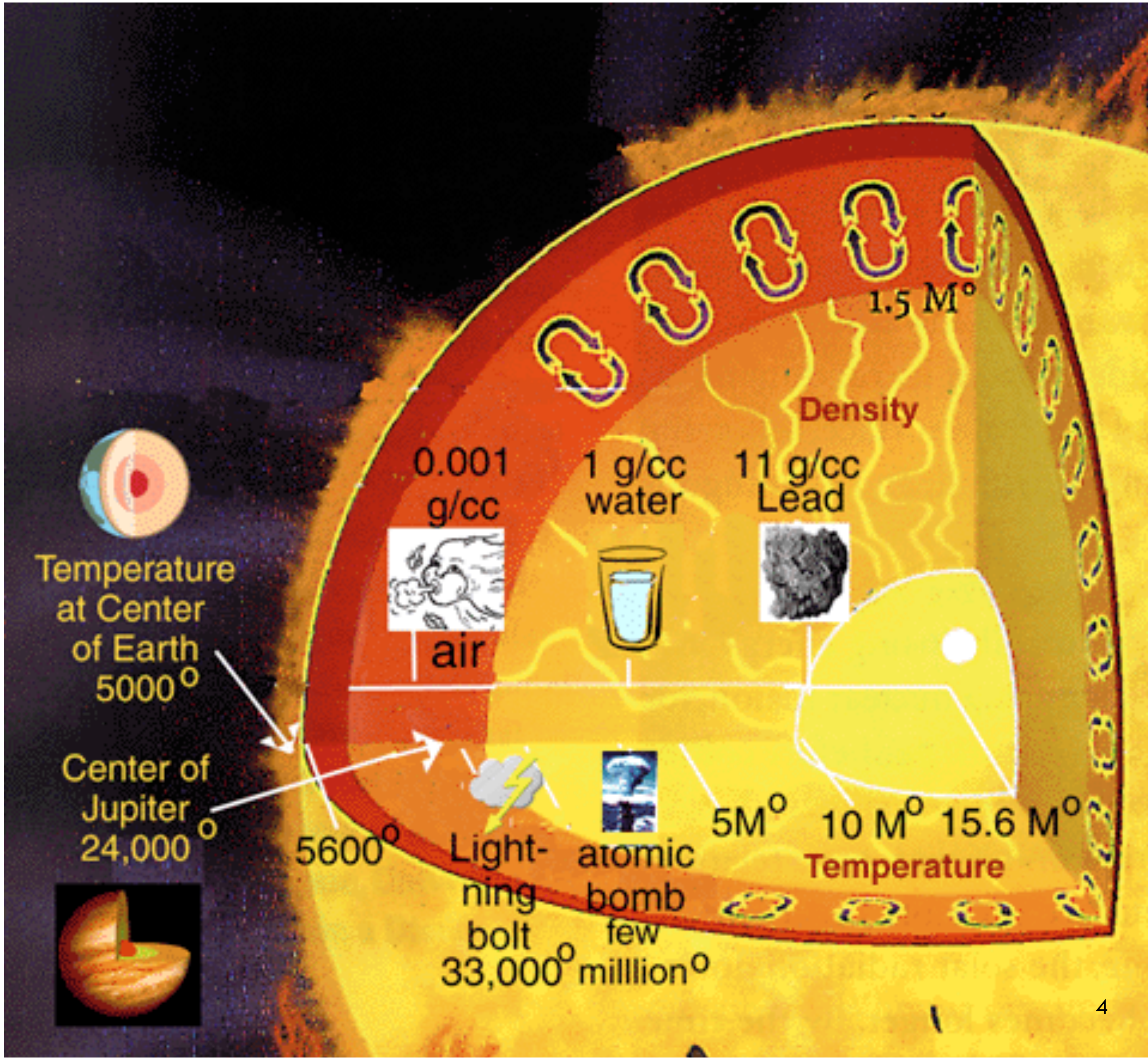
The Sun is divided into six regions:



- *core*
- *radiative zone*
- *convection zone*
- *photosphere* (the visible surface)
- *chromosphere* (the lower atmosphere)
- *corona* (the upper atmosphere)

This picture summarises how the temperature and density of the Sun change from its interior to the surface.

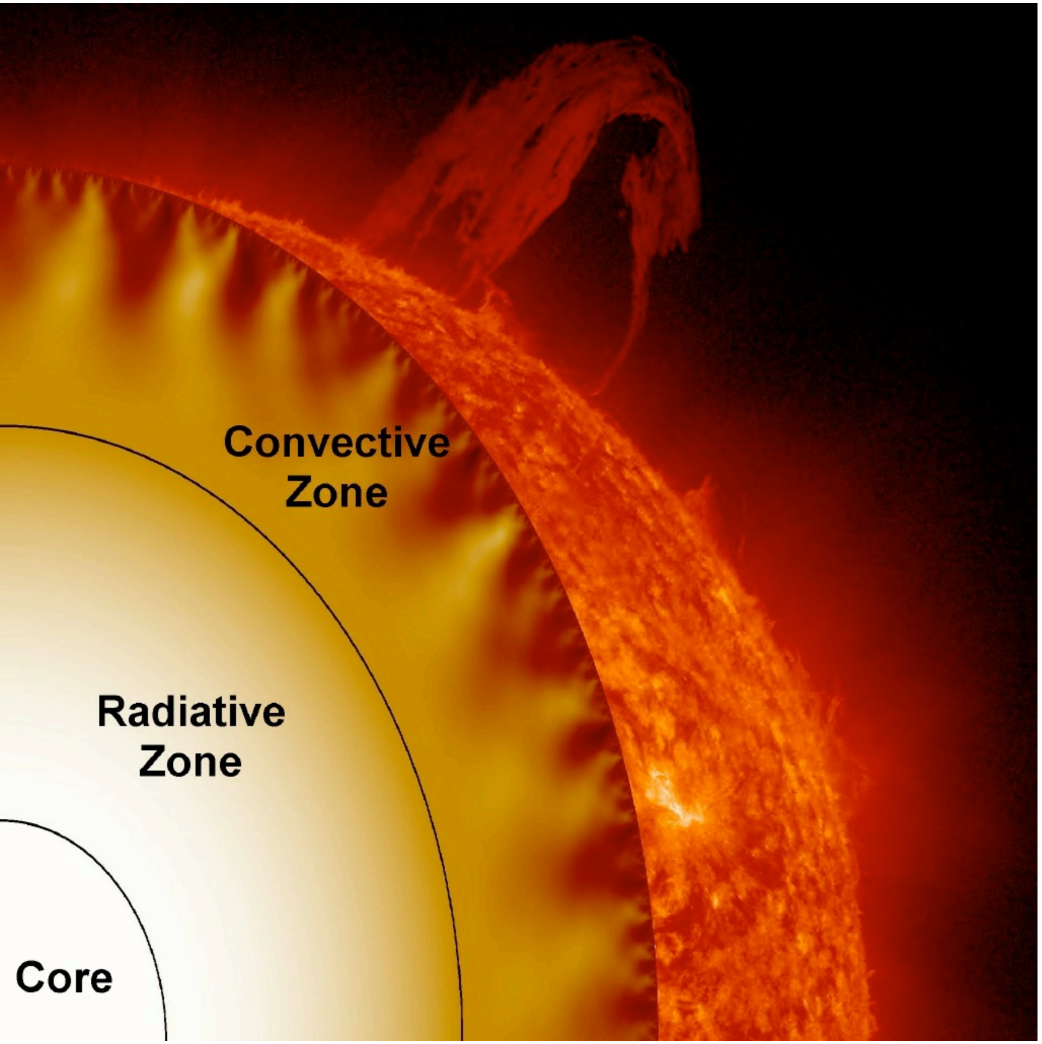
Let's take a look at each of these regions in turn.



The core

The core is the region of energy generation. The temperature at the centre of the Sun is 15 million degrees – hot enough for hydrogen fusion to take place. The core is completely ionised, with a density of 160 g cm^{-3}, or 14 times denser than lead. Nonetheless, the core is a plasma, with the nuclei and electrons moving about freely as in a gas.

Each second, the Sun fuses 600 billion kg of hydrogen, losing 4 billion kg of its mass.

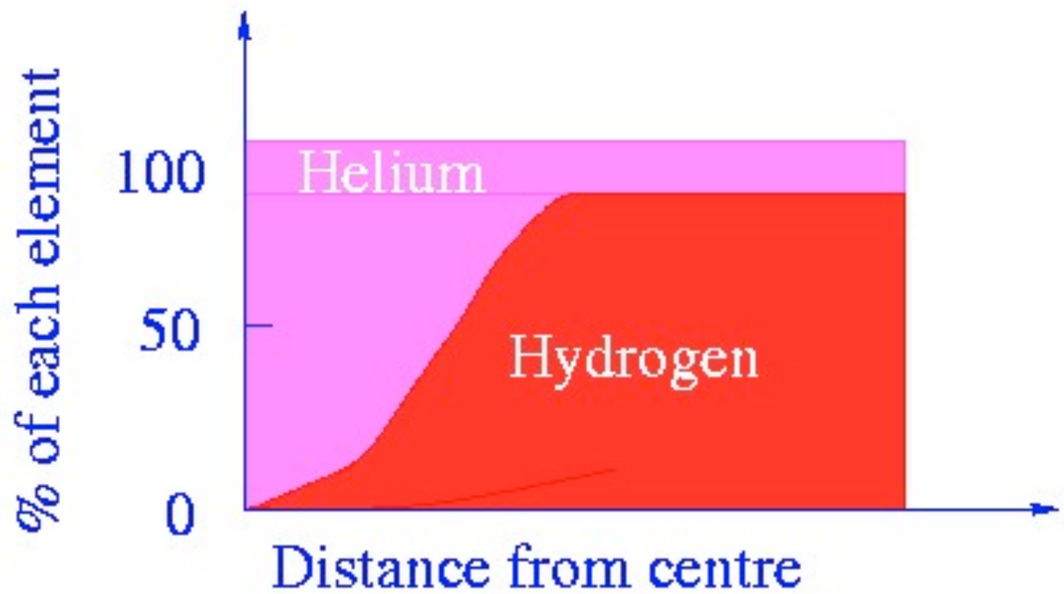


The core extends from the Sun’s centre to about one-quarter of its radius, or about 175 million km. It contains about 1.6% of the Sun’s volume, but about one-half of its mass.

The continual conversion of hydrogen into helium means that the composition of the core is slowly changing. It began with a uniform mixture of 71% hydrogen, 27% helium.

After 5 billion years, a substantial fraction of the hydrogen in the core has been converted to helium.

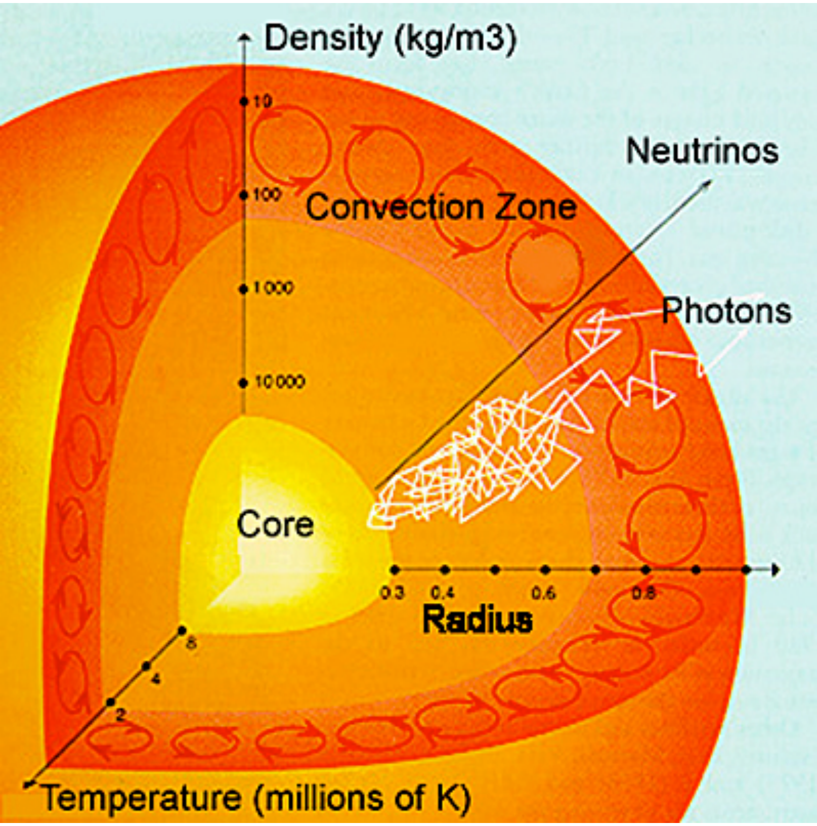
By 10 billion years, the core is totally helium.



The energy produced in the Sun's core has to be transported to the outside. Two different mechanisms operate to transport the energy outwards, and these define the structure of Sun.

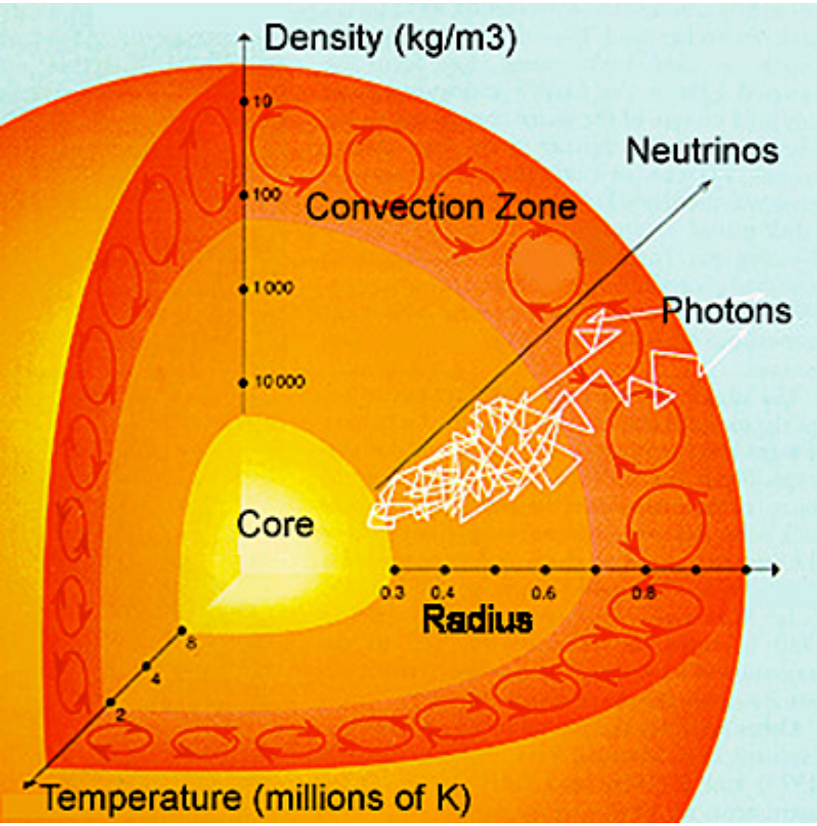
The innermost layer is called the *radiative zone*, because the energy is transported by radiation and not the movement of material. This zone reaches from the core boundary out to 71% of the Sun's radius.

As we discussed last lecture, radiation generated in the core does not reach the outside directly. Instead, the photons are continually absorbed and re-radiated by the material in the radiative zone. A typical photon moves only 0.09 cm before undergoing another collision, so that it takes on average about 170 thousand years to reach the surface, moving at an average speed of 0.01 cms^{-1}!



The temperature in the interior of the Sun decreases towards the surface. As a photon moves out from the centre, it is continually absorbed and re-emitted by particles. These particles have lower and lower energy, so the photon is re-emitted each time with lower energy, so its wavelength becomes longer.

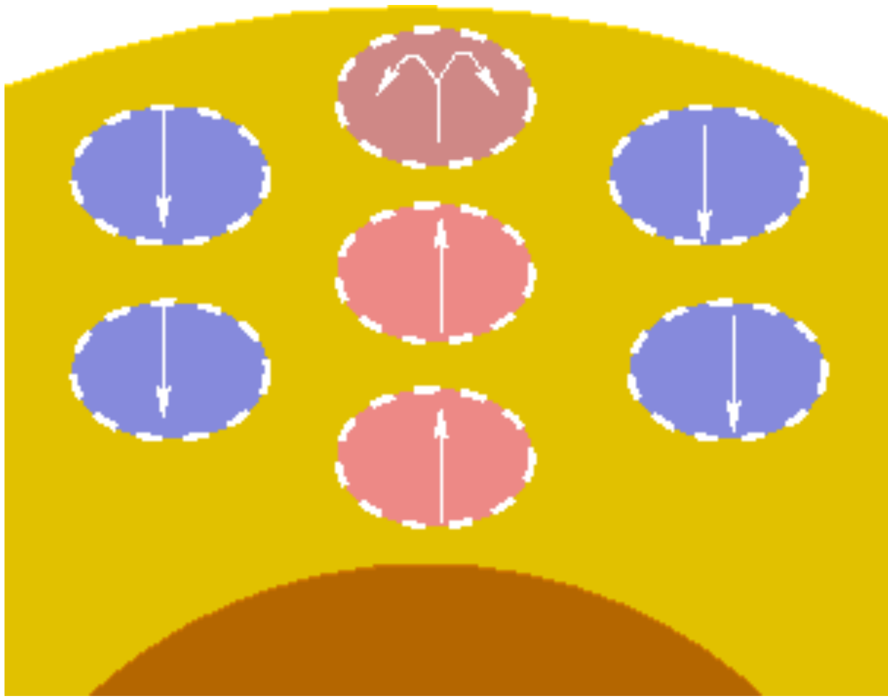
By about 70% of the way out to the surface, the temperature has dropped to about two million degrees, and some of the heavier nuclei begin to recombine with electrons.



When this happens, the *opacity* of the gas suddenly rises: the atoms are much more efficient at blocking radiation, so the energy has to be released some other way.

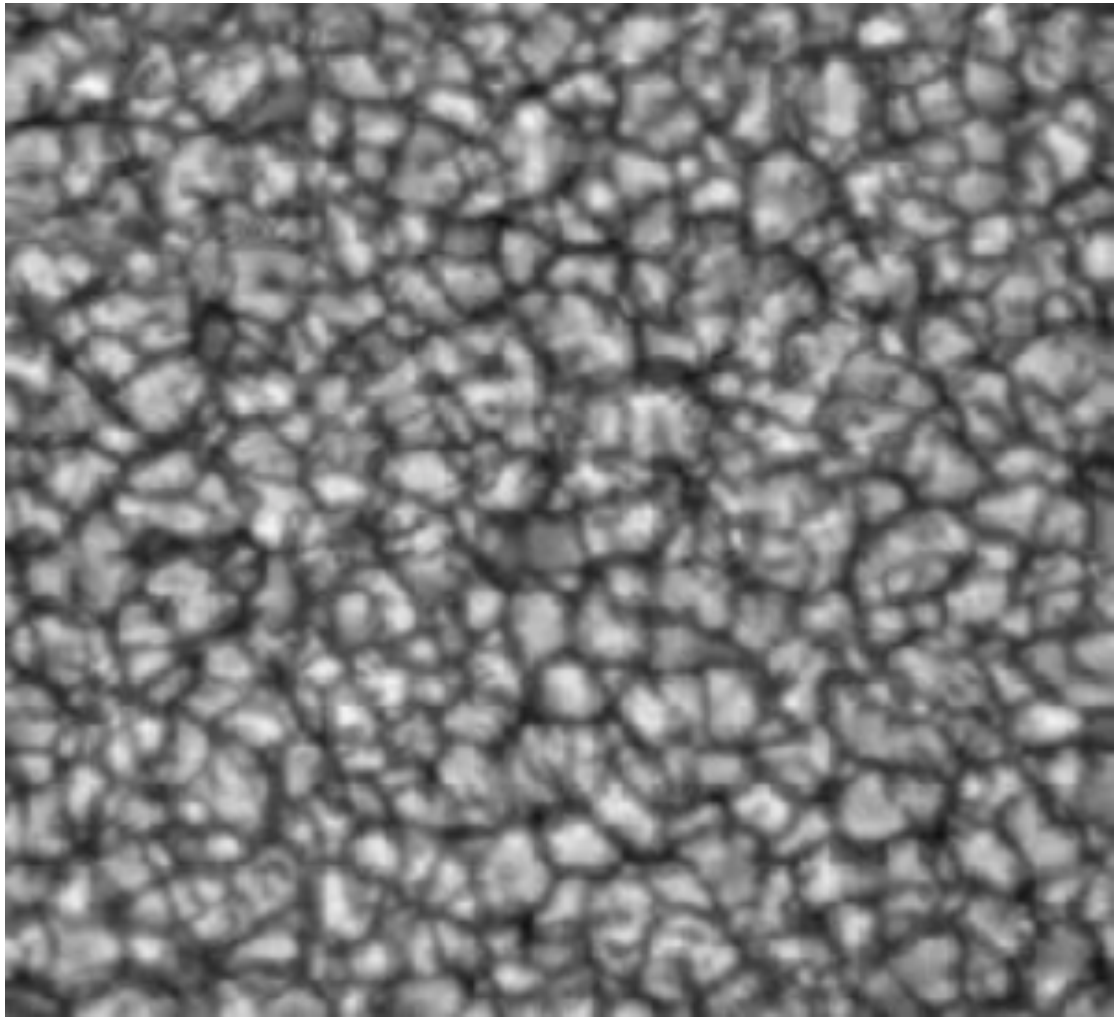
Convection starts: the transport of energy by the bulk motion of gas.

The neutral gas blocks the outward flow of heat by absorbing it and becoming extremely hot. The gas expands, becoming less dense than its surroundings. The bundles of hot gas float to the surface of the convection layer, where they radiate away their excess energy, become cooler and denser, and sink back down. The result is that there is a net transfer of energy but not of material.



The convective currents take about 10 days to transport the energy the last third of the Sun's radius.

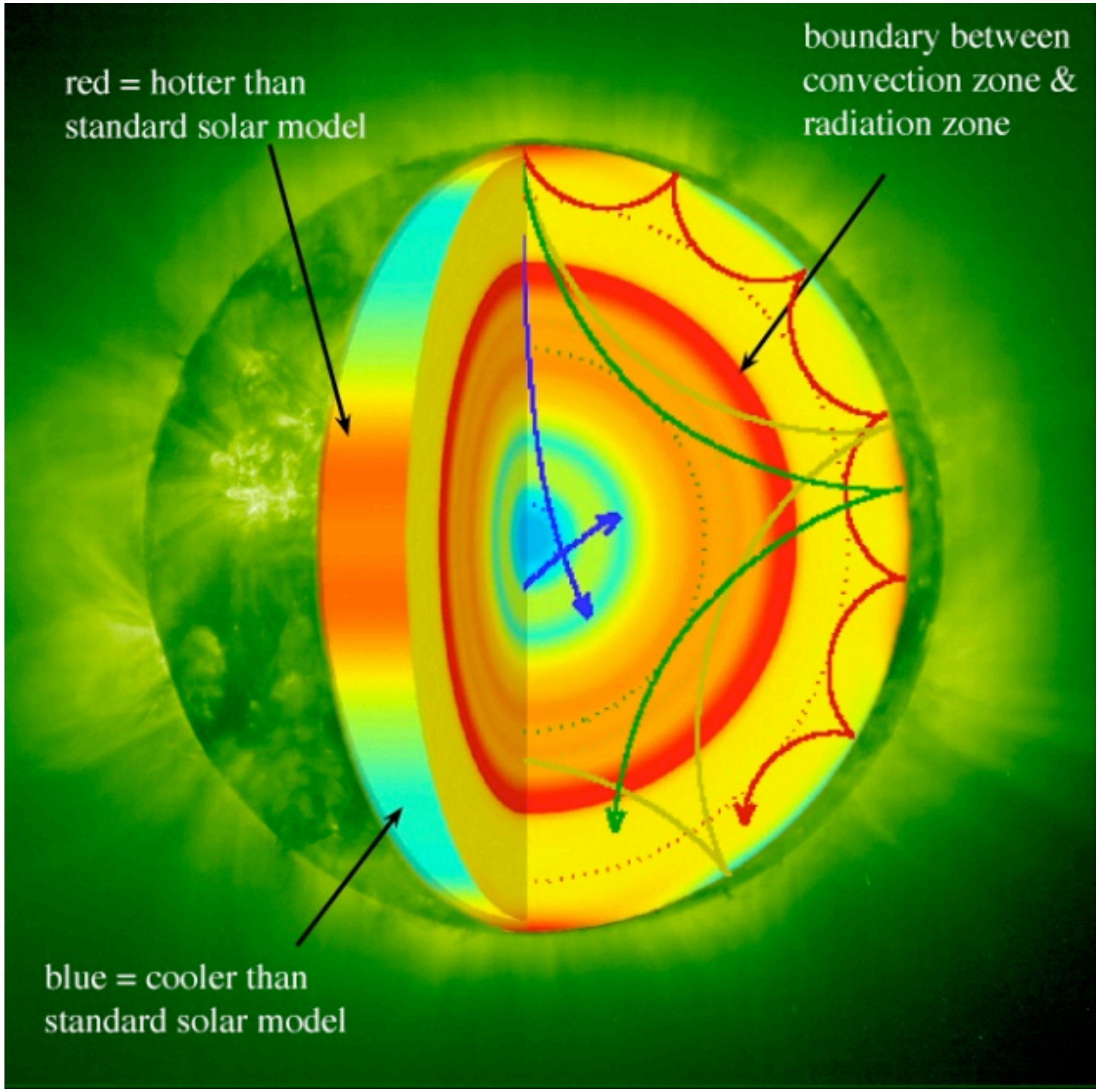
These convection currents are visible on the surface as *granules*. Hot gas rises in the centres, radiates its heat, then sinks along the dark edges. Granules typically last 5–10 minutes, and are about 1300 km in size.



High-magnification images of the Sun, showing granules evolving. The image is 27,000 km on each side, and shows 35 minutes of data.

