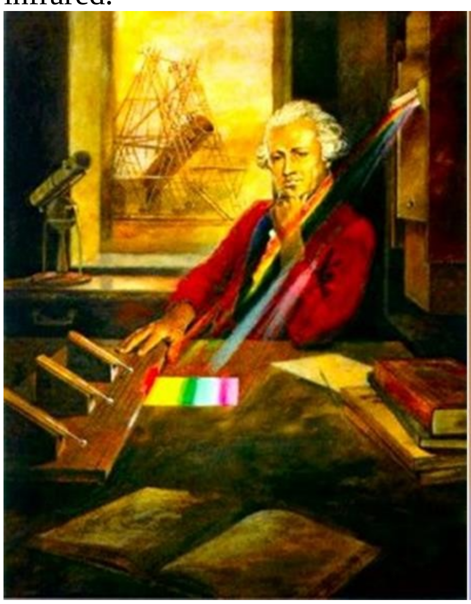
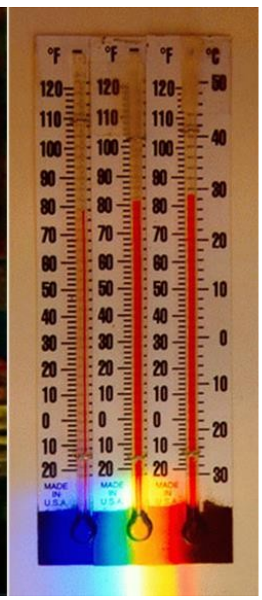
Spectroscopic observations of the Sun