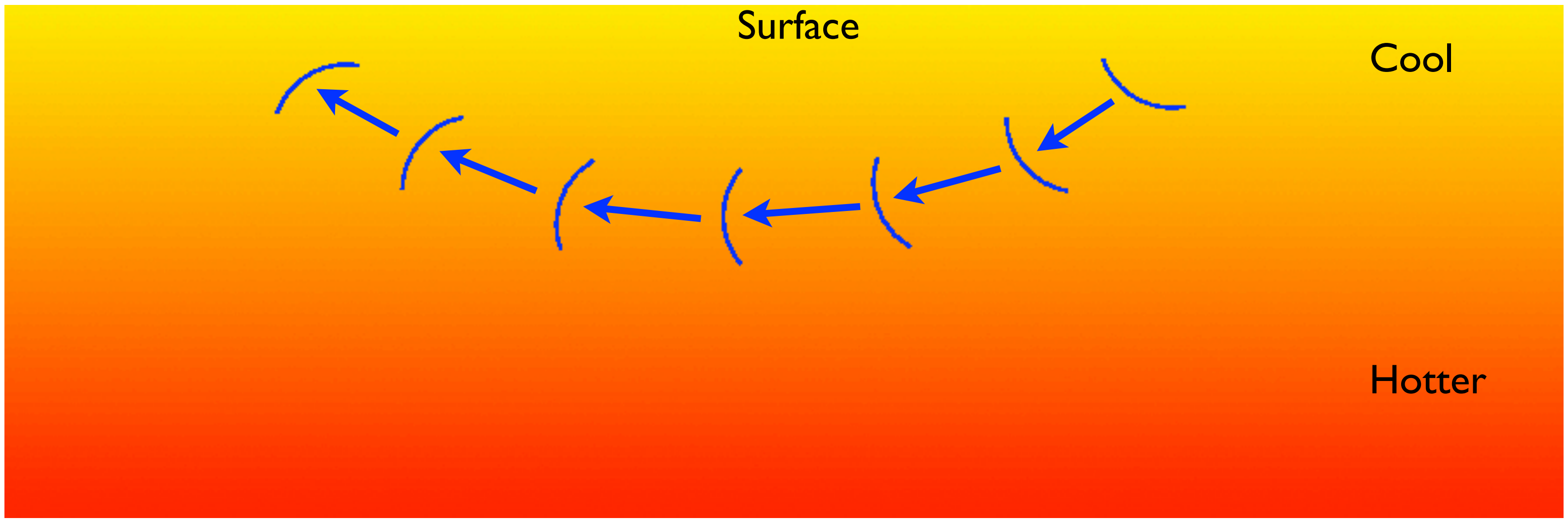
Theoretical models of how the Sun works are all very well. But can we actually look into the Sun's interior?

Helioseismology is a tool for doing exactly that. Just as seismologists use waves from earthquakes to probe the Earth's interior, astronomers can use the vibrations of the Sun to look into the Sun's interior.

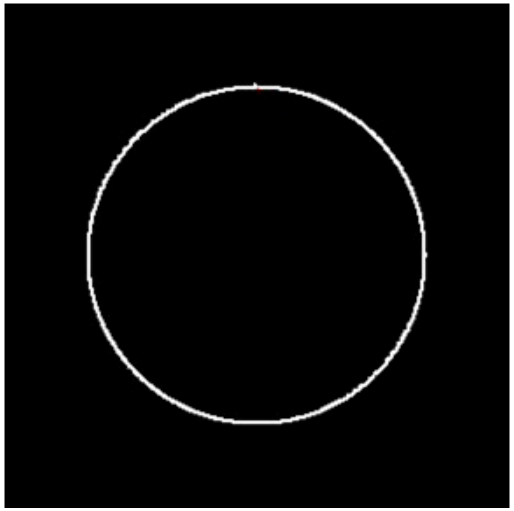


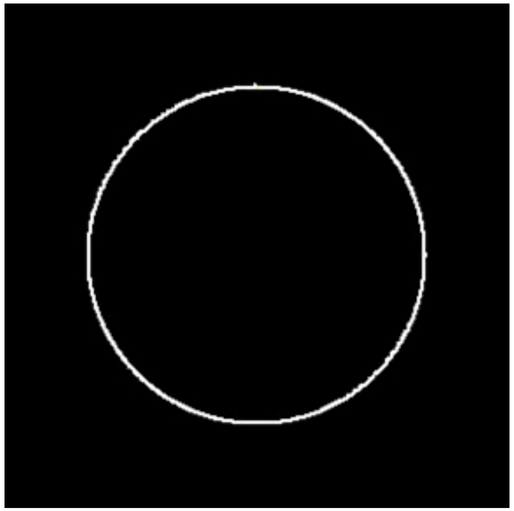
The Sun vibrates as sound waves in the interior cause the photosphere to move up and down.

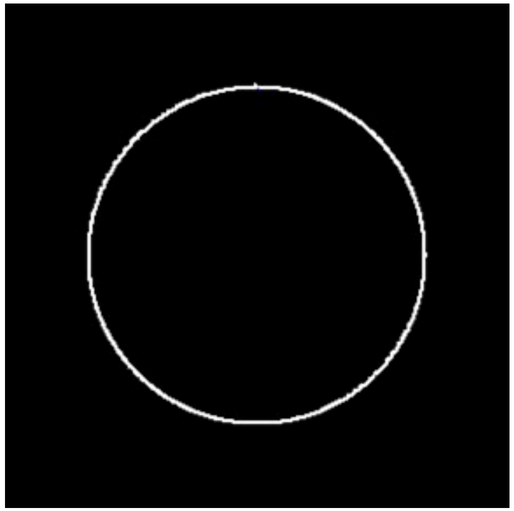
Convection is noisy (think of a boiling kettle!), so the convection zone generates a broad spectrum of frequencies. These reflect from the surface, and are refracted back by the temperature gradient in the interior. The speed of sound increases with temperature, so as the wave travels to the interior, the inner edge pulls ahead and the wave is turned back towards the surface.



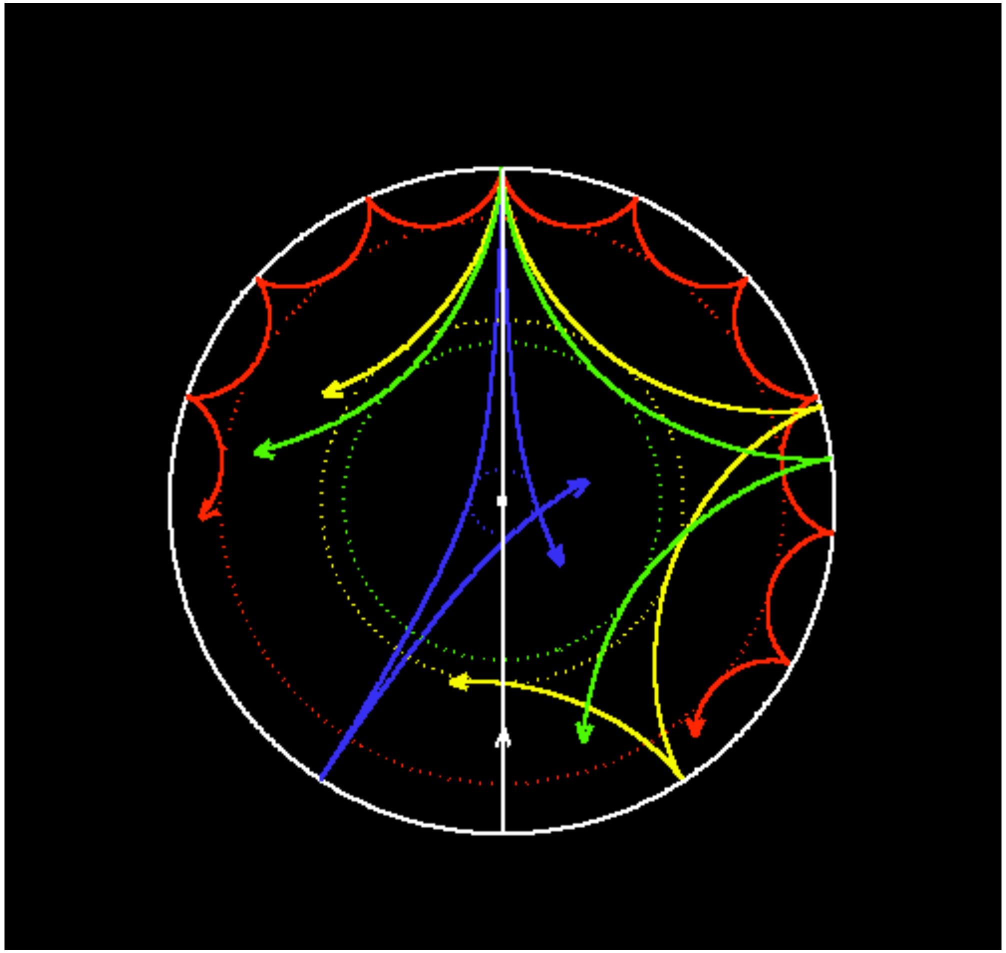
So each wave travels around the Sun in a series of arcs. It is trapped in a spherical shell between the surface and depth at which it turns. A typical wave takes about five days to circle the Sun.





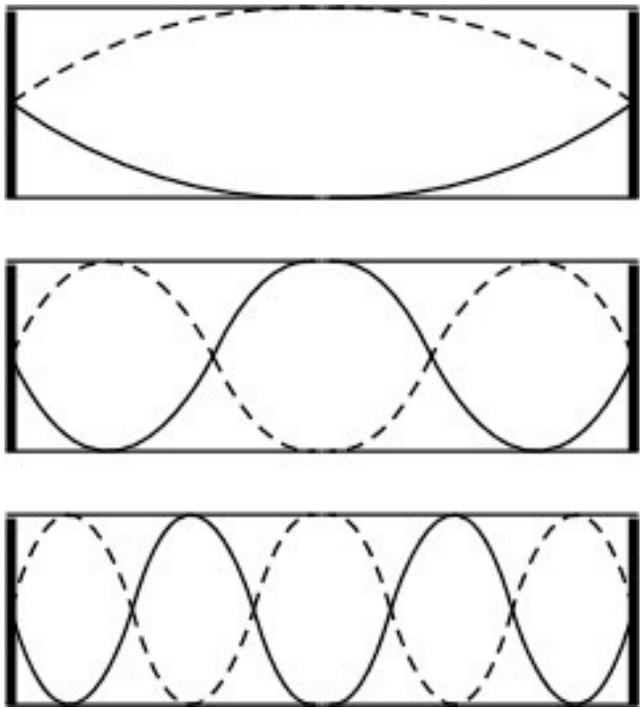


Waves of different frequency (or wavelength) penetrate to different depths. Some stay near the convection zone; others travel to the very centre.



The Sun can vibrate in many complicated patterns because it is vibrating in three-dimensions.

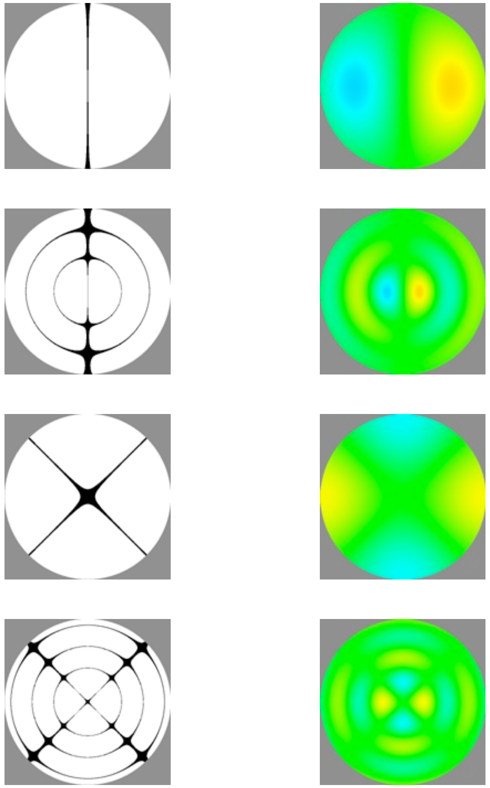
You are probably familiar with the modes of vibration of a one-dimensional object – say, a violin string. Only vibrations where an integer number of half-wavelengths fit on the string are stable.



We can describe which vibration we have by how many *nodes* it has – places where the string does not move.

This picture shows n = 0, 2 and 4.

In two-dimensions (like the vibration of the surface of a drum), the vibrations are more complicated. Now the regions which do not move are *lines* instead of points, and we need two numbers to describe which type of vibration we have.



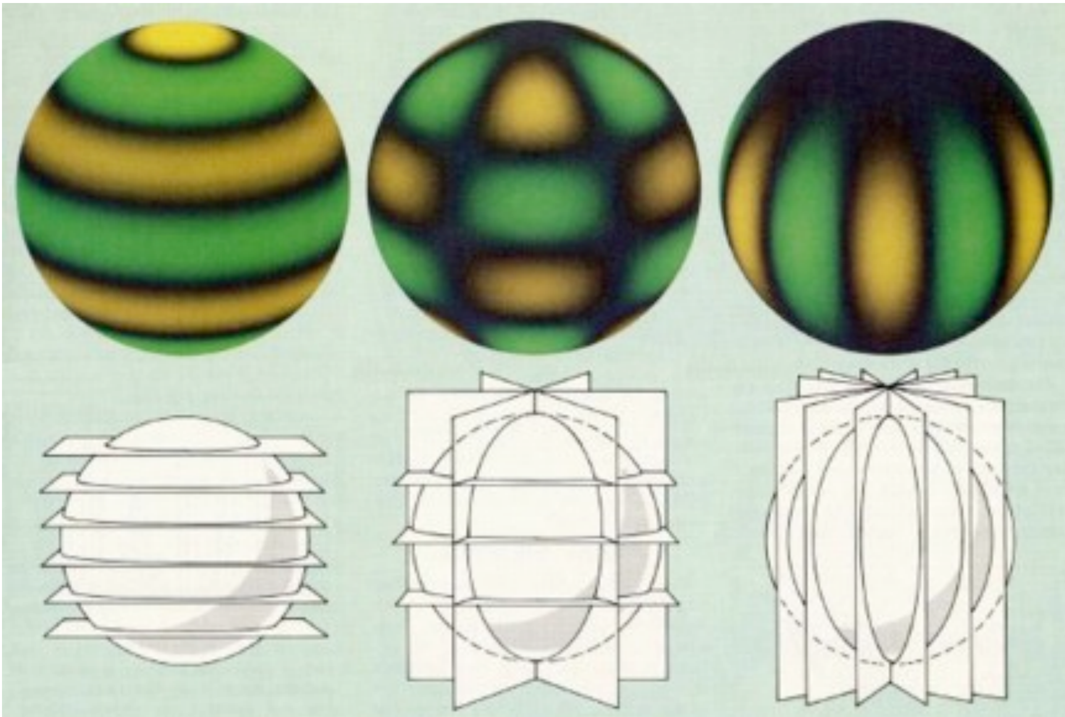
$n = 1, l = 1$

$n = 1, \; l = 3$

$n = 2, \; l = 1$

$n = 2, \; l = 4$

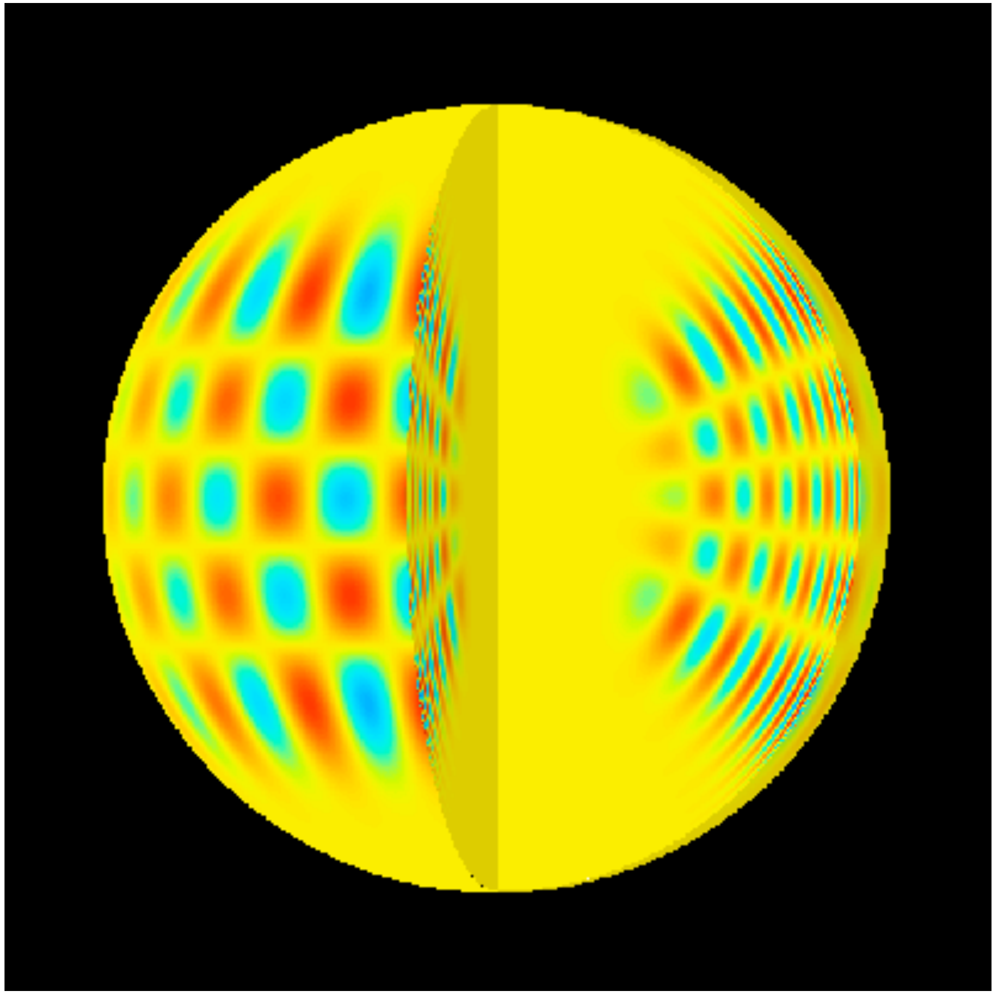
In three dimensions things are more complicated again. Instead of nodal *lines*, we now have nodal *surfaces*. You can probably guess that we need three numbers to describe which mode we have.



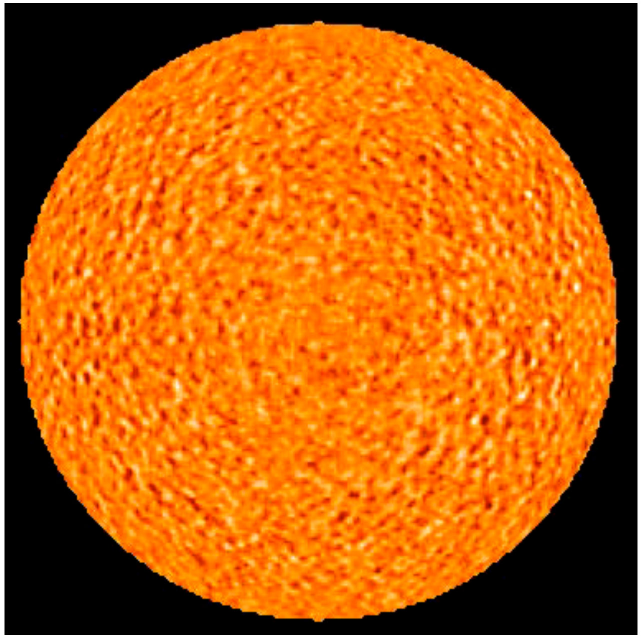
l = 6, *m* = 0   *l* = 6, *m* = 3   *l* = 0, *m* = 6

l describes the number of vertical surfaces, m the number of horizontal surfaces.

The third number n describes how many nodes there are radially, so the nodal surfaces are nested spheres. This image shows a wave with $n = 14$, $l = 20$ and $m = 16$.



The Sun doesn't just vibrate in one mode at a time: it vibrates in *all* of them at once!

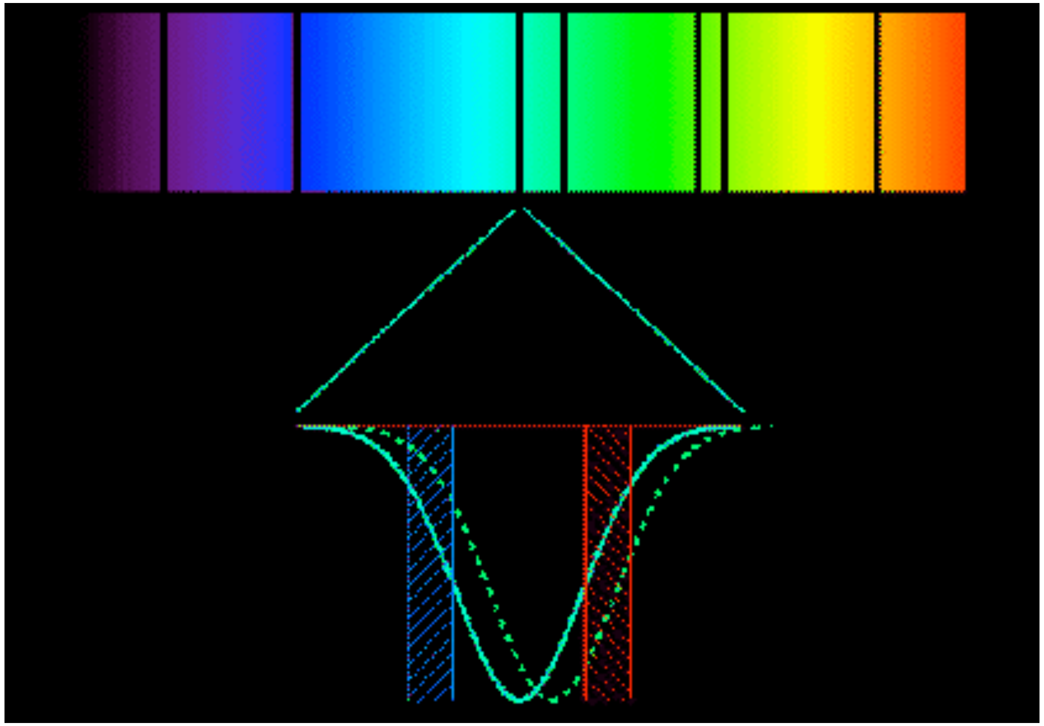


So how do we measure these modes, and how do we convert this into information about the Sun?

To measure the oscillations, we need to measure either *brightness* or *velocity* variations across the face of the Sun (to determine the mode number) and as a function of time (to determine the frequency of the vibration).

Velocity variations can be measured using the Doppler shift. The light from the Sun is sent alternately through two very narrow-band filters on either side of an absorption line. When the two images are subtracted, you get an image of the velocity of each point over the face of the Sun.

When the absorbing material is stationary, the intensities in the two filters are the same. When the material moves away (dashed line), the absorption in the red filter is much stronger than in the blue filter.



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Here is a Doppler image, showing the velocity field over the Sun's surface. But this image is dominated by the rotation of the Sun: the left edge is approaching us at about 2 km/s while the right moves away. If we subtract the rotation, we are left with the oscillations.

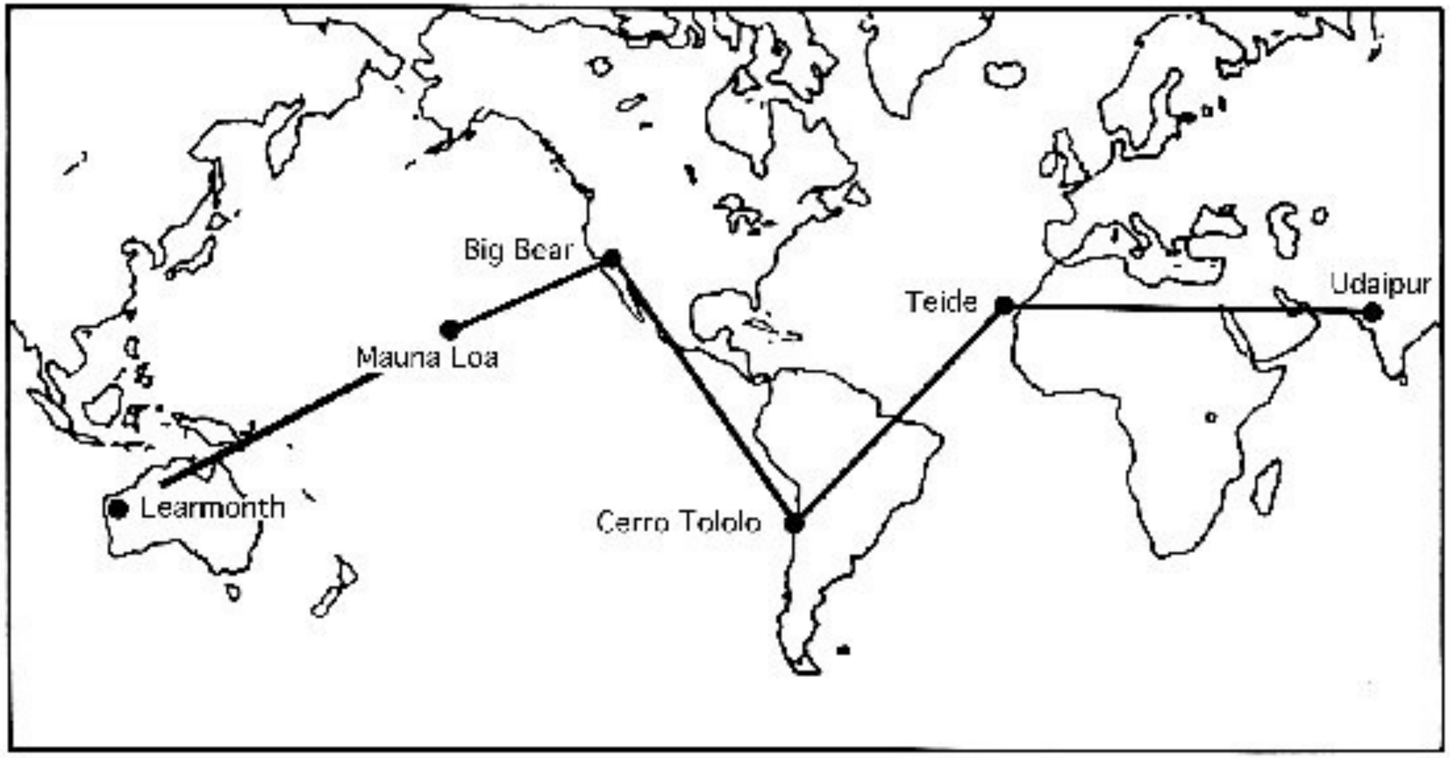
The period of oscillation is about 5 minutes, and the longer you observe for, the more precisely you can measure the frequency. We need to measure about 10,000 cycles, so observations of *months* are necessary.

Unfortunately, it's hard to observe the Sun continuously for months at a time: even the best astronomers have problems observing it in the night!

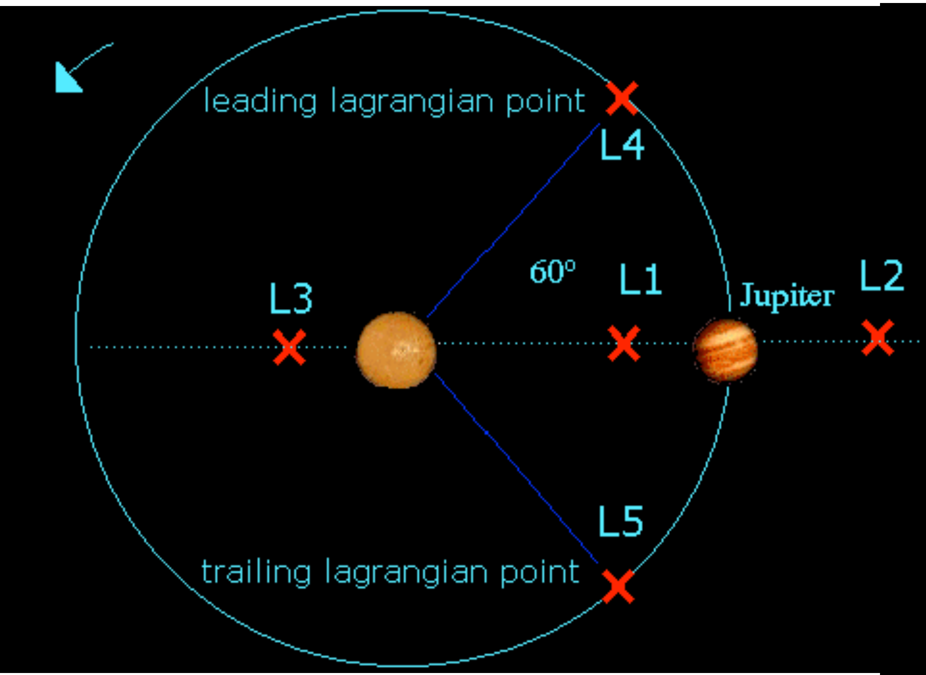
There are three solutions:

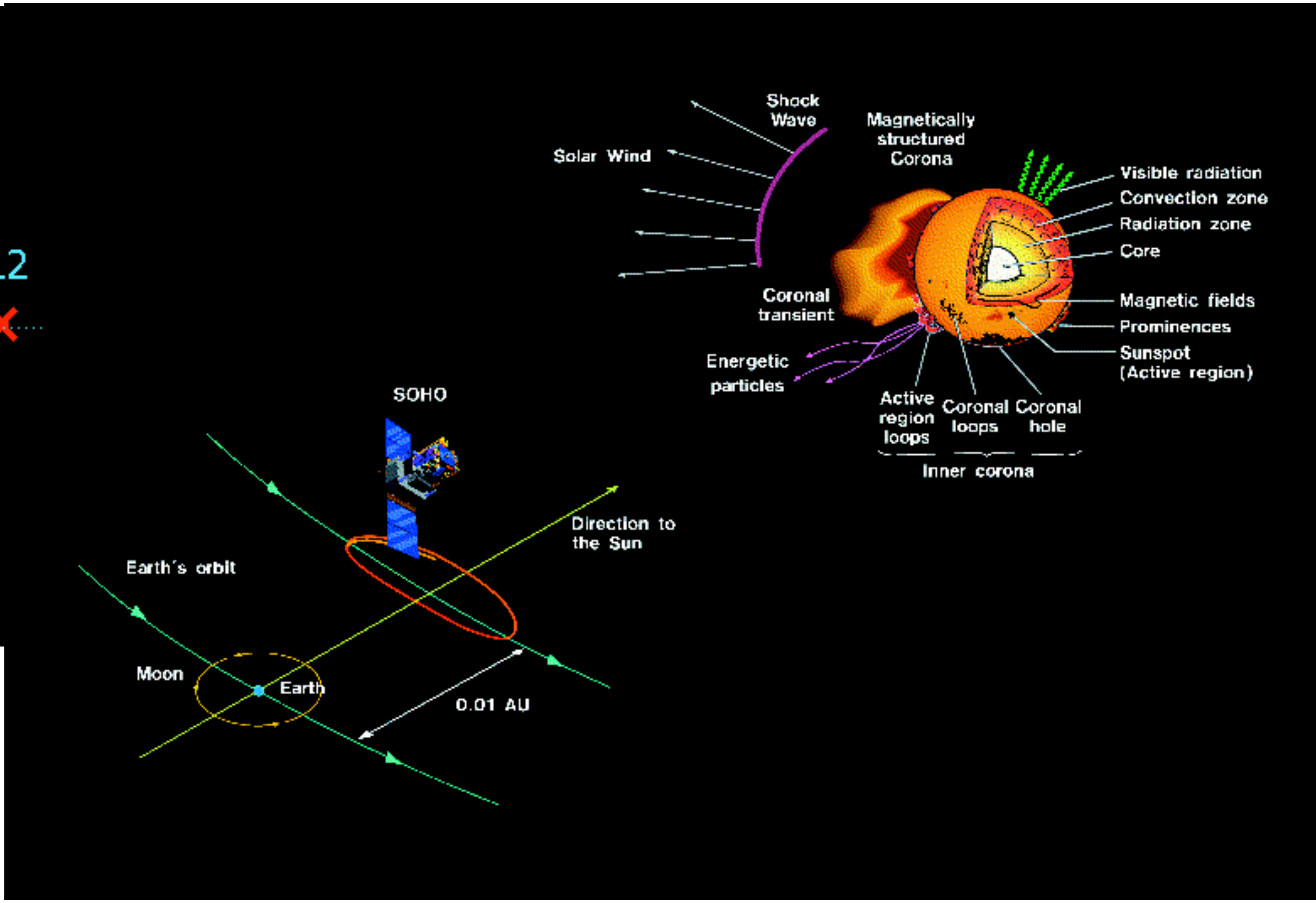
- observe at the South or North Pole
- have a network of observatories around the globe
- observe from space

All three approaches have been used. The GONG (Global Oscillation Network Group) has six stations spread around the globe, which together can see the Sun continuously.

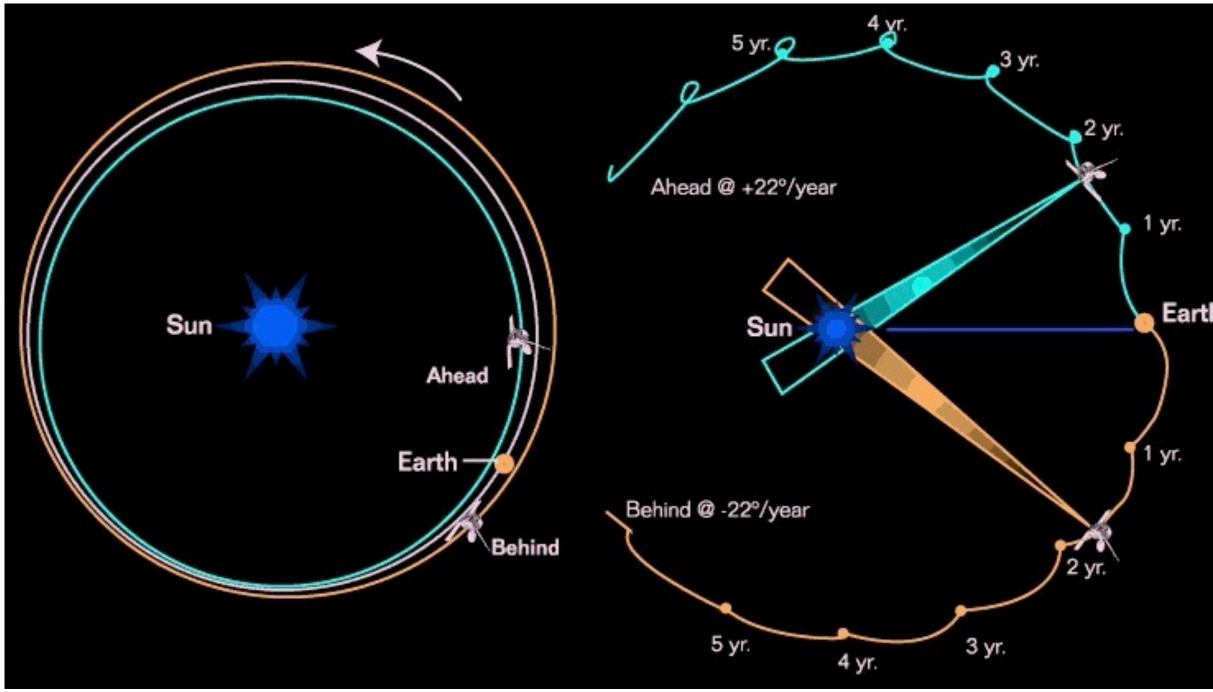


The *SOHO* satellite was put into orbit near the Earth-Sun L1 point, where it has an uninterrupted view of the Sun.

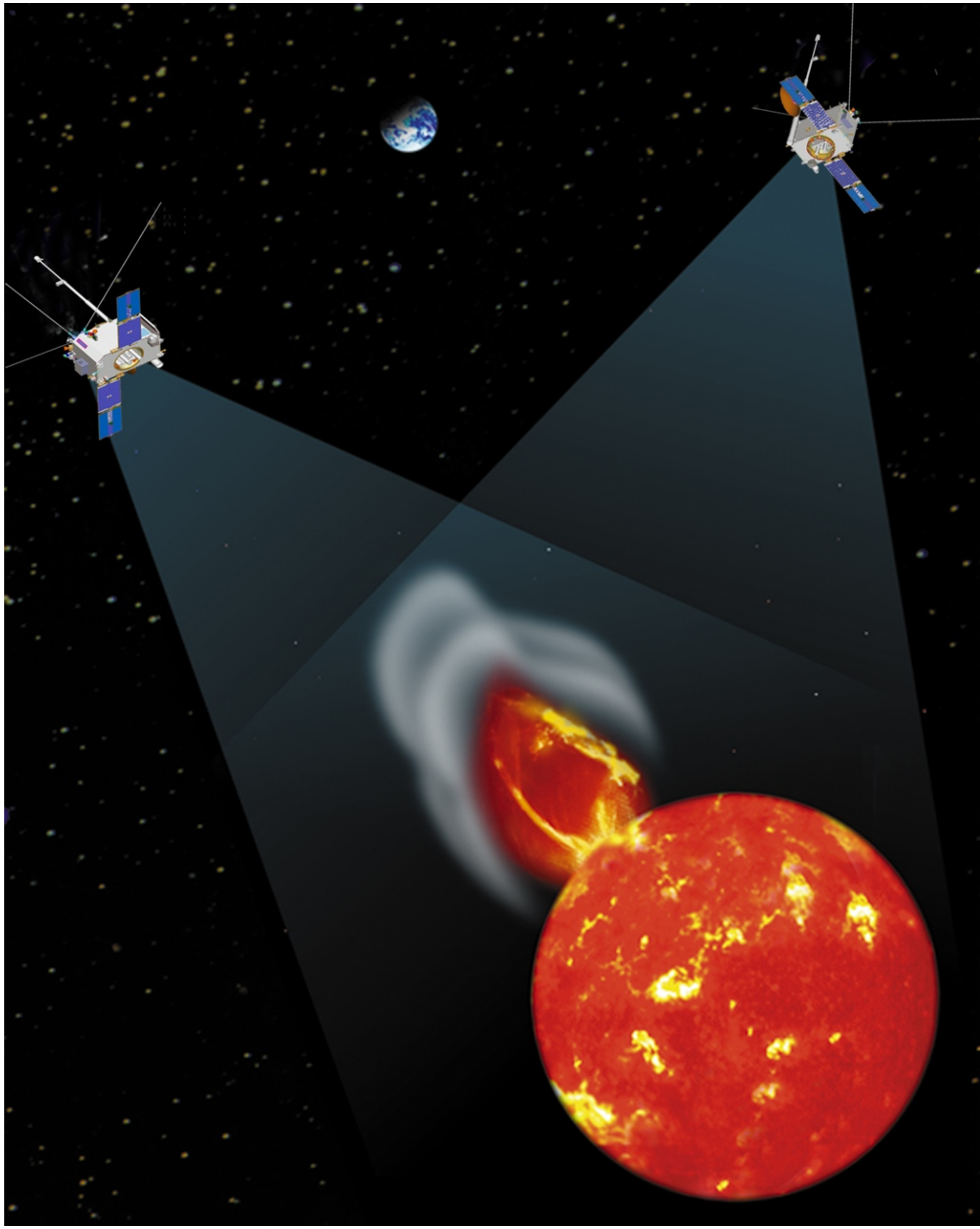


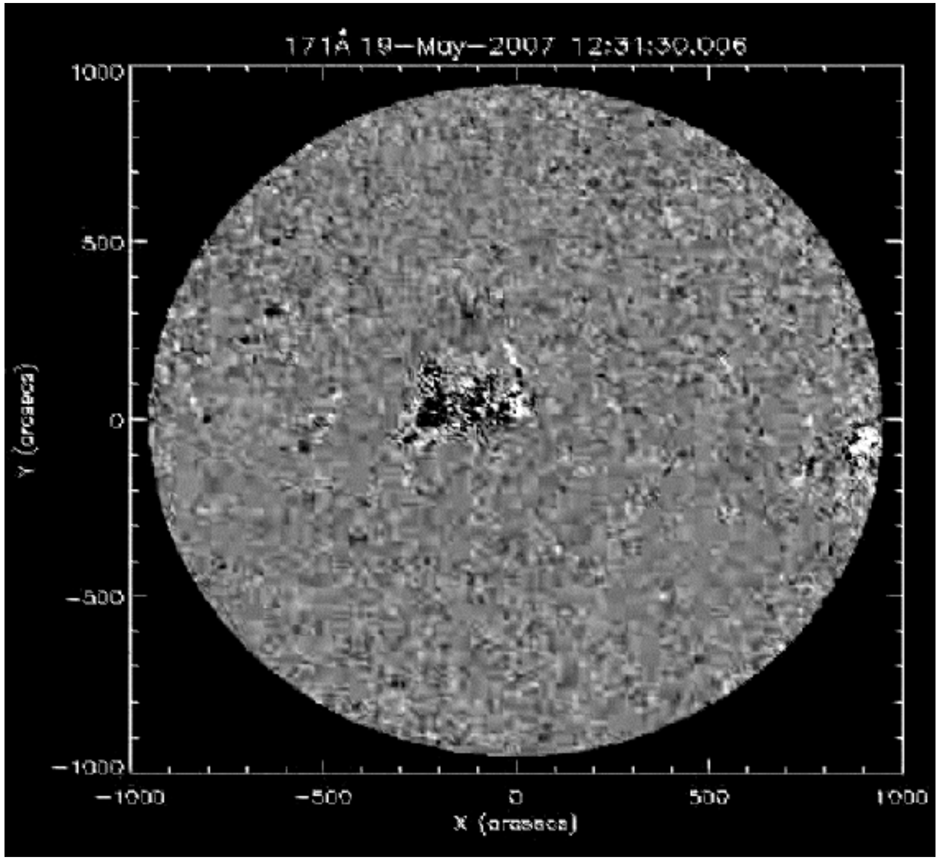


The *STEREO* mission was launched in 2006. STEREO is actually two satellites, one orbiting ahead of the Earth and one behind. The satellites used the Moon to swing them into slightly different orbits, so the angle between the two probes increases by about 22° each year. They have just passed behind the Sun and have started to approach Earth again.

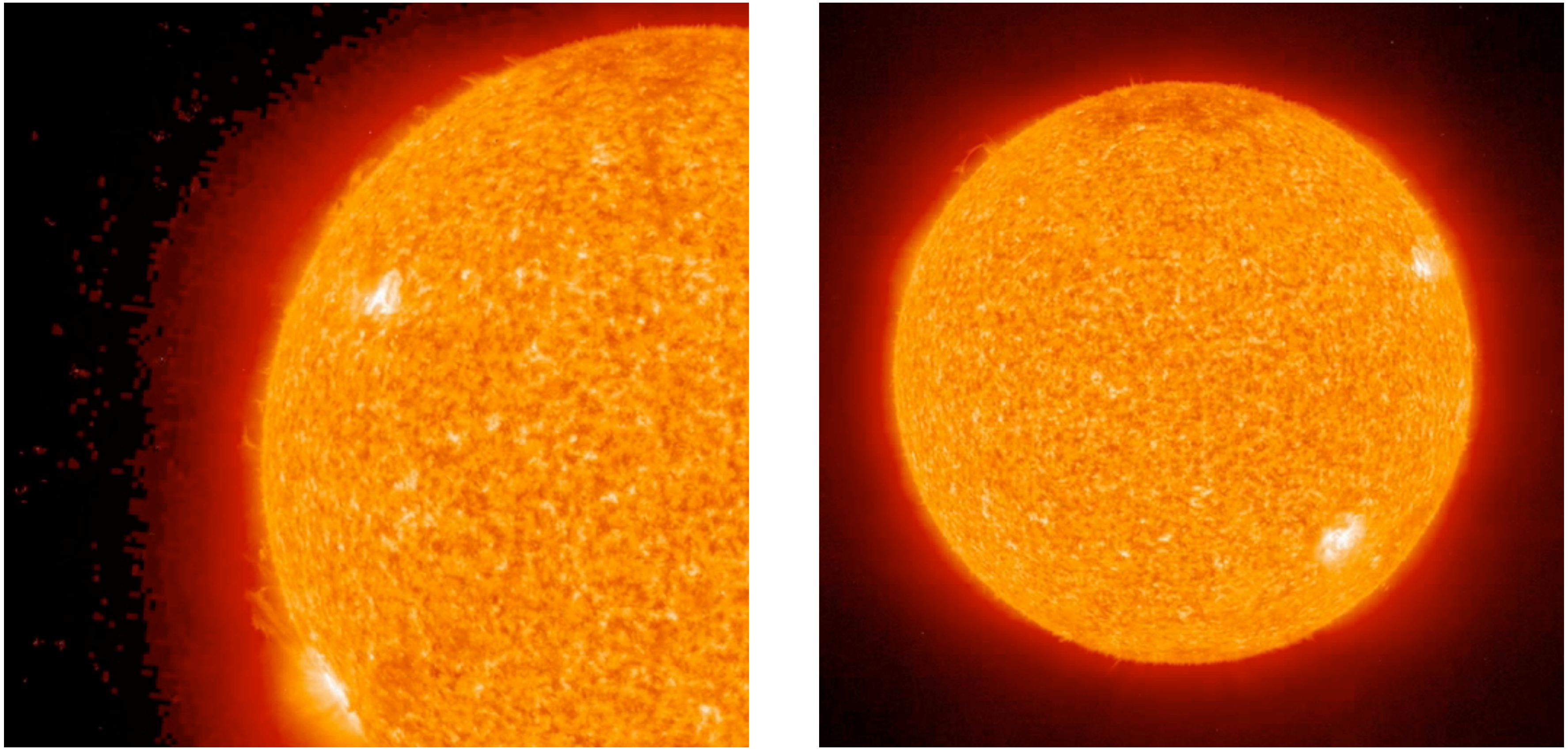


Since the two spacecraft observe the Sun from different angles, we can assemble a 3D picture of the Sun, and be able to monitor and predict space weather with much greater accuracy.



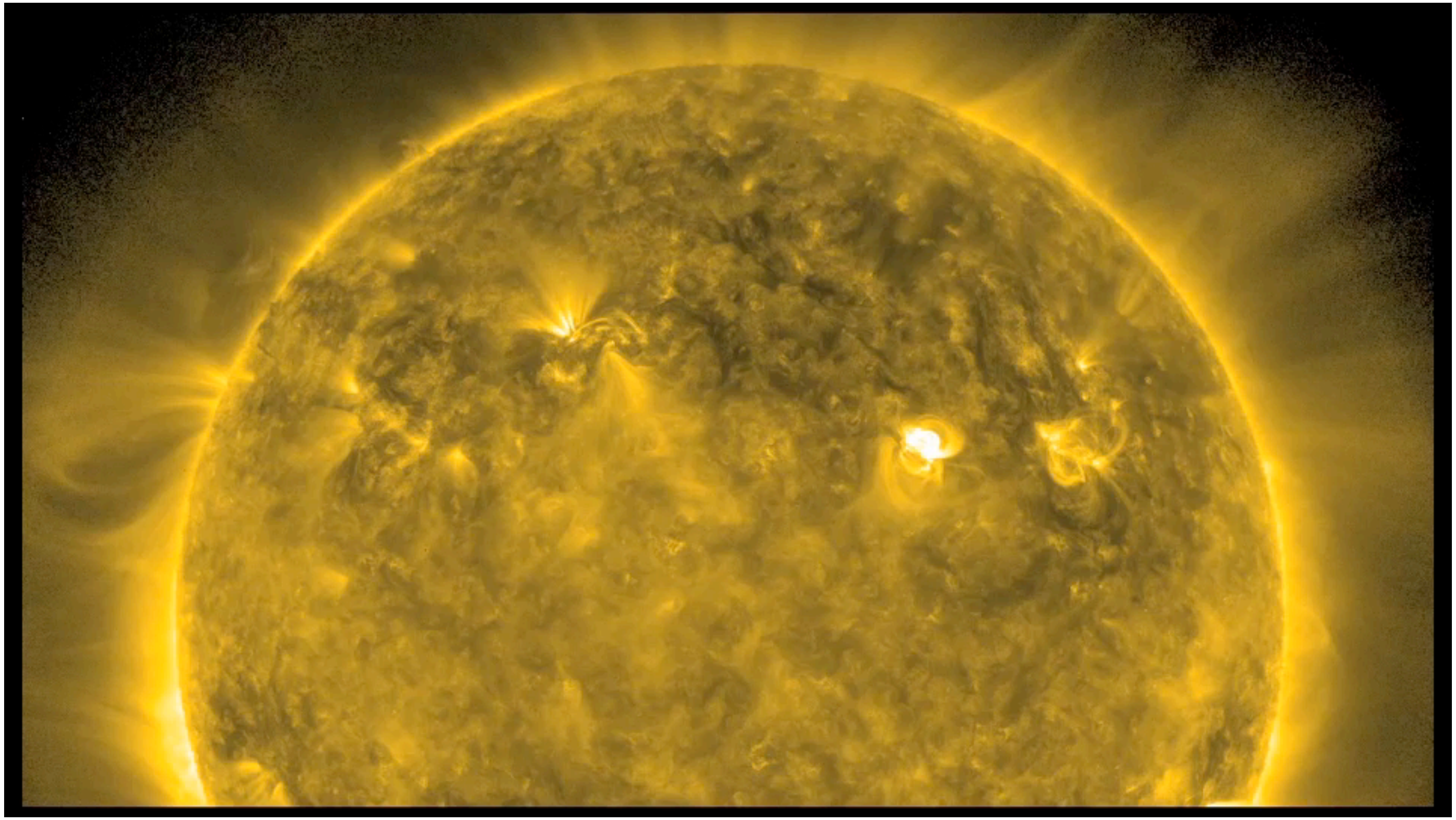


A solar tsunami, caused by a CME, blasting across the Sun's surface at millions of km/h



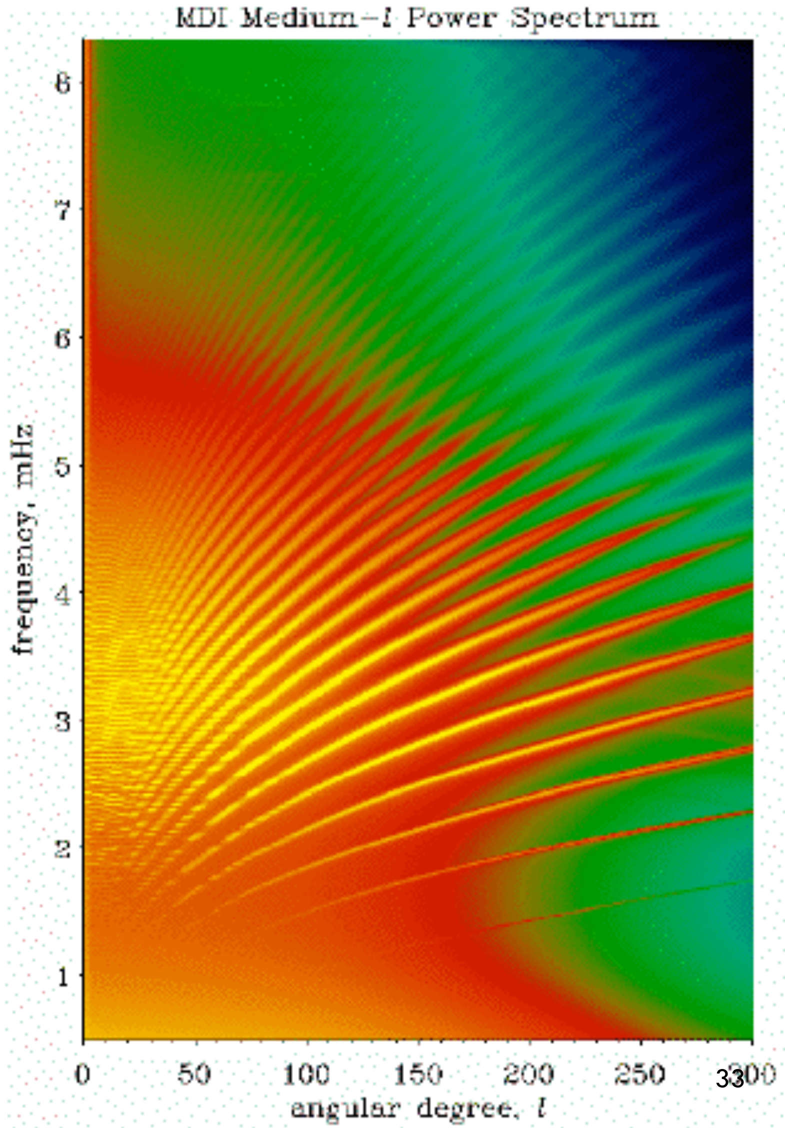
Eruptive prominence seen by STEREO Ahead (left) and Behind (right) on Sep 26–27 2009

The *Solar Dynamics Observatory* was launched in 2010, and has been sending back images since.

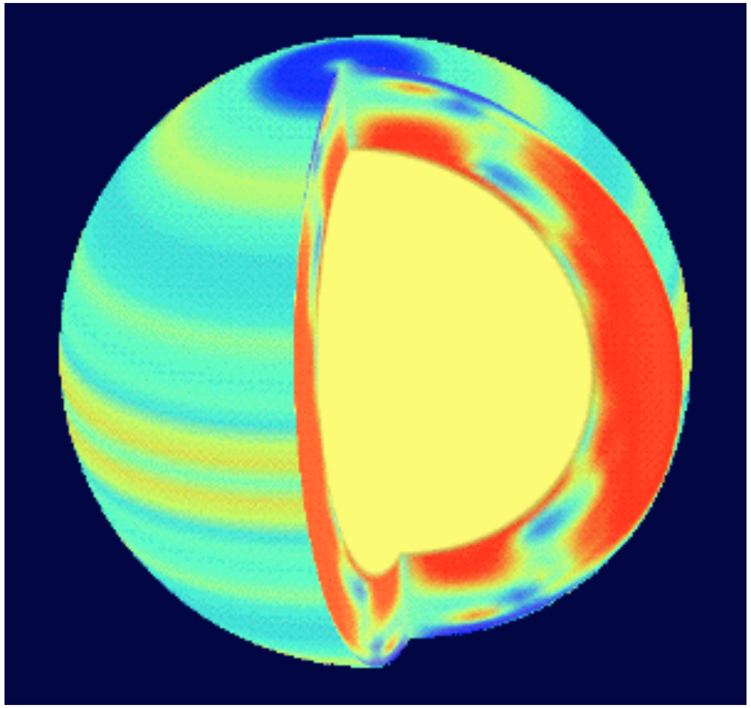


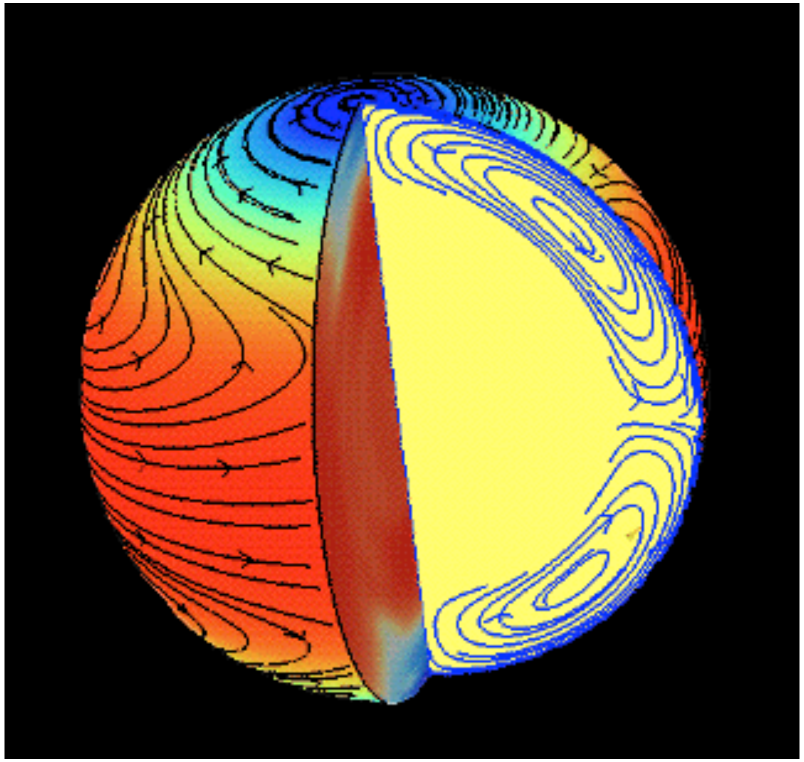
This is a power spectrum from MDI/SOHO, showing how much acoustic energy is each one of the millions of modes. Most of the power (in yellow) is in modes with frequencies near 3 mHz – a period of about 5 minutes.

Now that we know how much power is in each mode, and since different modes travel to different depths in the Sun, we can use the oscillations to determine the conditions inside the Sun.

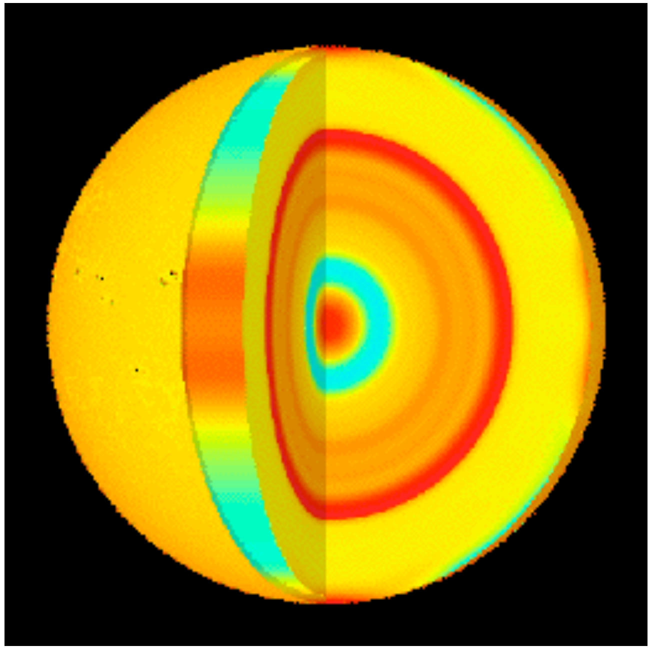


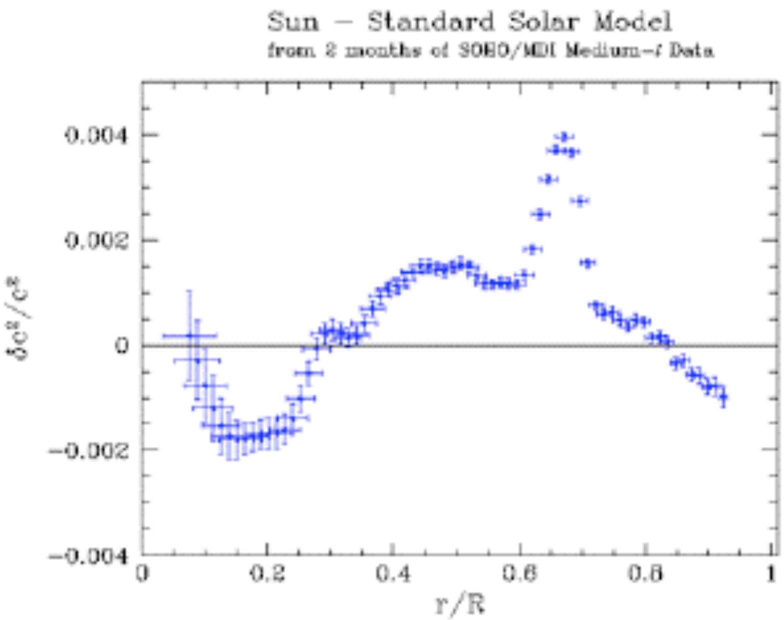
Researchers have found the Sun rotates in bands, with the equator rotating faster than the poles. New results find there are bands moving faster than their neighbours, much like the bands on Jupiter. In addition, there is a polar “jet stream” below the surface, and a general flow from the equator to the poles.





The speed of sound (and hence the temperature) agrees very well with predictions of solar models. However, there are some discrepancies (red shows temperatures higher than predicted). The temperature is higher than expected just below the base of the convection zone, and lower than expected at the edge of the core. This may mean the rate of fusion in the Sun is lower than expected; possibly it varies over long time periods.





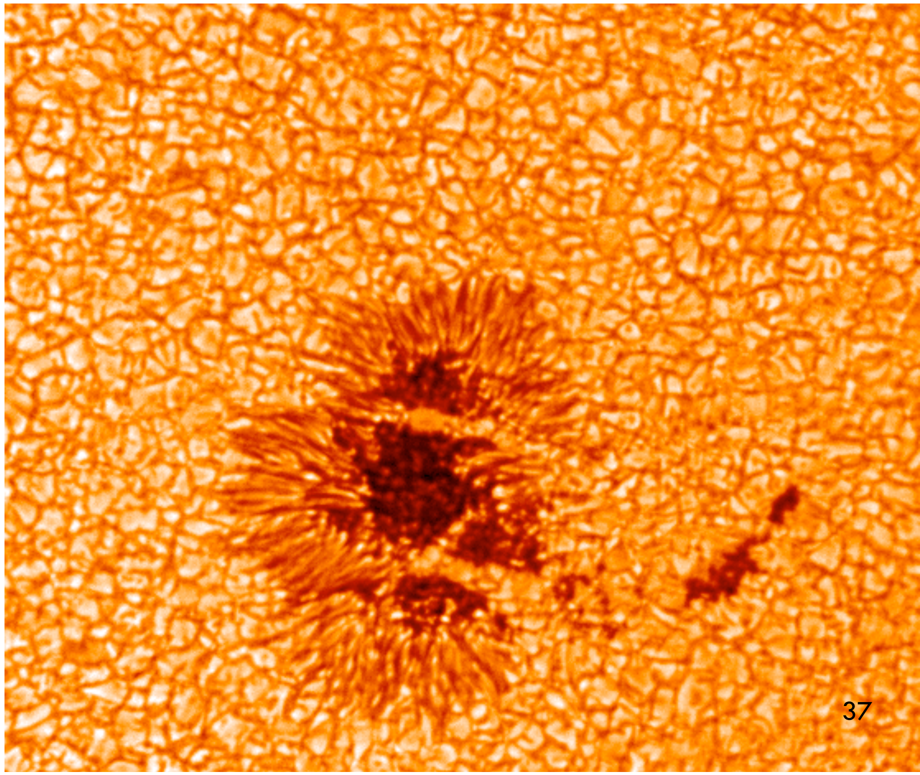
The photosphere

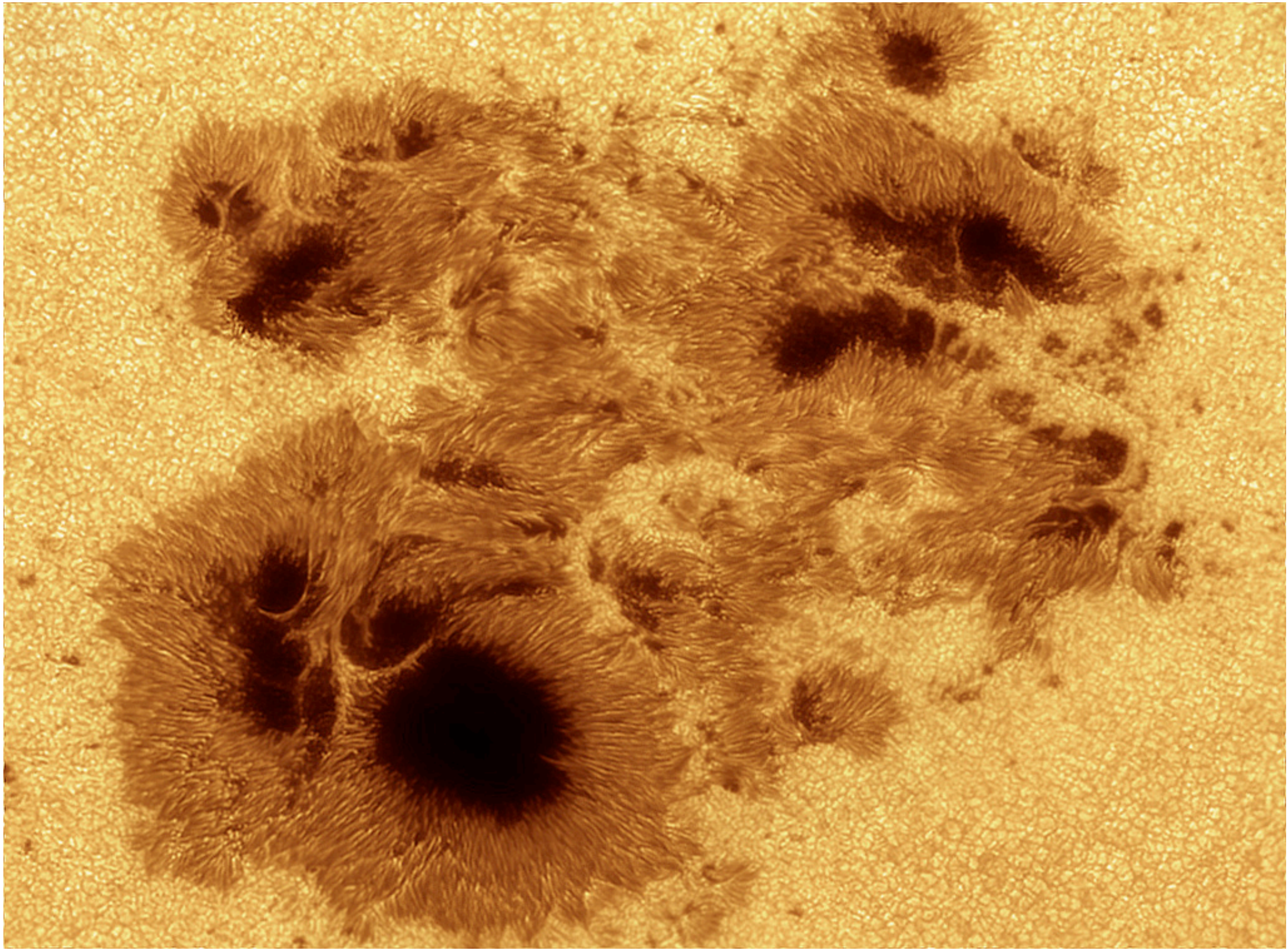
Let's continue our journey outwards. The *photosphere* is the layer where most of the Sun's energy escapes into space.

The photosphere is a few hundred kilometres thick, and has a temperature of 5780 K.

We have already seen how the photosphere is covered with granules, each as large as Brazil. But there are even more dramatic features in the photosphere: *sunspots*.

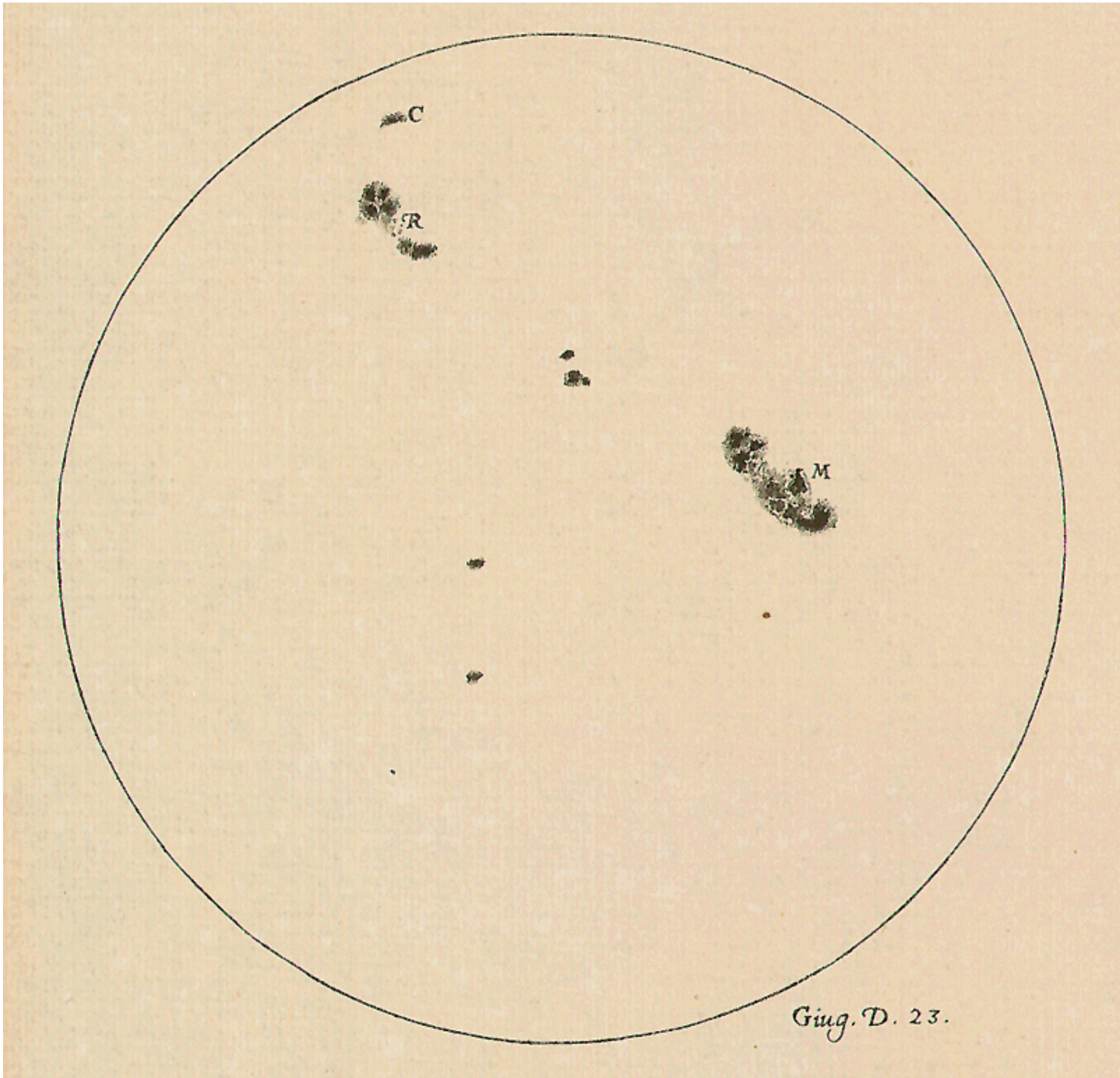
Sunspots can be many times larger than the Earth. They appear dark because they are cooler than their bright surroundings, about 2000 K cooler. Most sunspots remain visible for only a few days; others can last for weeks or months. Sunspots have a dark centre called the *umbra*, surrounded by the lighter penumbra, which consists of radial filaments. Matter flows outward along these filaments, and down above the umbra.

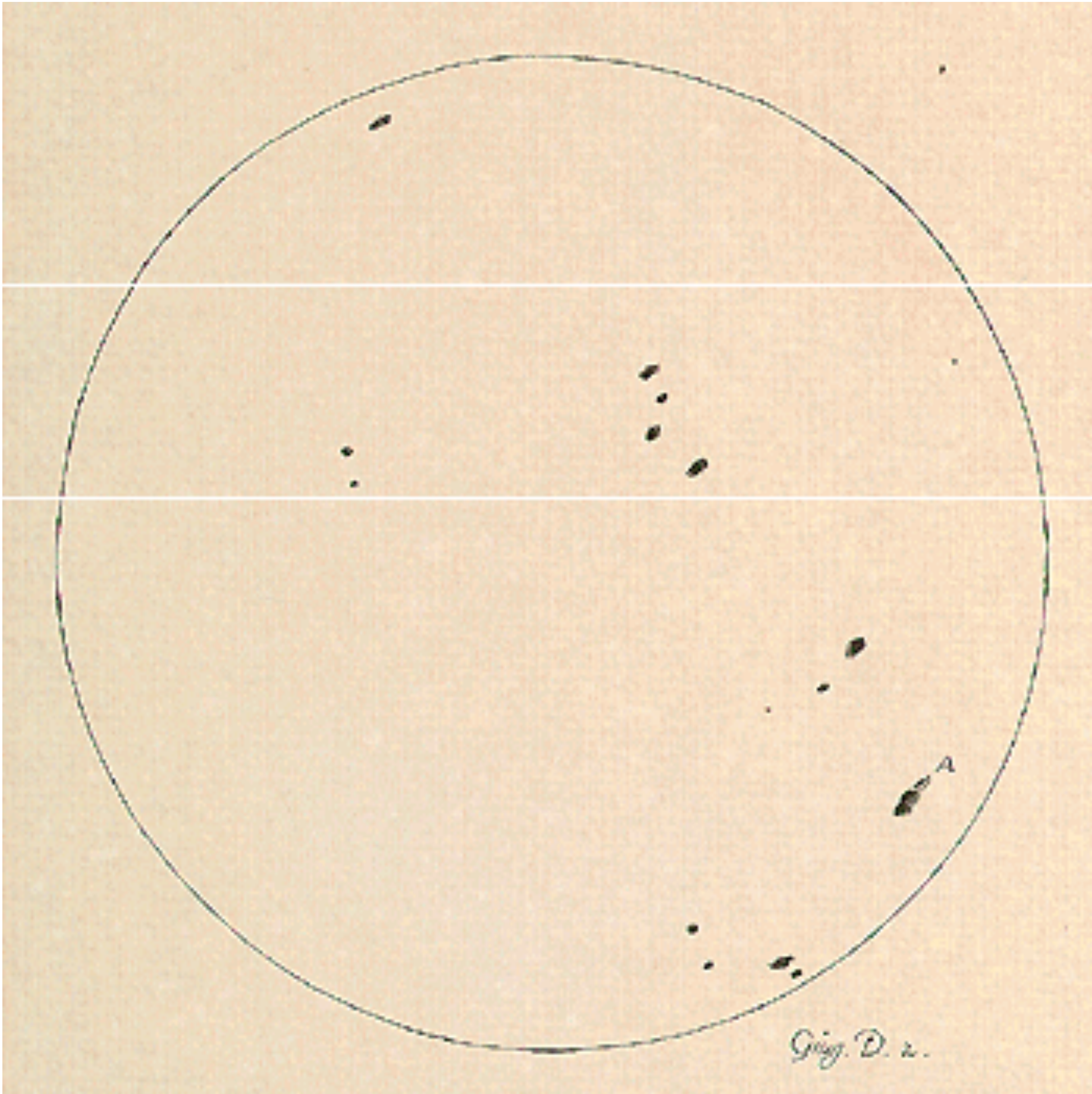




Sunspot group AR 2192 (about the size of Jupiter), which crossed the Sun in October 2014.

One of Galileo's drawings of sunspots, from 23 June 1613

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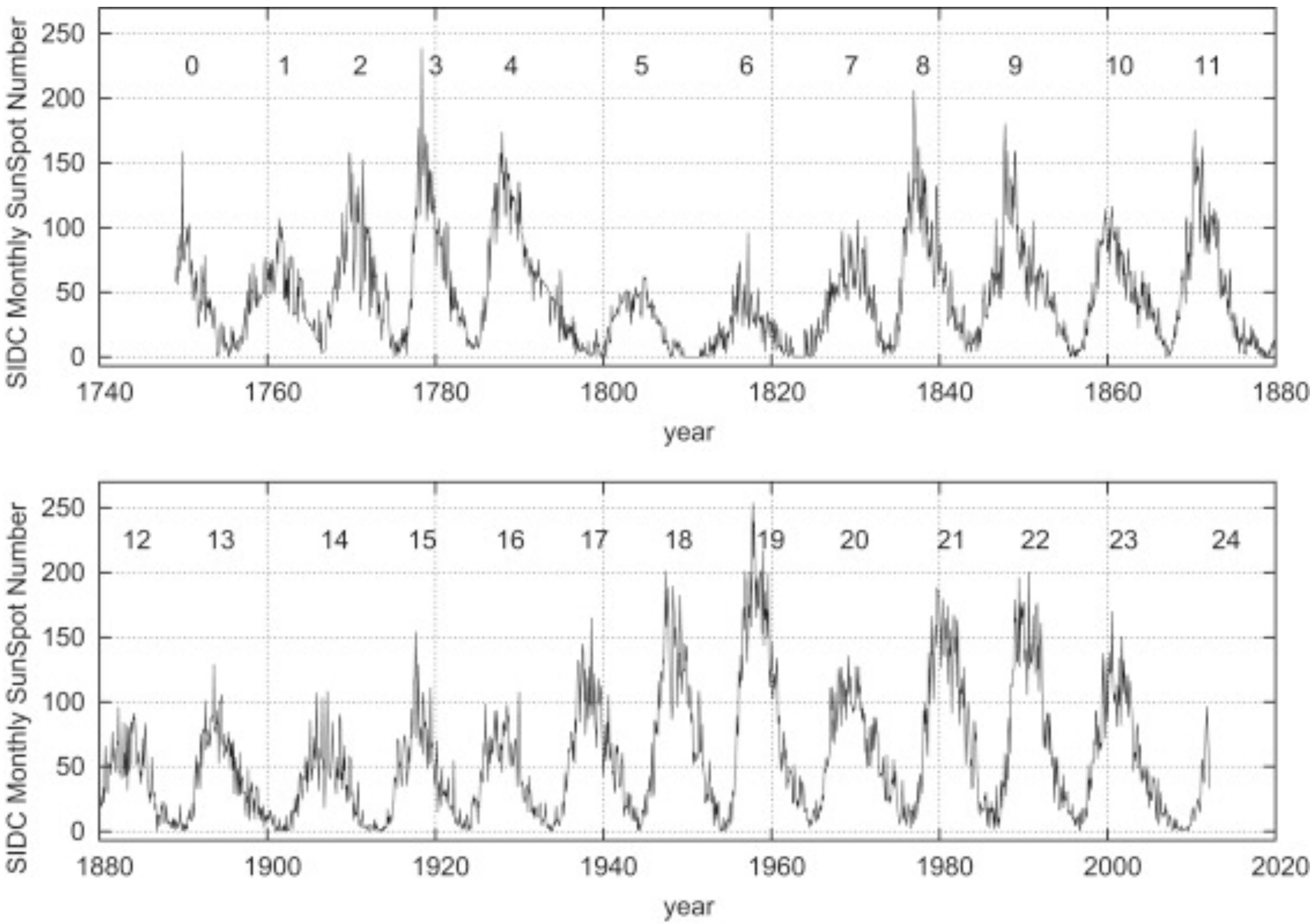
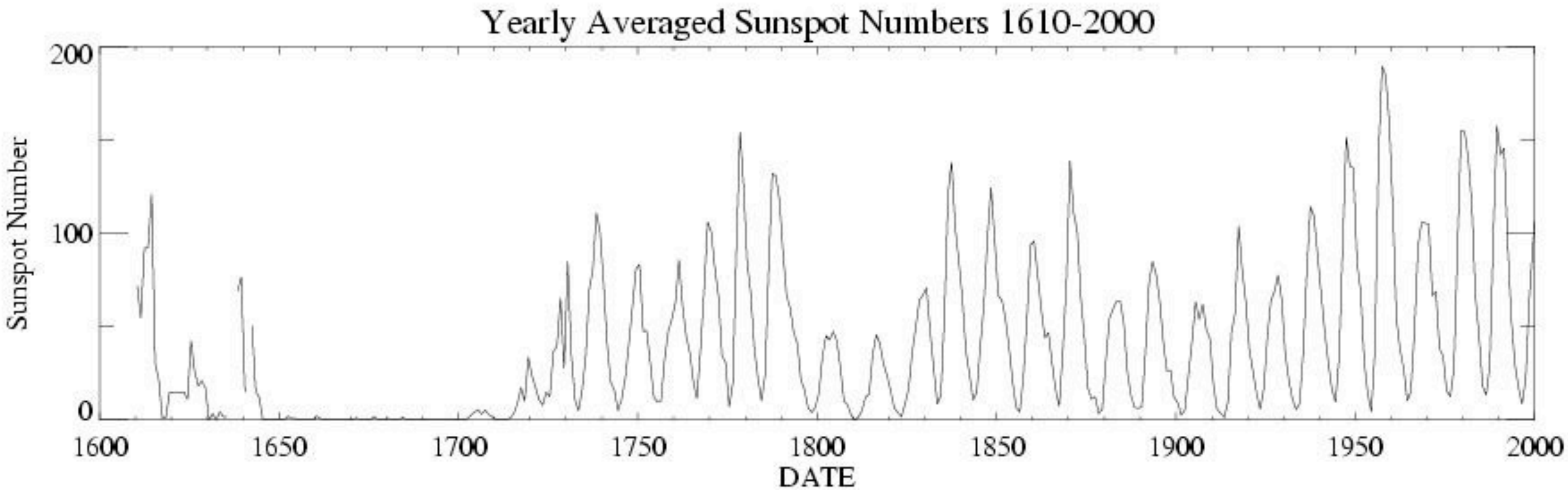
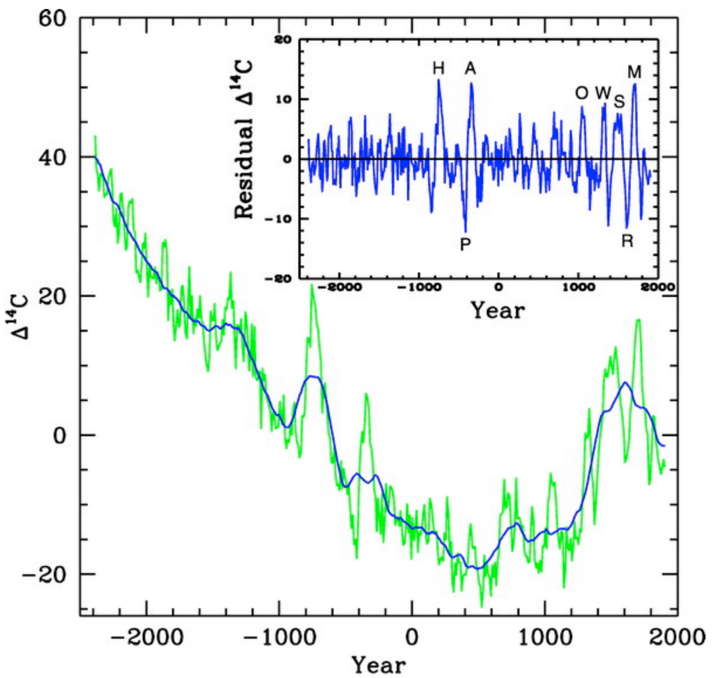
The number of sunspots visible on the Sun waxes and wanes in an approximately 11-year cycle (although individual cycles vary from 8 to 14 years).



The Sun went through a period of inactivity in the late 17th century. From 1645–1715 very few sunspots were seen: the *Maunder minimum*. This period of solar inactivity corresponded to a climactic period called the “Little Ice Age”, when rivers like the Thames froze regularly and it snowed in Rome.

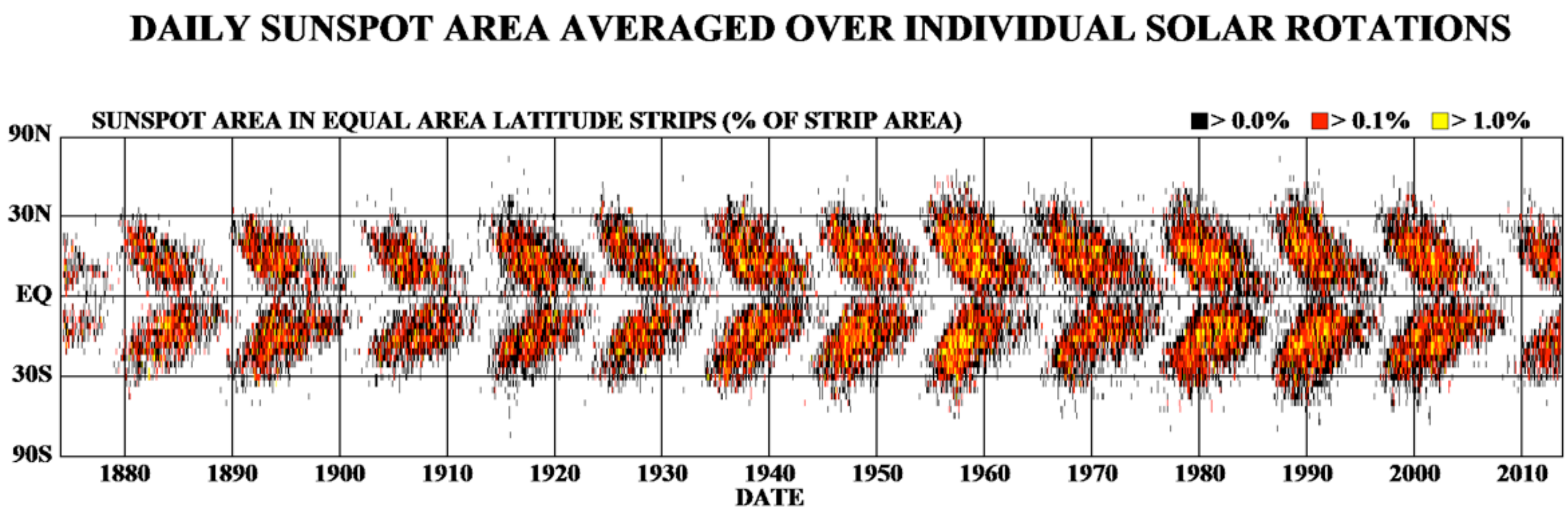


Several attempts have been made to identify other periodicities in the Sun's activity. By analysing radiocarbon measurements, authors suggest there is a Maunder-type minimum about every two centuries, which means there is another one due in the next few decades.

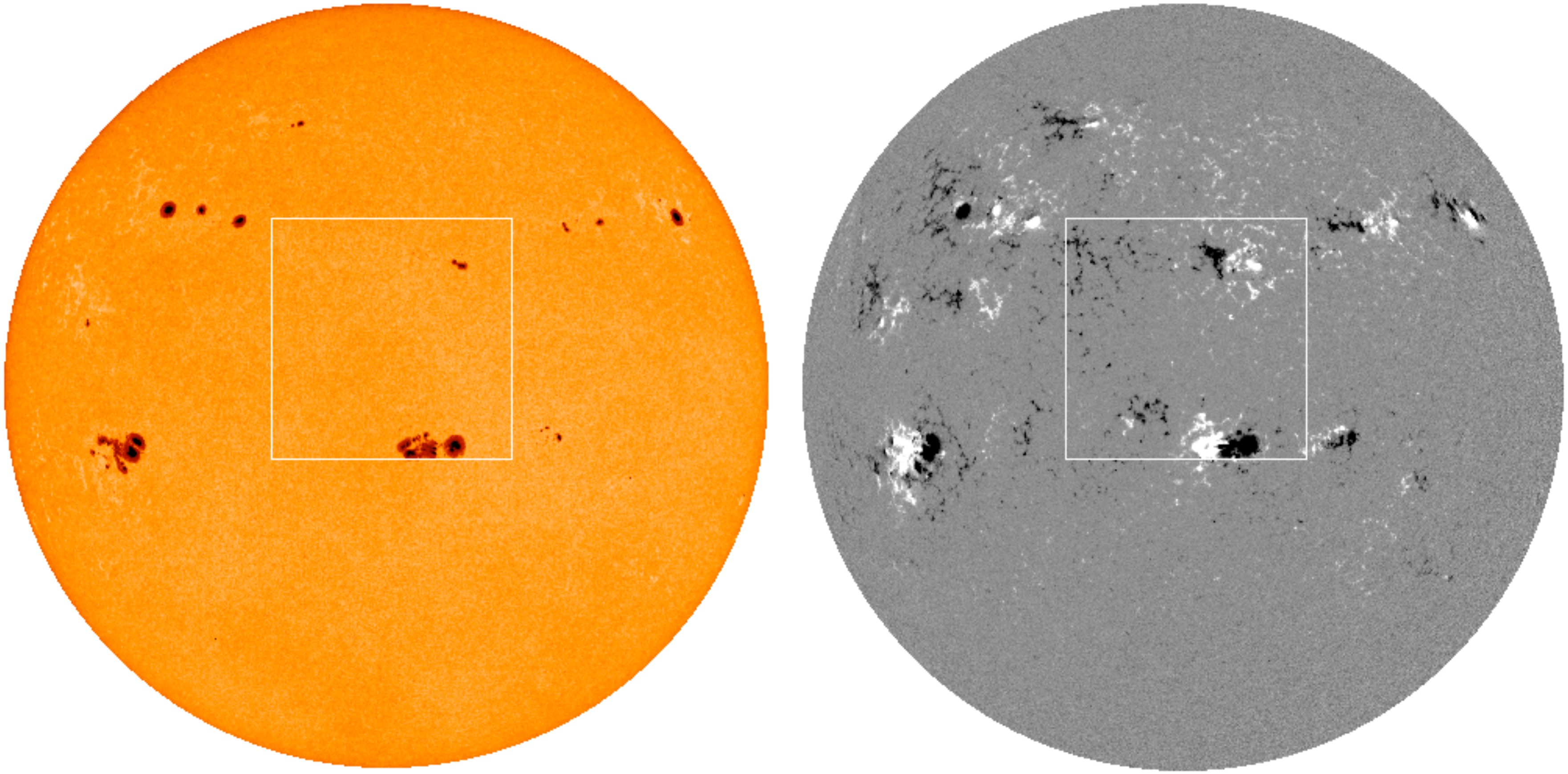


Activity of the Sun over the last 4000 years, based on measures of ^{14}C, which is sensitive to solar activity. After removing the long-term trend (the solid line), the residuals have a period of ~210 years; the M represents the Maunder minimum. (From Bonev et al. 2004)

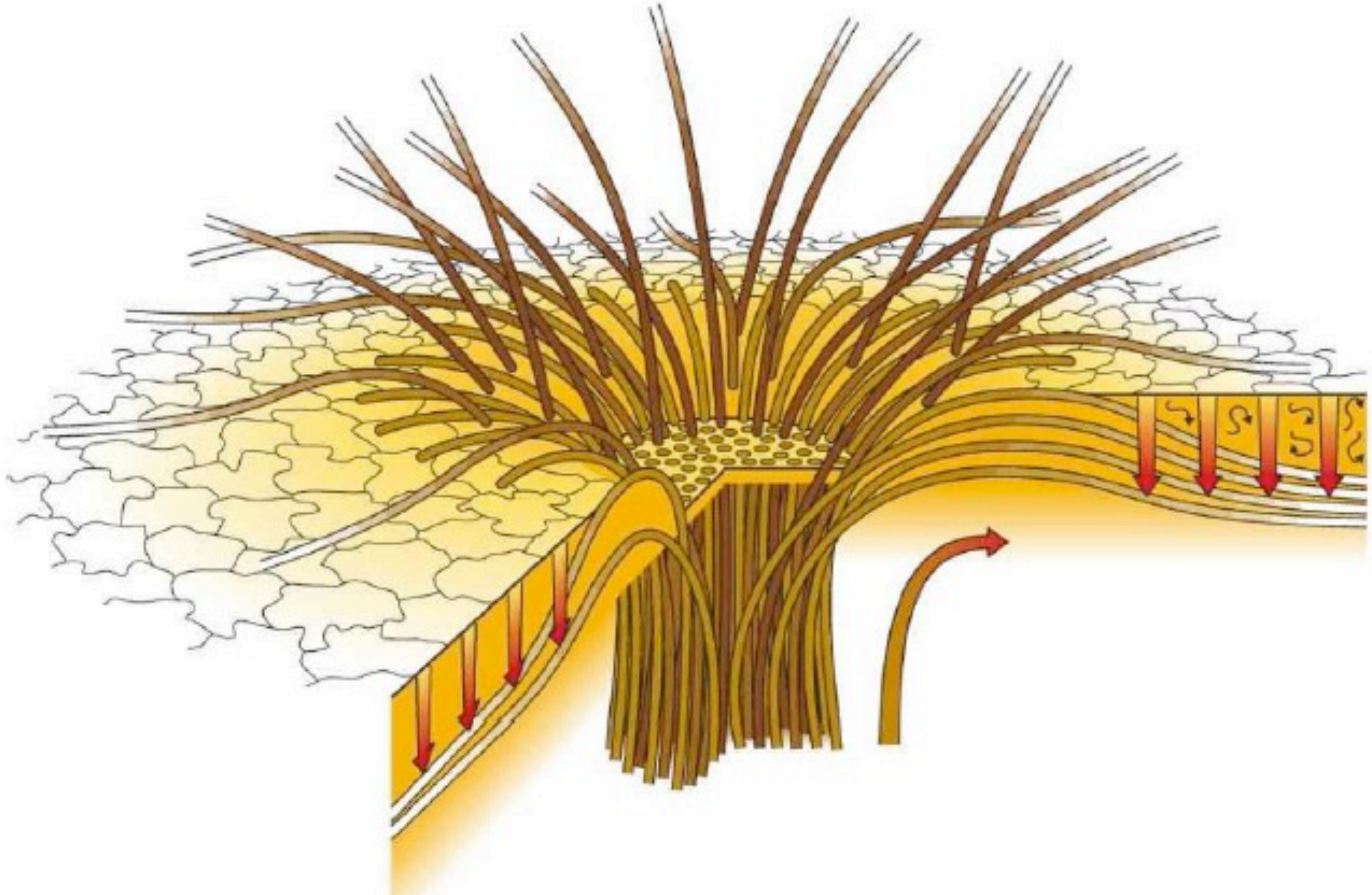
Sunspots do not appear at random on the Sun's surface, but are concentrated in two belts between latitudes 10 and 30 degrees. At the start of each solar cycle, spots are found at high latitudes; the bands move closer to the equator, then fizzle out near the equator. Spots from the new cycle appear at high latitude while the spots from the old cycle are near the equator.



Sunspots are associated with strong magnetic fields. When sunspots come in pairs, they have opposite polarity (shown as black and white in the magnetogran

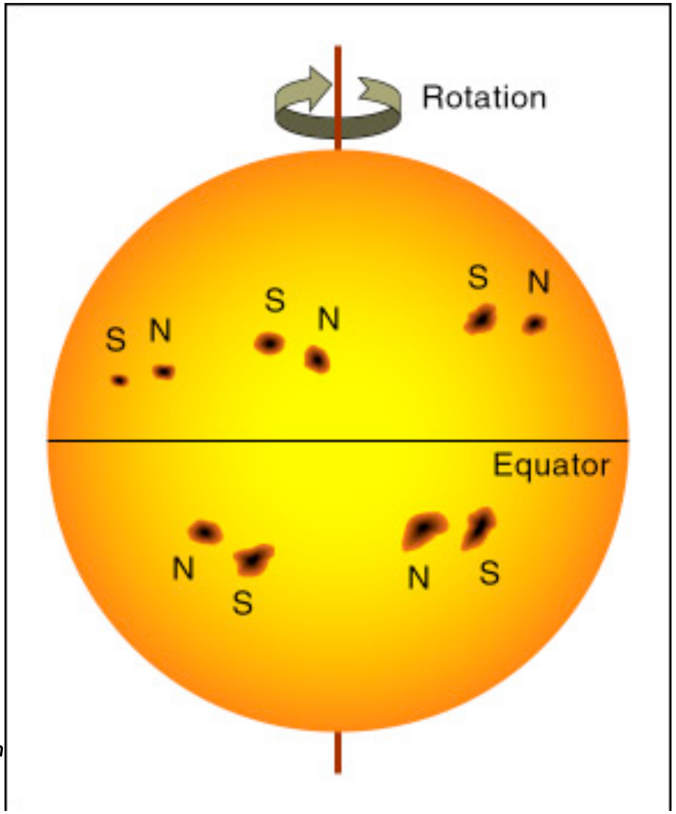


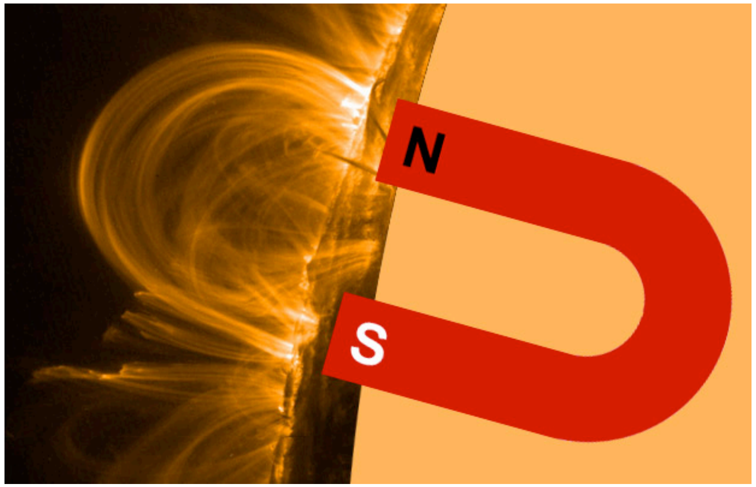
SOHO continuum (left) and magnetogram images for 28 Feb 2000, near the peak of the sunspot cycle.



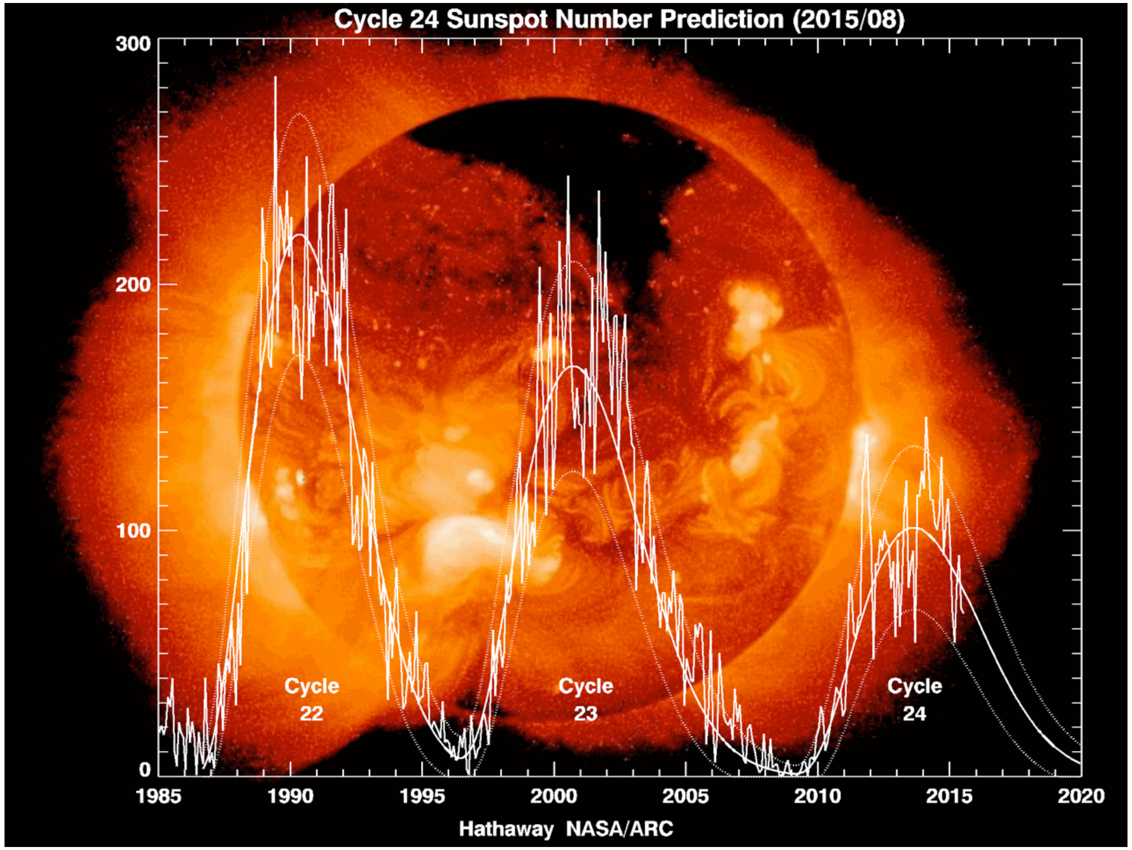
Sketch of the upper portion of a sunspot. The magnetic field is held together by converging fluid in a vertical umbral column, and then splays out through and above the penumbra where the fluid is unable to confine it, alternating between flux tubes rising almost freely into the upper atmosphere and tubes forced back beneath the photosphere by descending convective flow (indicated by the broad vertical arrows). (From Gough 2009, arXiv:0909.5338)

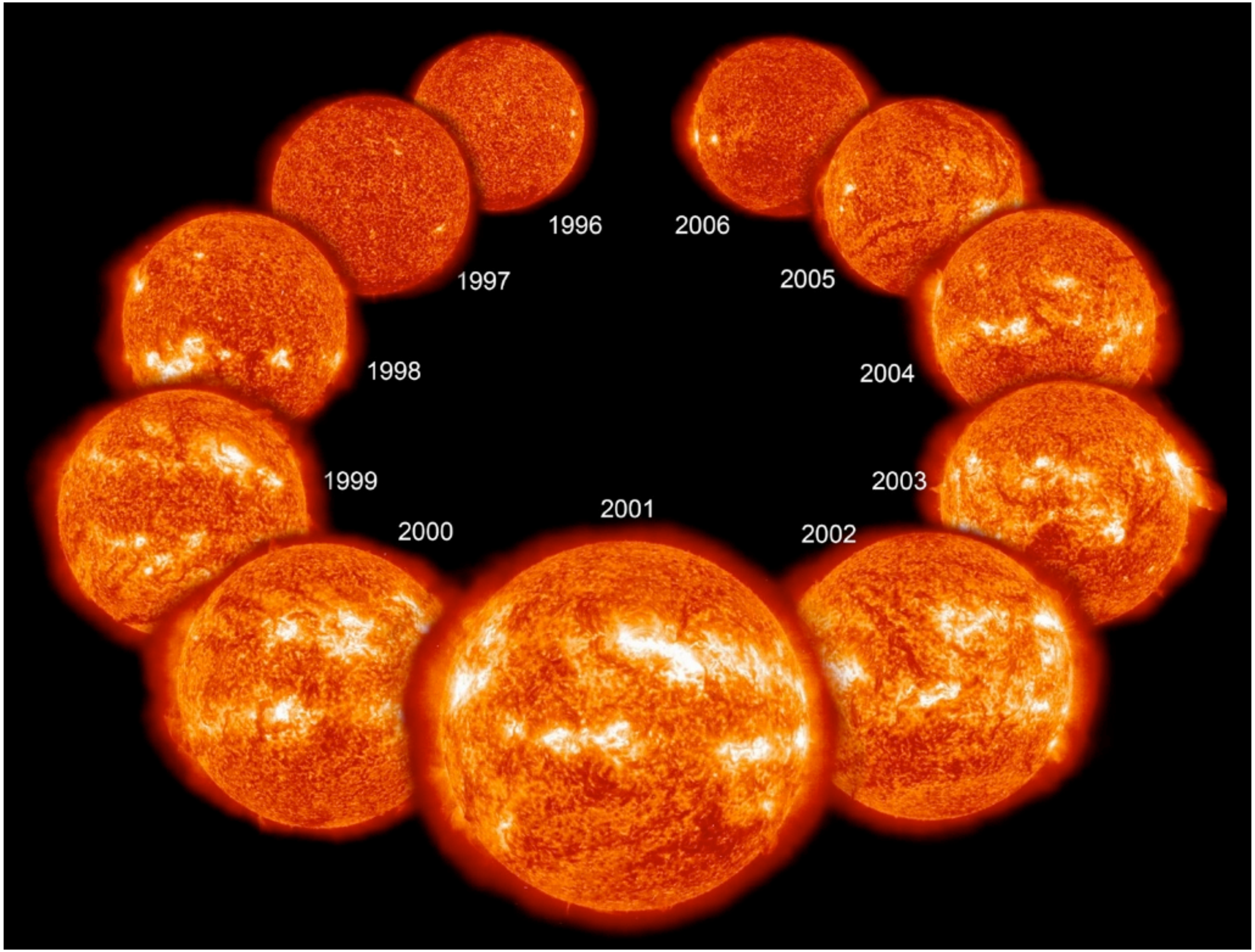
During a given sunspot cycle, the leading sunspot in each group has the same polarity in the northern hemisphere, and the opposite polarity in the southern hemisphere. In the next sunspot cycle, the leading polarity in each group is opposite to what it was in the previous cycle.





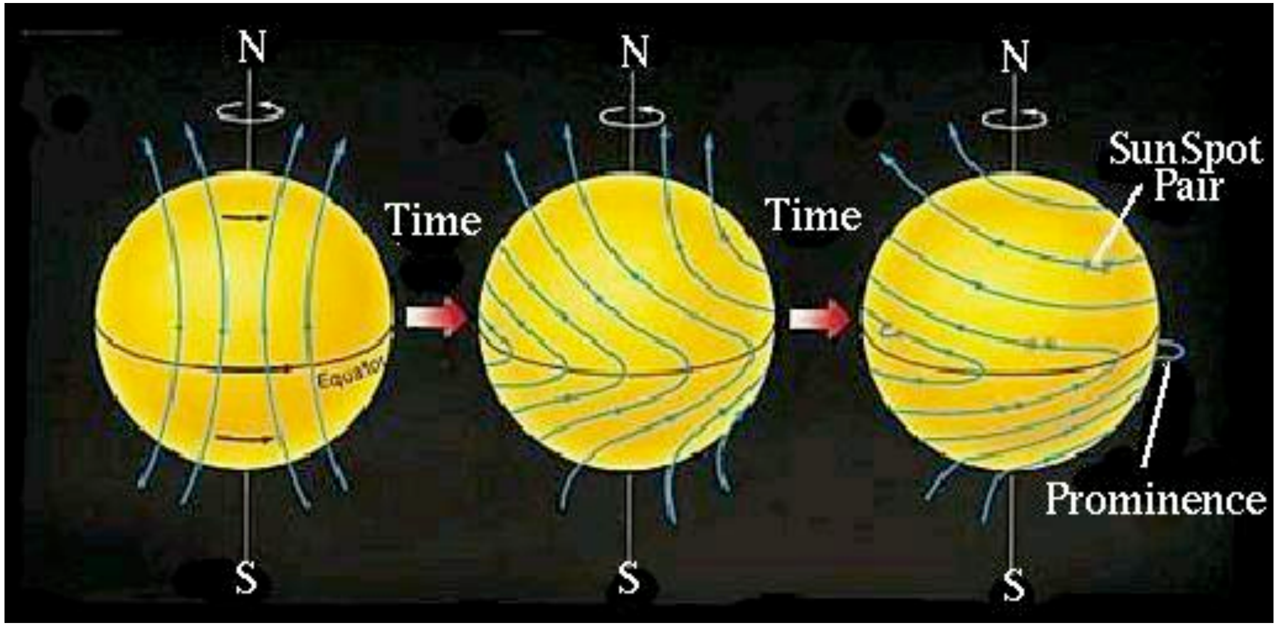
Solar minimum occurred in 2007. The first sunspot in the next 11-year sunspot cycle – Solar Cycle 24 – was observed in January 2008, nearly a year later than predicted. Sunspot numbers picked up in 2010 and 2011, but since then have been dropping. Cycle 24 is shaping up to be the weakest cycle in a century.



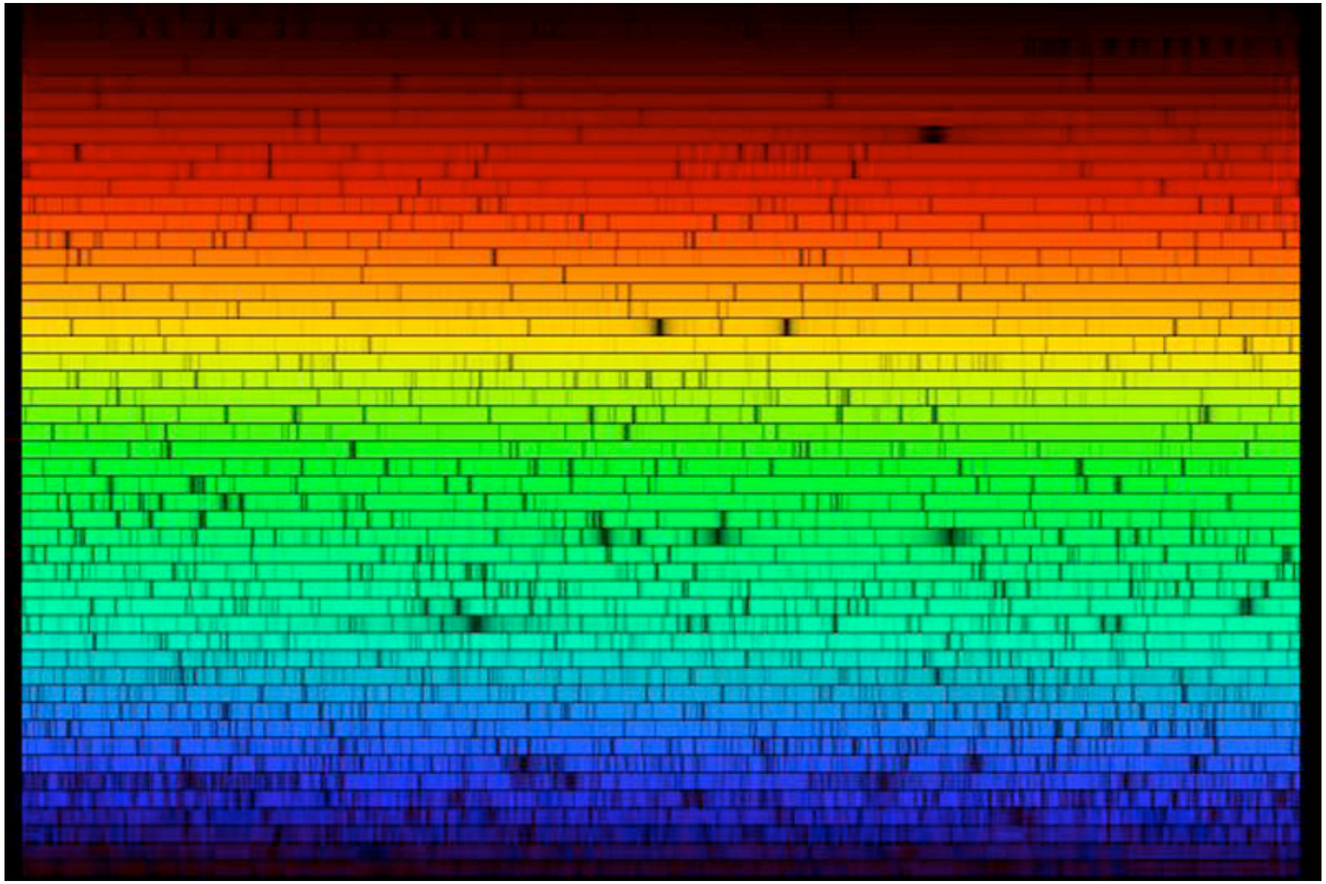


A complete solar cycle observed by SOHO

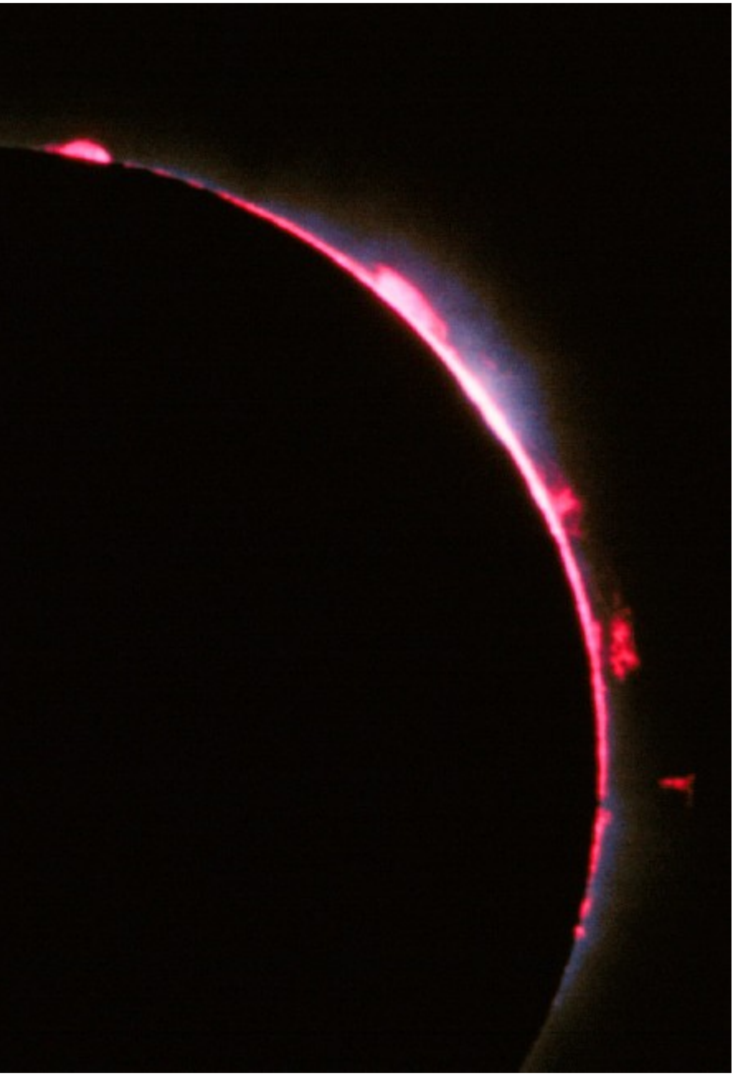
The Sun's magnetic field is confined to shallow layers near the surface. As the Sun rotates, since the equator rotates faster than the pole, the magnetic field lines get wound up. Occasionally a loop of magnetic field breaks free: we see the feet of the loop as a pair of sunspots.



The upper layers of the photosphere are cooler and less dense than the deeper layers, so they produce dark absorption lines in the solar spectrum.

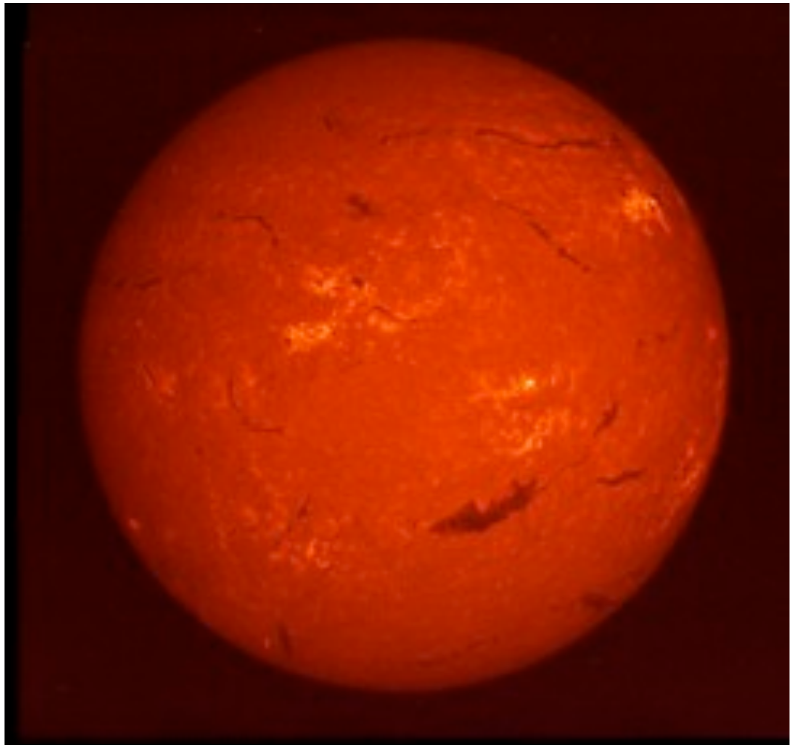


The chromosphere

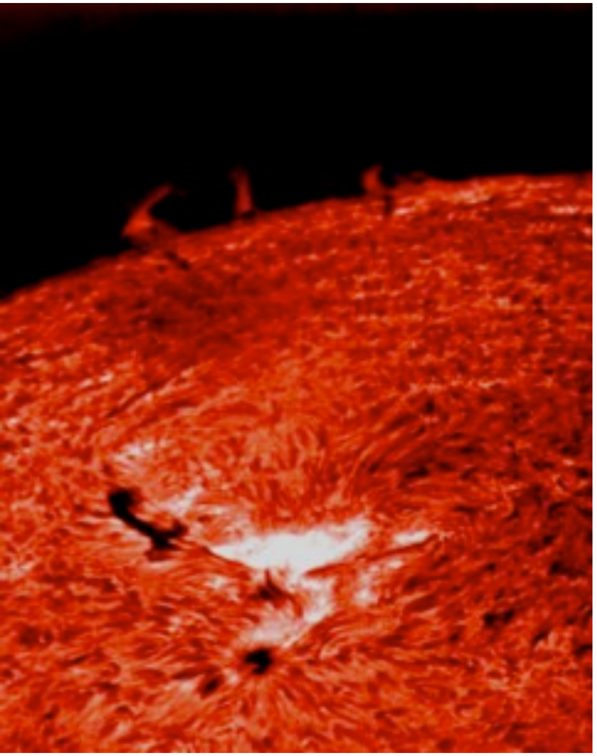


Above the photosphere is an irregular layer, about 2500 km thick, where the temperature rises from 6000° to about 20,000° – the *chromosphere*. The thin, hot gas emits Hα radiation, but it can only be seen during total eclipses, when the light from the rest of the Sun is blocked and a thin band of colour can be seen along the rim.

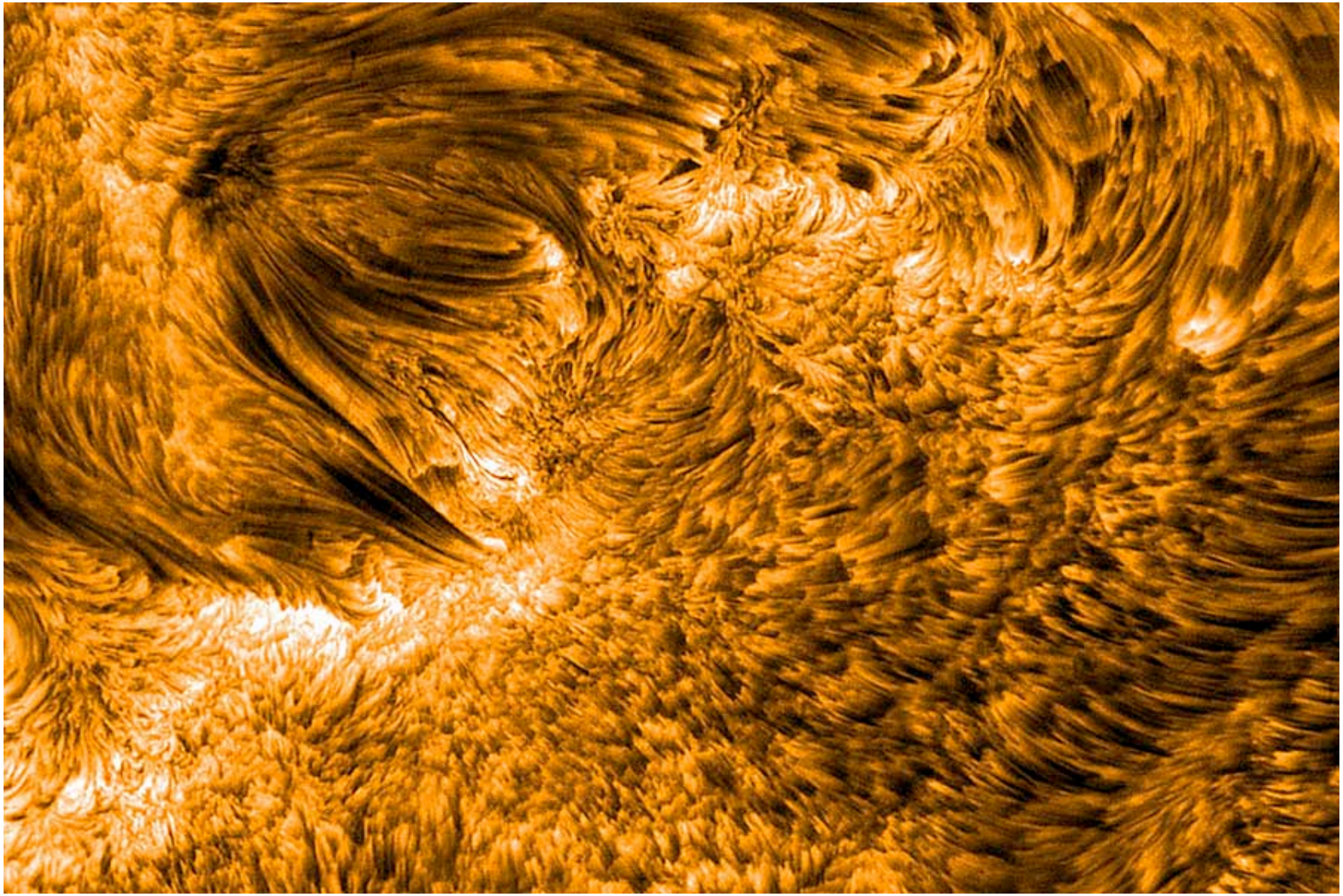
When the Sun is viewed through a narrow filter which isolates the Hα emission, a wealth of new features appears:



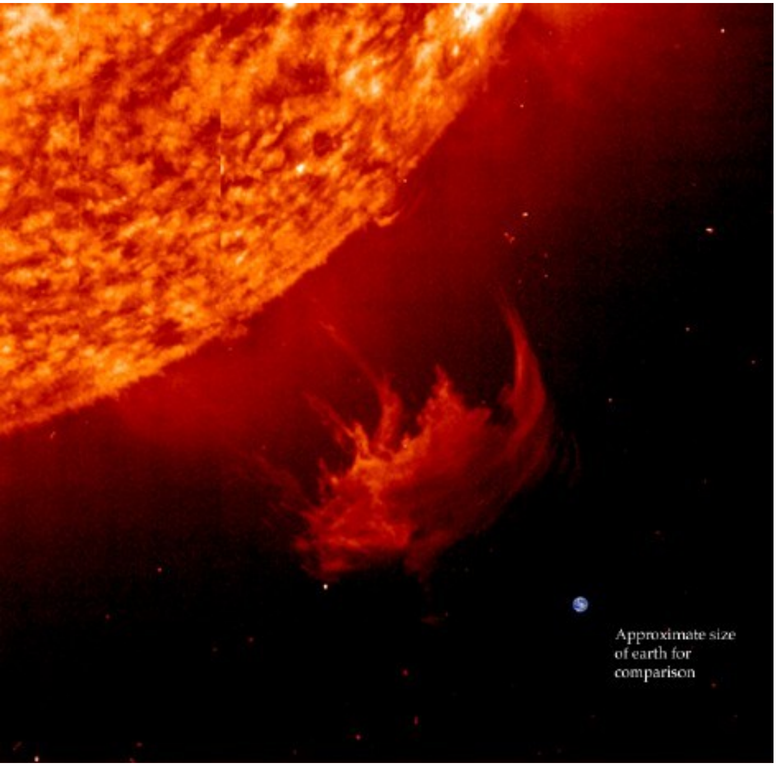
– dark *filaments* and light *plage*



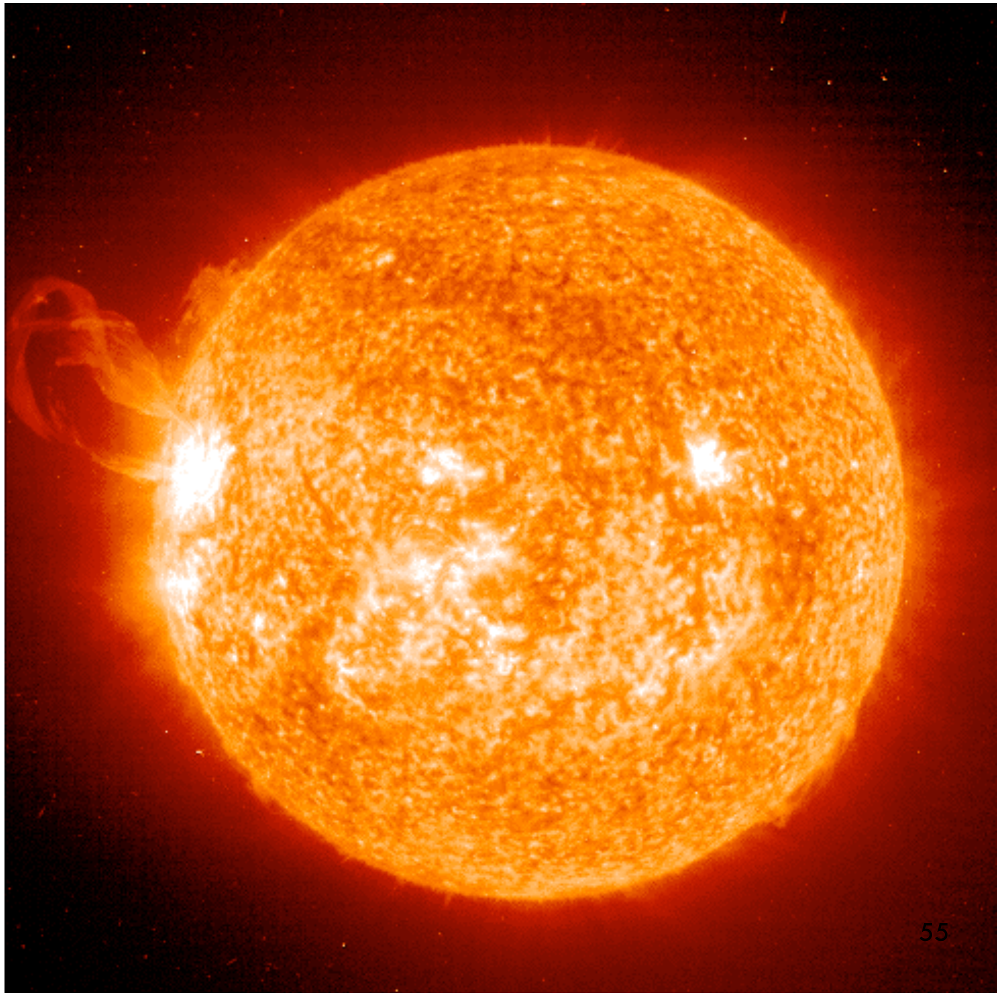
– *spicules*, short dark streaks which are very short-lived but which eject material into the corona



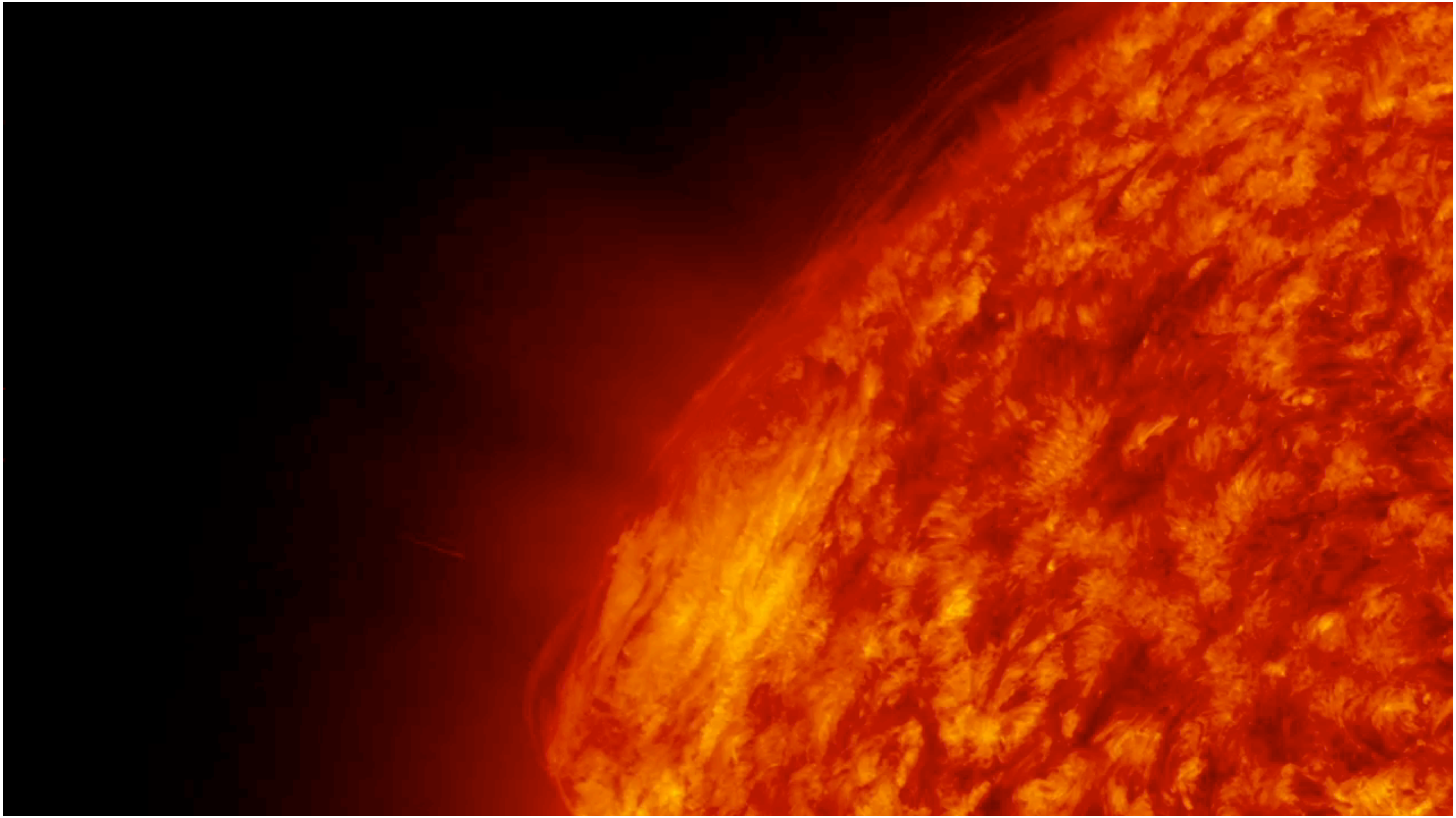
Spicules seen by the Swedish Solar Telescope



When a filament is seen off the edge of the Sun it is called a *prominence*.



Some prominences erupt off the edge of the Sun in minutes or hours; these blobs of gas are truly enormous.



Prominence erupting in the first-light images from SDO

The corona

Above the chromosphere is the extended outer atmosphere called the *corona*. It extends several solar radii from the surface.

The corona is a million times less bright than the photosphere, so it can only be seen during total eclipses, or by masking out the Sun using a coronagraph.

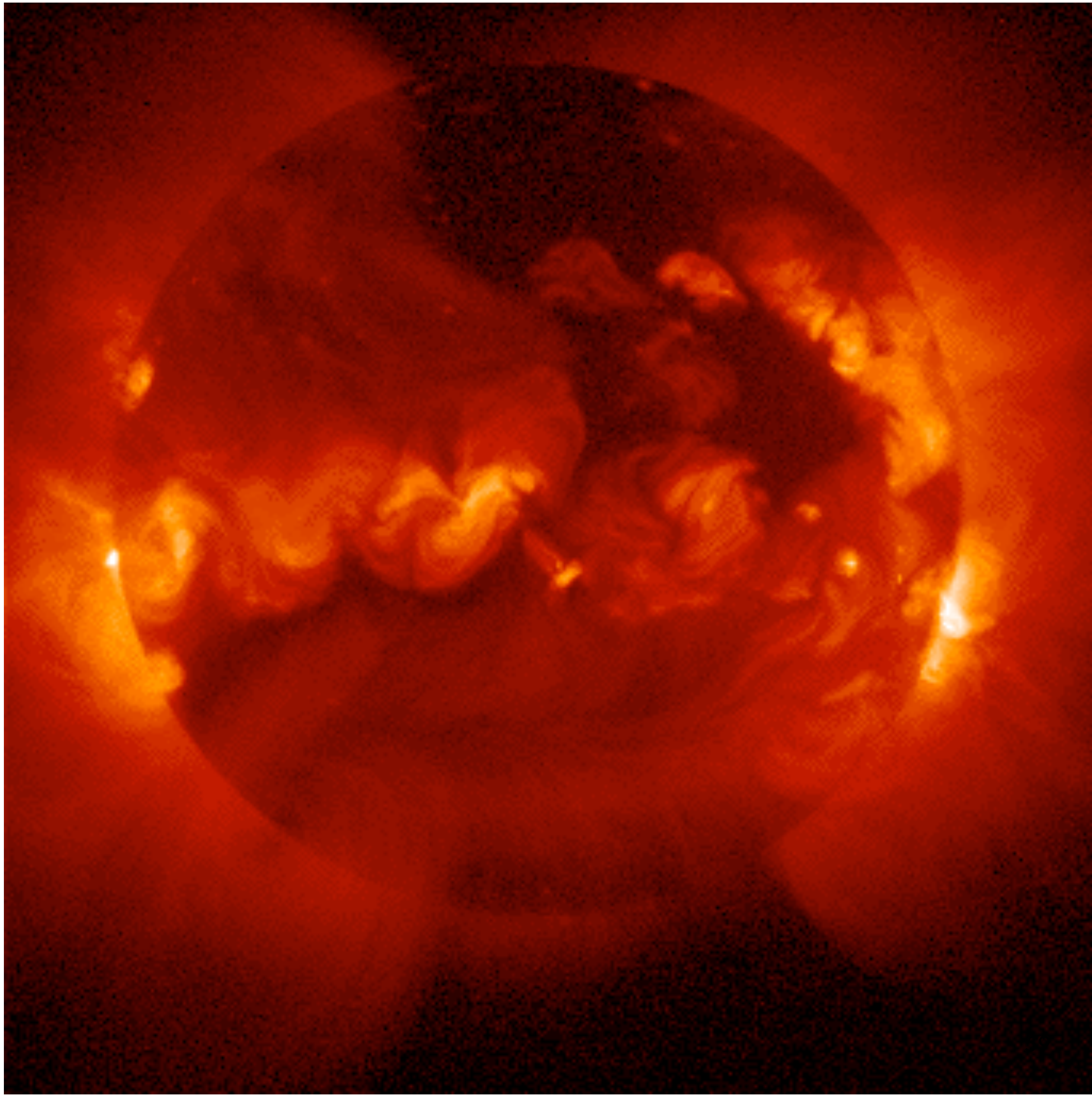
The corona is extremely tenuous: about 10 billion times less dense than the Earth's atmosphere at sea level. However, it is extremely hot, with temperatures of more than 1,000,000 K just above the photosphere.

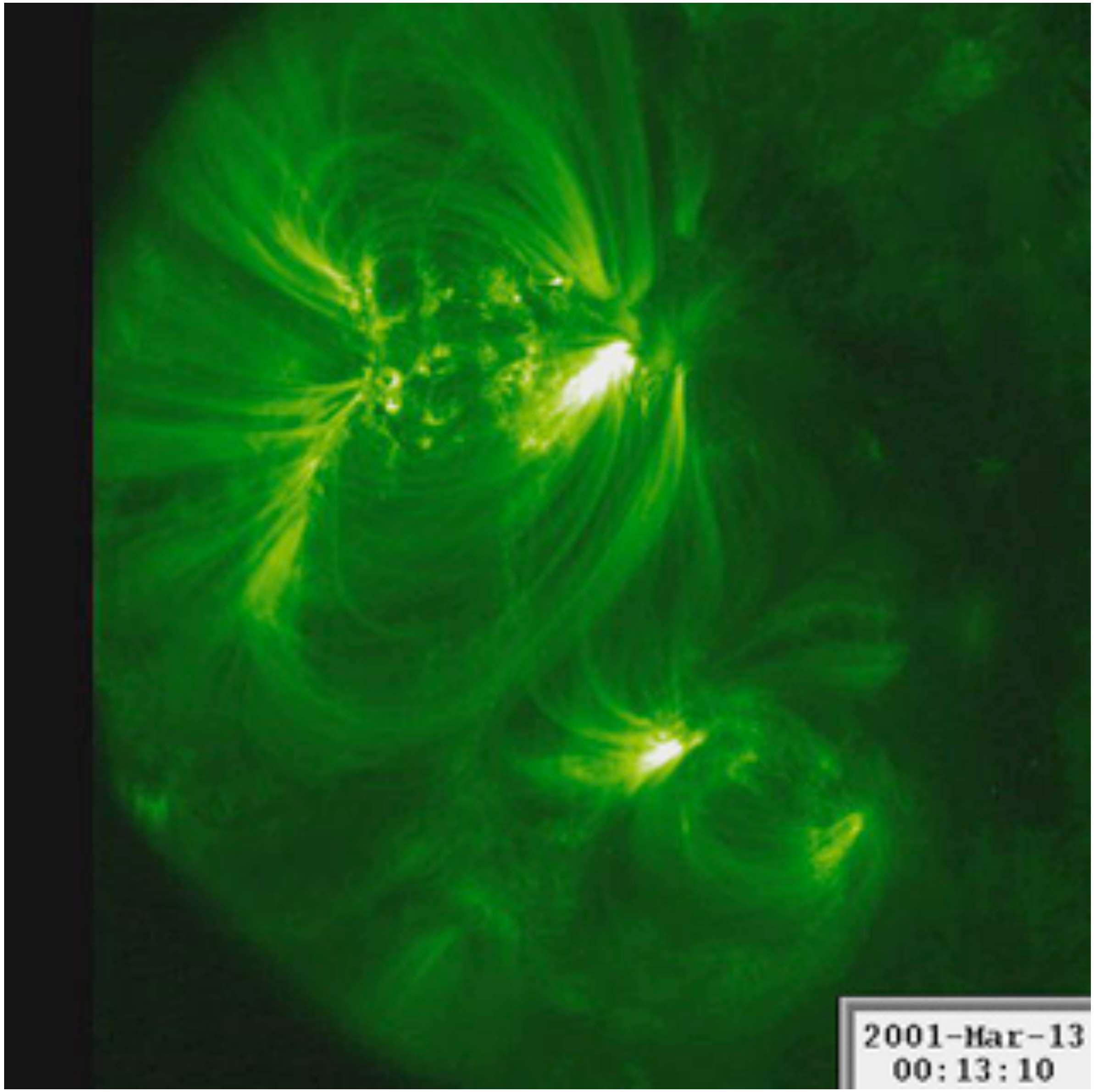
The source of the heat of the corona is a mystery. However, the extreme heat means that the corona is visible in X-rays.

X-ray images of the Sun show that the corona is a violent, ever-changing place.

Coronal loops are found around sunspots. They are associated with the magnetic field lines connecting magnetic regions on the solar surface, and can last for days or weeks, though most change rapidly.

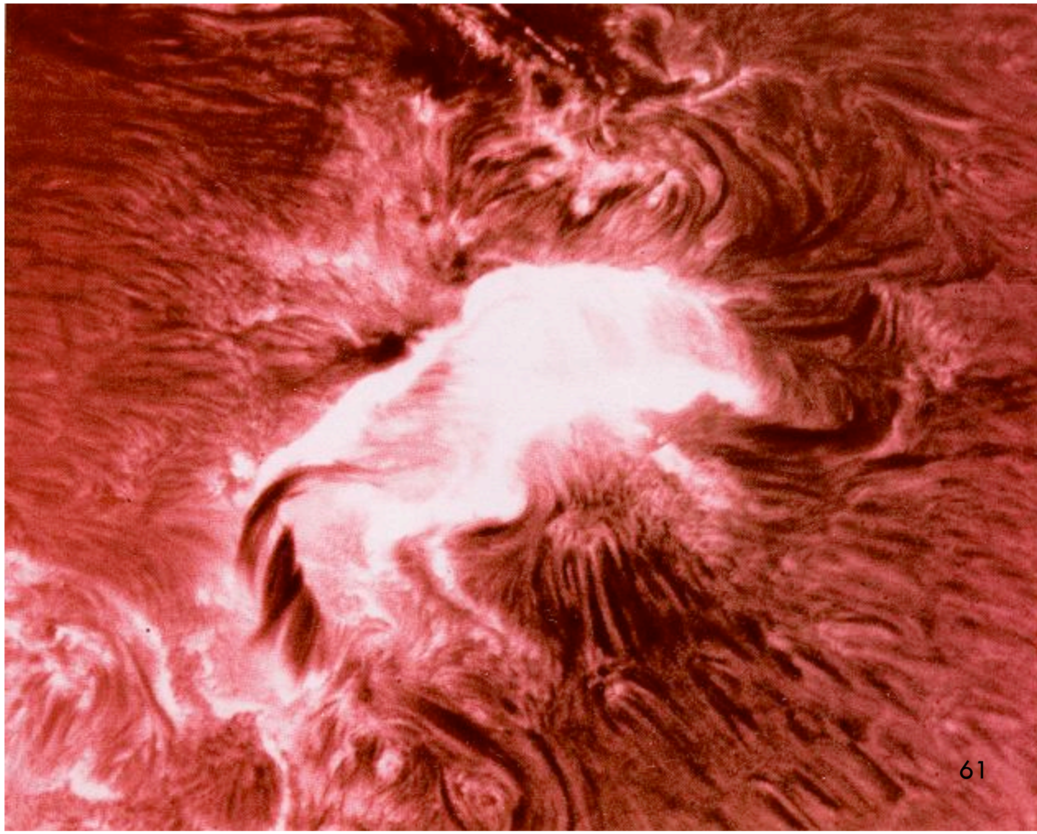
The dark regions at the poles are *coronal holes*.

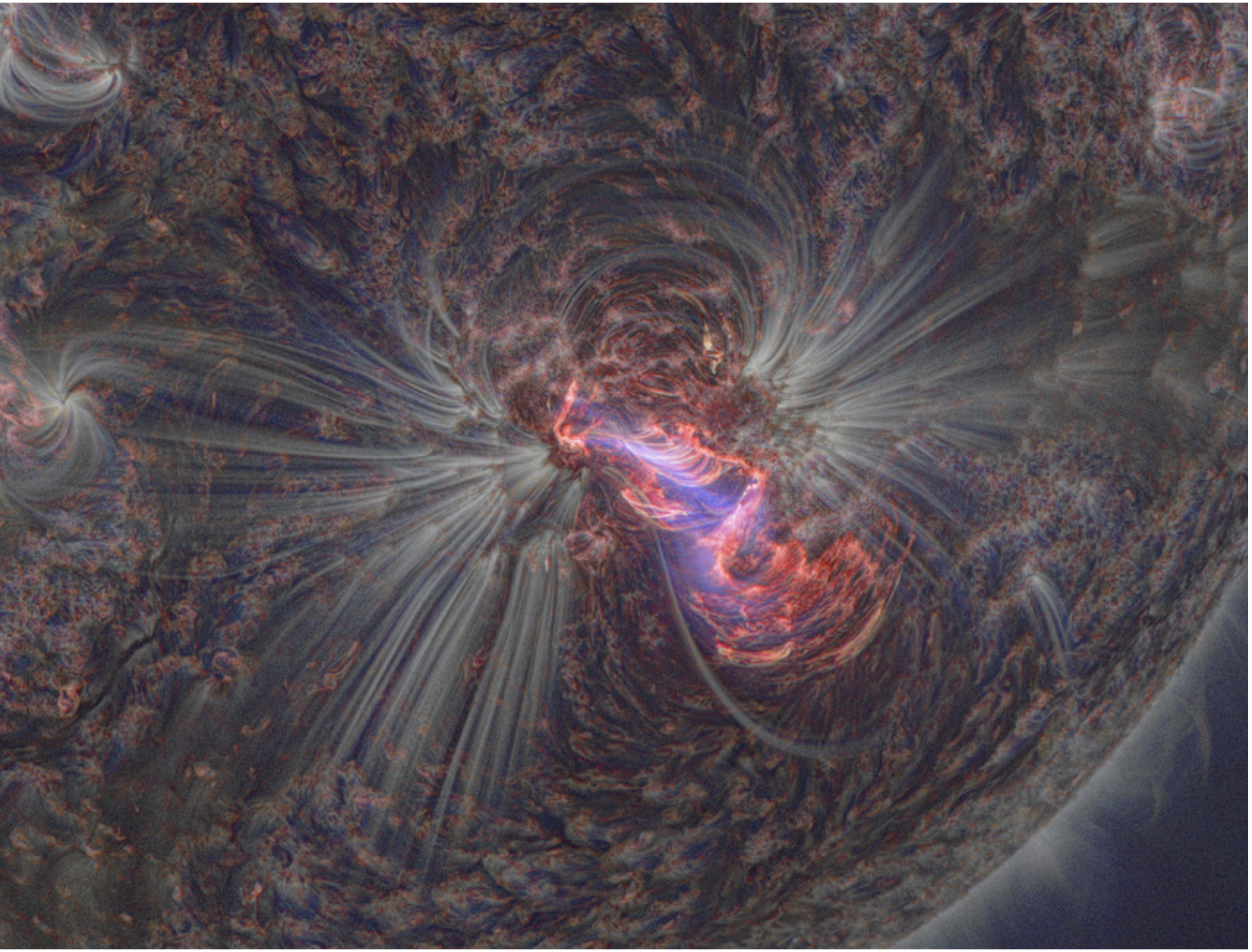




SOHO/TRACE movie of coronal loops.

Solar flares are tremendous explosions on the surface of the Sun. They typically last a few minutes and release energy across the whole EM spectrum, from radio to X-rays, as well as energetic particles.

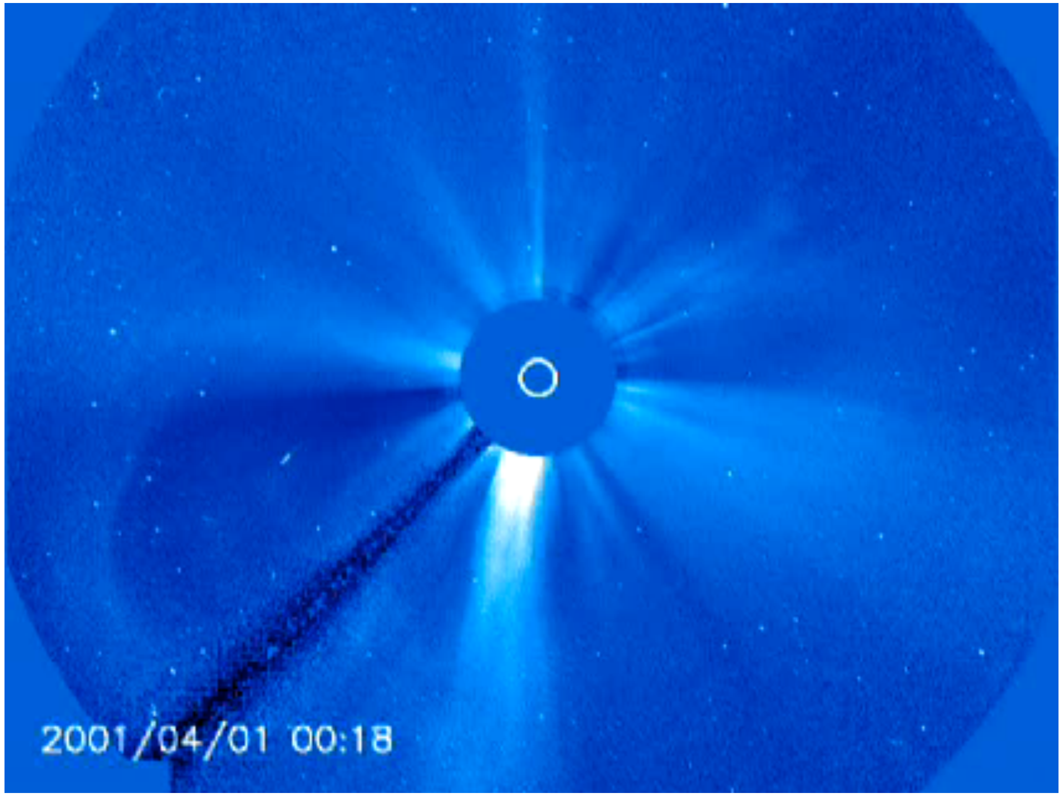




Solar flares are observed in Hα filters, white light, or (more recently) X-ray images. They are associated with sunspots, and are more common at the peak of the activity cycle.

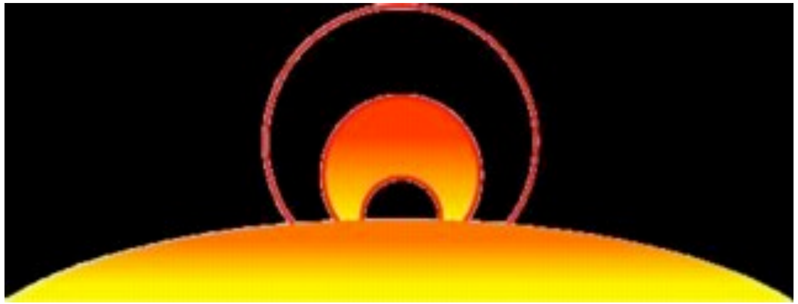
Solar flare from solar active region AR2192 on 24 Oct 2014.

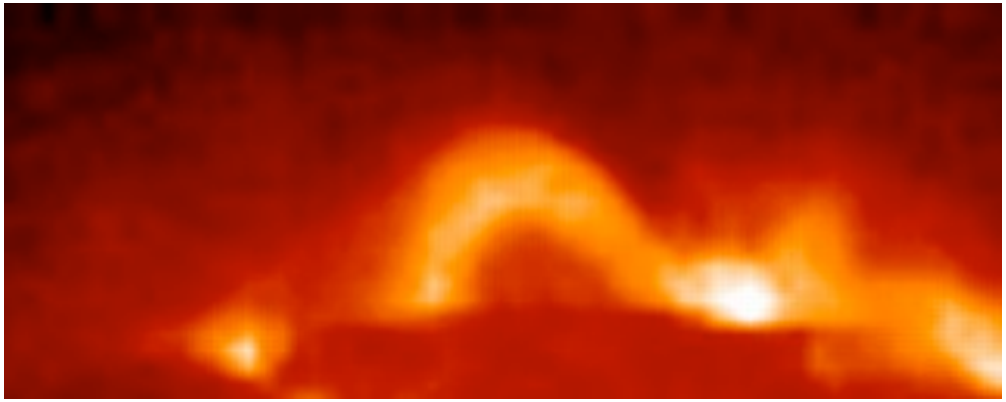
Solar flares are often, but not always, associated with *coronal mass ejections*, where enormous quantities of material are ejected from the surface of the Sun. The two events now appear to be related but not identical.



Movie showing several coronal mass ejections and associated proton showers, from LASCO, the coronagraph on SOHO.

All of the features seen in the photosphere, chromosphere and corona appear to be associated in some way with the Sun's magnetic field. Loops of magnetic field protruding into the corona trap hot gas, which can be seen because of the X-rays produced.

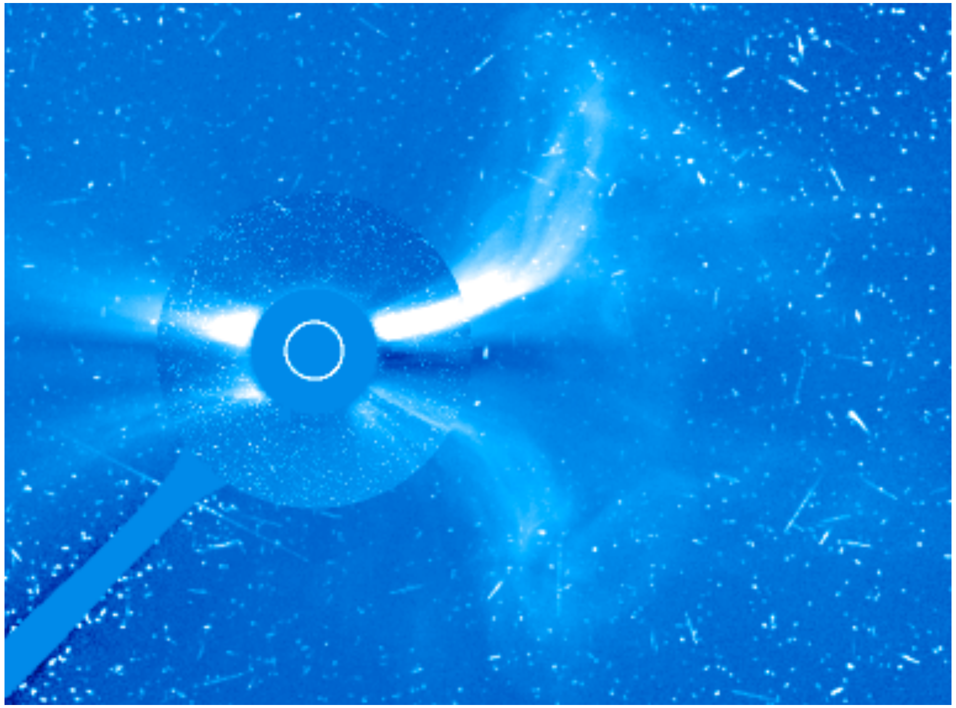




Sketch of a magnetic loop, compared to a real image from Yohkoh.

Flares and coronal mass ejections appear to be caused by the twisting or crossing of magnetic fields, and the subsequent explosive release of energy when the fields re-arrange themselves.

Here is a series of images showing a giant coronal mass ejection emerging from the Sun. The points and streaks in the last two images are caused by protons accelerated to 10% the speed of light, arriving about an hour behind the light.



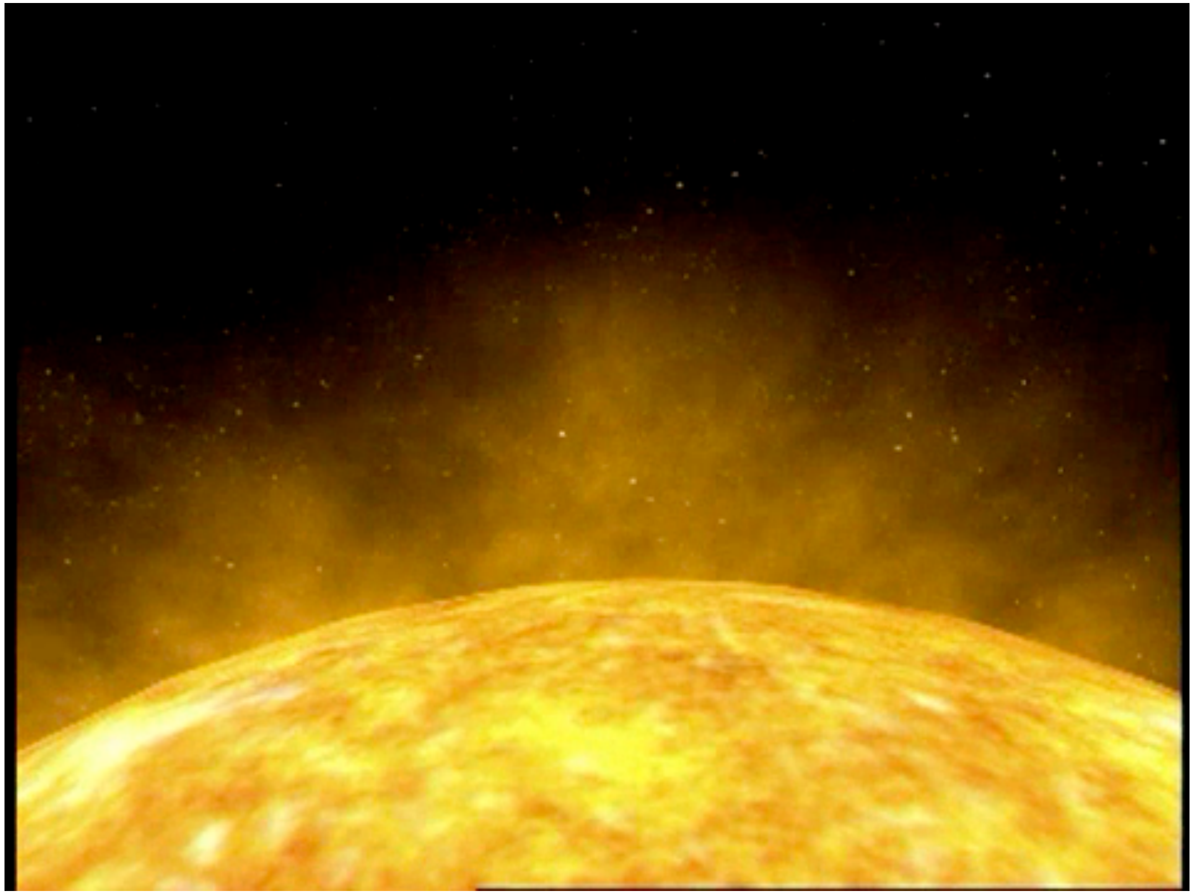
The solar wind

The Sun emits a wind of high-speed charged particles. This may be considered as an extension of the Sun's outer atmosphere.

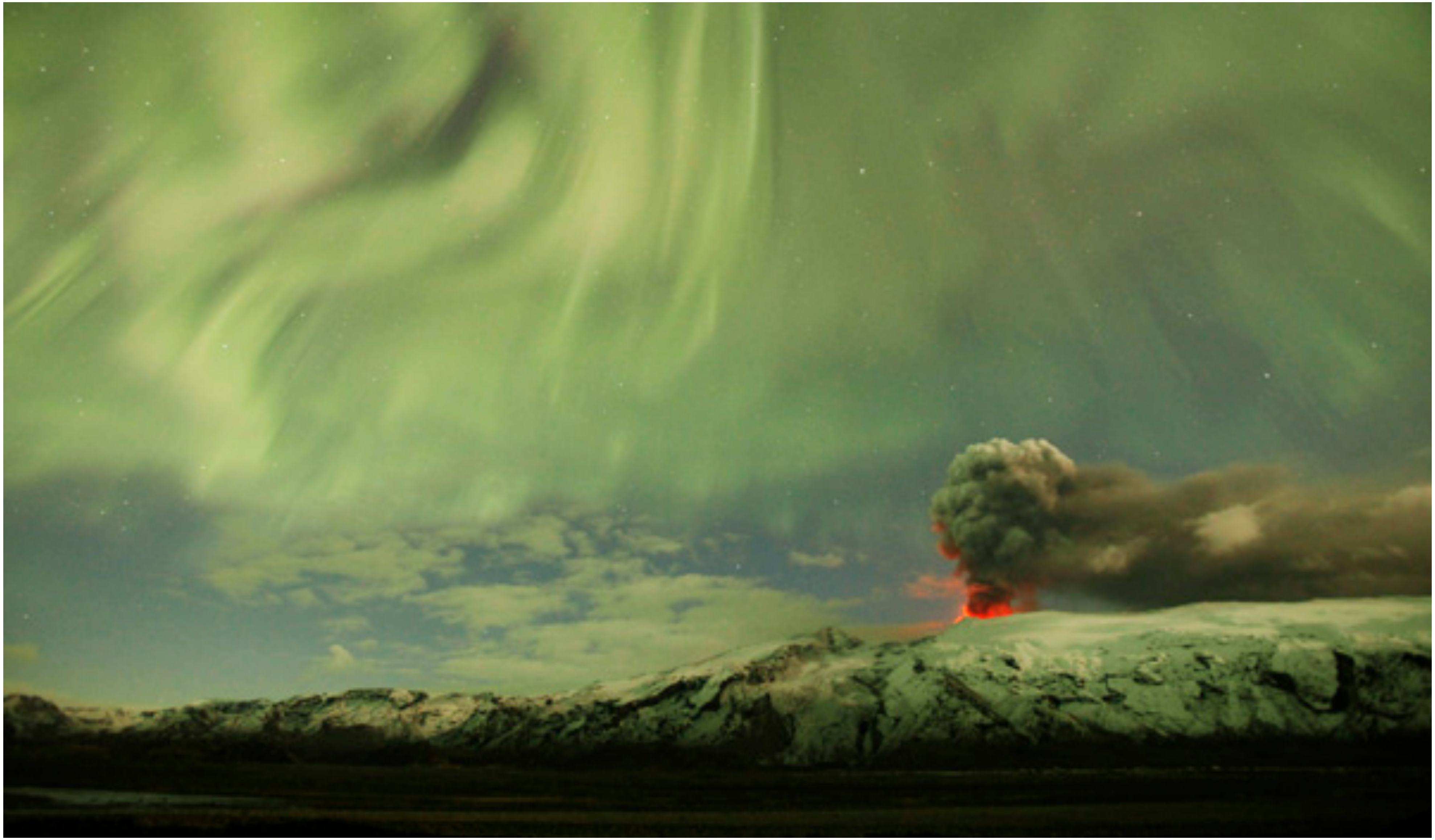
The solar wind consists primarily of electrons and protons, with a few heavier ions. It blows continuously at an average velocity of 400 km/s.

It escapes from the Sun primarily through coronal holes at the poles, and is responsible for auroras when particles from the solar wind are trapped in the Earth's magnetic field.

The solar wind is responsible for auroras when particles from the solar wind are trapped in the Earth's magnetic field.



When coronal mass ejections arrive at Earth, they can cause geomagnetic storms which can have severe effects on Earth. The changes in the structure of the Earth's magnetic field can disrupt signals in the ionosphere, affecting radio transmission. Satellites can be damaged by being charged by ions, resulting in electrical arcs; geomagnetic storms also heat the outer atmosphere, causing drag on satellites.



Aurora over Iceland's Eyjafjallajokull volcano in the evening. Photo: Reuters

On 28 August 1859, a solar “superstorm” erupted, the largest event ever recorded. It knocked out telegraph lines all over the US and Europe, and produced auroras which were seen as close to the equator as Cuba.

If a similar storm occurred today, the consequences would be much more severe.

In 1989, a giant solar magnetic storm induced a catastrophic failure in the Quebec power grid, leaving 6 million people without power for 9 hours in the middle of winter. The economic cost of such incidents is likely to rise as more technology is susceptible to storms.

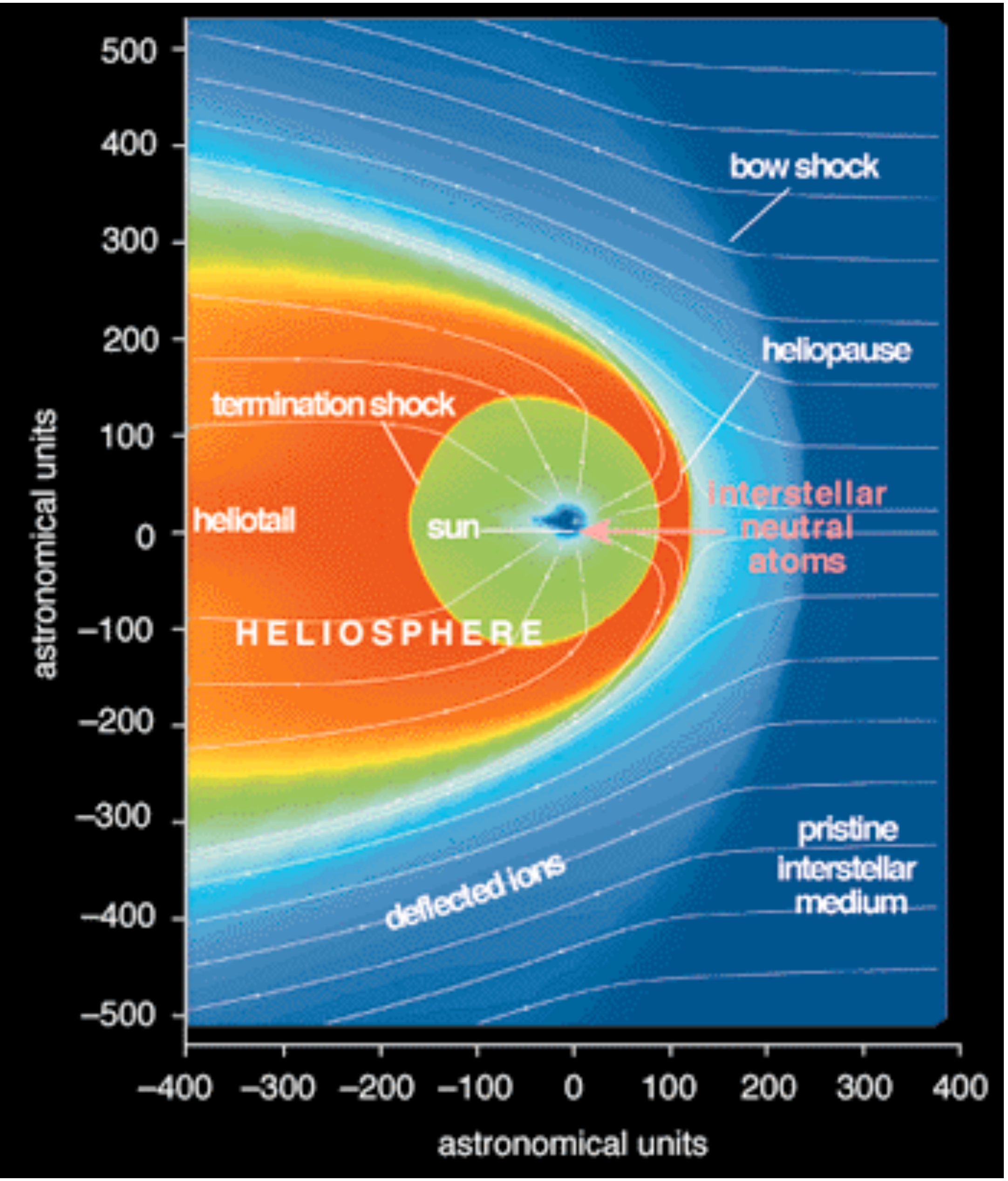
Much effort is going into improving our ability to forecast space weather.

SPACE WEATHER FORECASTING

Are We Ready for the Next Solar Maximum? No Way, Say Scientists

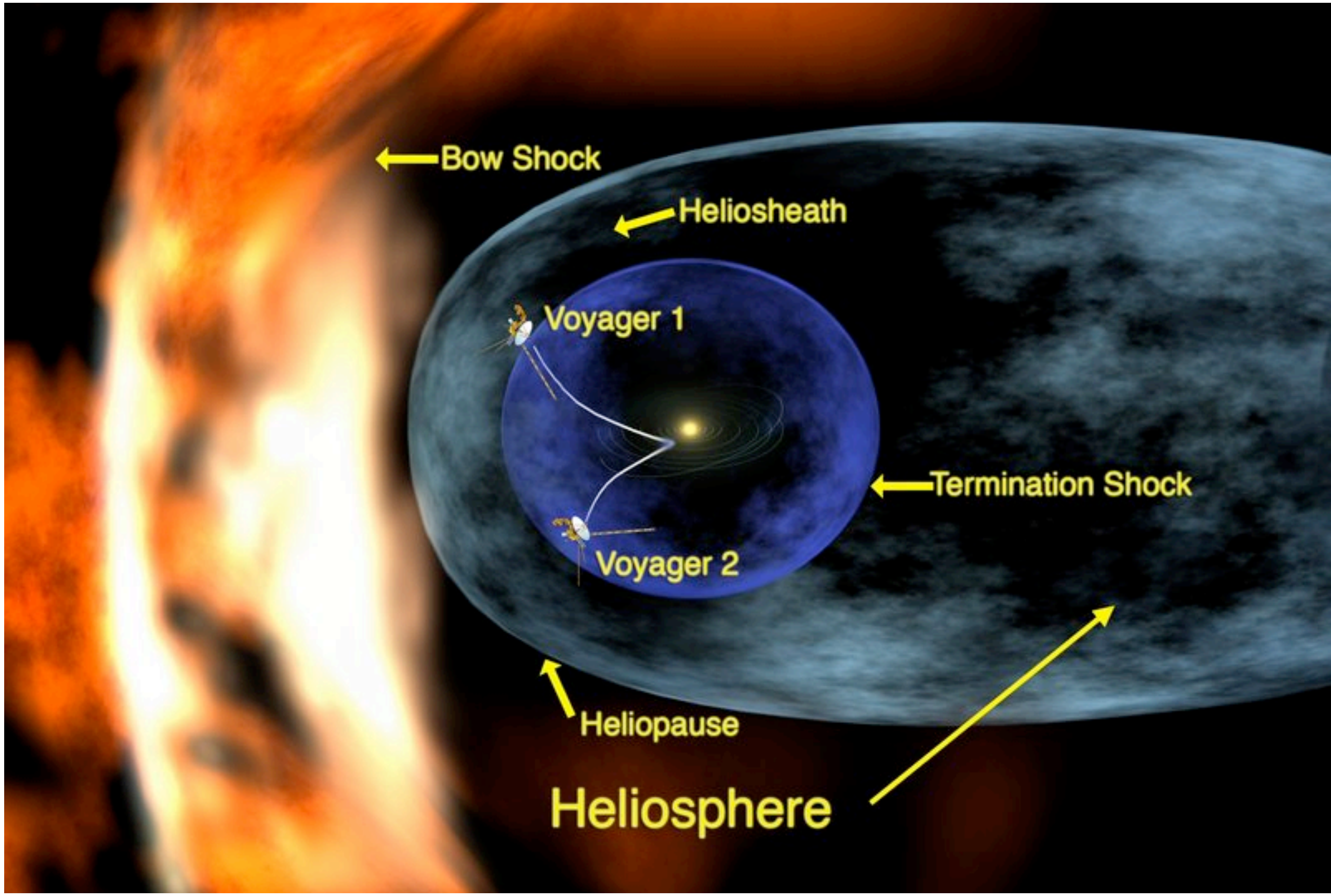
Forecasters testing their skills against the sun's mounting ferocity find themselves still in the early days of space weather prediction

The Big One for space physicists struck on 28 August 1859. The sun had blasted a billion-ton magnetic bubble of protons and the like right at Earth. On smashing into the planet's own magnetic cocoon at several mil- 11-year sunspot cycle of solar activity looms in 2012 or 2013. A space weather symposium* last month asked, "Are we ready for Solar Max?" The unanimous answer from participants was "No." "I think we are better space weather. "The general trend would be increasing vulnerability to the effects of space storms," says Baker, who chaired a December 2008 workshop report on the subject by the Space Studies Board of the U.S. National



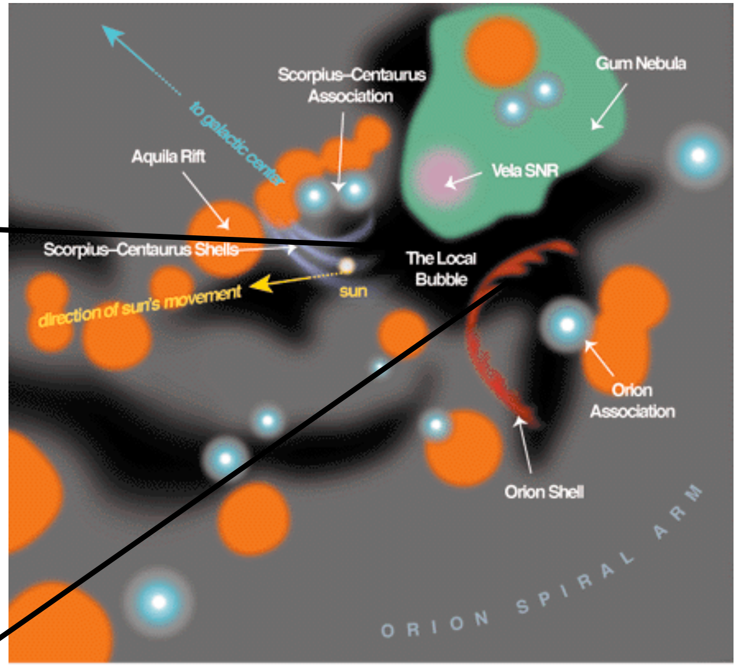
The region where the expanding solar wind meets the interstellar medium is called the *heliopause*; the wind becomes subsonic at the termination shock. The Sun's motion through the ISM produces a *bow shock* outside both of these.

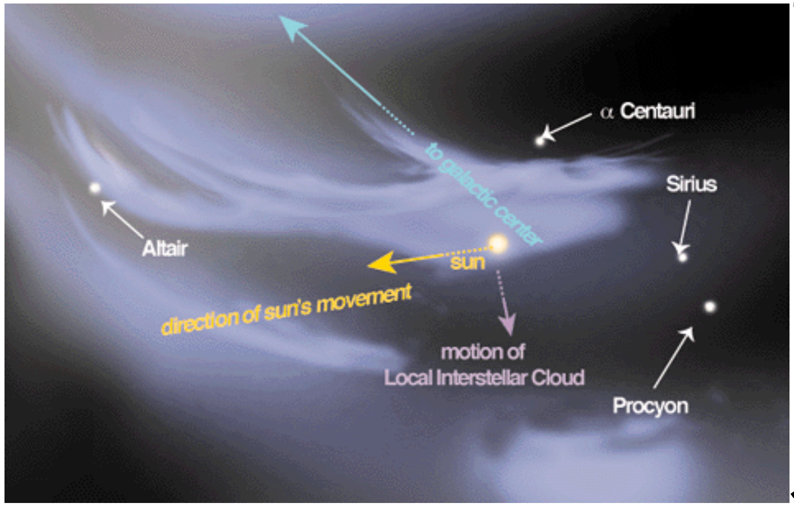
In May 2005, NASA announced that Voyager 1 had crossed the termination shock in November 2003.



The Sun is currently in an extremely low density region called the Local Bubble, with densities ~0.005 atoms cm^{-3}

In the next few million years, the Sun will encounter clouds of densities 10 atoms cm^{-3} or higher. This will shrink the heliopause down to 14 AU (between Saturn and Uranus).





Next week

we'll discuss how stars are formed, born in the vast interstellar clouds of dust and gas.

Further reading

There are lots of good books about the Sun out there at the moment. Make sure you get one which is recent, to ensure it includes information about the current generation of solar space missions. A couple of good books I found include:

- "**15 Million Degrees: A journey to the centre of the Sun**" by Lucie Green (Viking, 2016) is a fine read, starting from the basics.
- "**The Cambridge Encyclopedia of the Sun**" by Kenneth Lang – an excellent summary of everything there is to know about the Sun.
- "**Journey from the Center of the Sun**" by Jack Zirker (Princeton UP, 2002) – quite a nice book, with lots of information about the people who made the discoveries.

- There's a truly wonderful book written recently, about the discovery of the solar cycle and space weather: "**The Sun Kings**" by Stuart Clark, subtitled: "The unexpected tragedy of Richard Carrington and the tale of how modern astronomy began" (Princeton UP, 2007). It starts with the 1859 "superstorm" and has lots of fascinating information about what we've learned about solar activity. A ripping good read.

- Check out Galileo's drawings of sunspots at "The Galileo Project", http://galileo.rice.edu/index.html; look in Science > Sunspots > Galileo's Sunspot Drawings

There is a truly enormous number of excellent web sites about the Sun. I can't possibly list them all here, but here are a few to get you started;

- NASA's Heliophysics page: http://science.nasa.gov/heliophysics/
- The Stanford Solar Center, http://solar-center.stanford.edu, has lots of useful stuff, including current solar images
- The Solar Dynamics Observatory is at http://sdo.gsfc.nasa.gov/
- The SOHO web site is at http://sohowww.nascom.nasa.gov/, where you can find all SOHO's amazing images
- The STEREO web site is at http://stereo.gsfc.nasa.gov/
- There's a good introduction to the Sun at http://www.solarviews.com/eng/sun.htm
- You can hear the Sun singing (actually, solar oscillation data converted to sound and scaled up to human hearing range) at http://soi.stanford.edu/results/sounds.html
- A NASA article about the Quebec blackout: http://www.nasa.gov/topics/earth/features/sun_darkness.html
- You can find current solar images from a huge number of sources and wavelengths at http://umbra.nascom.nasa.gov/images/latest.html
- There's a marvelous series of images of the Sun published in the Boston Globe http://www.boston.com/bigpicture/2008/10/the_sun.html
- The World data center for the Sunspot Index is at the Royal Observatory of Belgium http://sidc.oma.be/index.php

Sources for images used:

- Solar Dynamics Observatory image of the Sun: from http://sdo.gsfc.nasa.gov/gallery/main/item/151
- Solar interior: from “The solar interior”, http://solarscience.msfc.nasa.gov/interior.shtml
- Photon transport: from http://solarcellcentral.com/sun_page.html
- Solar granulation movie: from Peter Brandt, http://www.kis.uni-freiburg.de/~pnb/granmovtext1.html (broken link)
- Helioseismology: from Stanford’s Helioseismic and Magnetic Imager (HMI) page http://hmi.stanford.edu/Description/hmi-overview/hmi-overview.html
- Refraction of waves: after Fig. 5.3 from “Journey from the Center of the Sun” by Jack Zirker
- Travelling waves in the Sun: from Helio- and Asteroseismology, http://solar-center.stanford.edu/helio-ed-mirror/english/engrays.html
- 1D vibrations: from PIRA Physics Test/Lecture Drawings, http://www.wfu.edu/physics/pira/PhysicsDrawings.htm#waves
- 2D vibrations: from Chladni Plate Mathematics by Paul Bourke, http://astronomy.swin.edu.au/~pbourke/modelling/chladni/. Used with permission.
- 3D vibrations: from Graphical representations of surface harmonics, http://gong.nso.edu/images/harmonics.shtml
- Vibrating Sun: from The Singing Sun, http://solar-center.stanford.edu/singing/singing.html
- Doppler imager and velocity fields: from Helio- and Asteroseismology, http://solar-center.stanford.edu/helio-ed-mirror/english/engdop-obs.html
- GONG sites: from http://gong.nso.edu/sites/
- SOHO orbit: from http://www.esa.int/esapub/bulletin/bullet86/huber86.htm and http://spaceguard.rm.iasf.cnr.it/NScience/neo/neo-what/ast-trojans.htm
- MDI/SOHO power spectrum: from http://solar-center.stanford.edu/art/lnu.html
- Resuts from MDI/SOHO: from Helioseismology, http://soi.stanford.edu/results/heliowhat.html
- Sunspot: from Some images of a medium size sunspot by Peter Brandt, http://www.kis.uni-freiburg.de/~pnb/spottext1.html
- Sunspot group AR 2192, from APOD 2014 October 24, http://apod.nasa.gov/apod/ap141024.html
- Galileo's sunspot drawings: from http://galileo.rice.edu/sci/observations/sunspot_drawings.html
- Sunspot numbers: from http://www.sciencedirect.com/science/article/pii/S1364682612000648
- SOHO continuum and magnetogram images: from SOHO Latest Images, http://sohowww.nascom.nasa.gov/data/latestimages.html
- Structure of a sunspot: from D. A. Gough, “Vainu Bappu Memorial Lecture: What is a sunspot?”, Fig, 9, http://arxiv.org/abs/0909.5338
- Polarity of sunspots: from Nature of the Universe, Chapter 11: The Sun, http://www.physics.hku.hk/~nature/notes/lectures/chap11.html; magnet picture from http://www.windows2universe.org/sun/atmosphere/sunspot_magnetism.html
- Cycle 24 sunspot numbers: from “Solar Cycle #24: On Track to be the Weakest in 100 Years” http://www.universetoday.com/103803/solar-cycle-24-on-track-to-be-the-weakest-in-100-years/
- Solar cycle observed by SOHO: from APOD 2007 December 3 http://apod.nasa.gov/apod/ap071203.html
- Solar magnetic fields: from 15-Phys-121: Astronomy and the Nature of the Universe by M. Hanson, http://www.physics.uc.edu/~hanson/ASTRO/LECTURENOTES/W03/Lec4/Page8.html
- Solar spectrum: by Nigel Sharp (NSF,NOAO), from APOD 2006 April 23 http://apod.nasa.gov/apod/ap060423.html
- Chromosphere: from Astr 1010: Survey of Astronomy, http://www.physics.utoledo.edu/~lsa/_a1010/mod25.htm
- Chromosphere features: from Evans Solar Facility Images, http://nsosp.nso.edu/esf/pics.html
- Solar spicules: from APOD 2008 November 2 http://apod.nasa.gov/apod/ap081102.html

- Earth compared to prominence: from SDAC, http://umbra.nascom.nasa.gov/sdac.html . Prominence: SOHO EIT image from 2005 July 29 at 18:24 UT, same site.
- Corona during an eclipse: from Astr 1010: Survey of Astronomy, http://www.physics.utoledo.edu/~lsa/_a1010/mod25.htm
- TRACE movie of coronal loops: from Solar Physics: Coronal features, http://science.nasa.gov/ssl/PAD/SOLAR/feature3.htm
- Solar flare: from Solar Physics: Solar flares, http://science.nasa.gov/ssl/PAD/SOLAR/flares.htm
- Flare from AR2192, from APOD 2014 Nov 22 http://apod.nasa.gov/apod/ap141122.html
- Animation of solar flare: from Best of SOHO Movies, http://sohowww.nascom.nasa.gov/
- LASCO movie of coronal mass ejection event: from Best of SOHO Movies, http://sohowww.nascom.nasa.gov/
- Magnetic loop and Yohkoh image: from Yohkoh Public Outreach Project: The Magnetic Sun, http://solar.physics.montana.edu/YPOP/Spotlight/Magnetic/loops.html
- Sequence of CME images from 5 Nov 1998: from Best of SOHO images Part 1, http://sohowww.nascom.nasa.gov/
- Animation of a CME impacting the Earth: from Best of SOHO Movies, http://sohowww.nascom.nasa.gov/
- Aurora over Alaska, image by Jan Curtis, from Astronomy Picture of the Day 2000 May 19, http://apod.nasa.gov/apod/ap000519.html
- Aurora over volcano: photo by Lucas Jackson http://blogs.reuters.com/photo/2010/04/26/luck-is-a-funny-thing/
- Richard Kerr: "Space Weather Forecasting: Are We Ready for the Next Solar Maximum? No Way, Say Scientists", *Science* 324 1640
- STEREO concept and orbit: from http://stereo.jhuapl.edu/gallery/images/artConcepts.php
- STEREO current location: from http://stereo-ssc.nascom.nasa.gov/where.shtml
- All STEREO movies from the STEREO Gallery http://stereo.gsfc.nasa.gov/gallery/stereoimages.shtml
- SDO movie: from SDO First Light Movies http://sdo.gsfc.nasa.gov/gallery/firstlight/
- The heliosphere: from The Galactic Environment of the Sun by Priscilla Frisch, American Scientist Jan–Feb 2000, http://www.americanscientist.org/template/AssetDetail/assetid/21173
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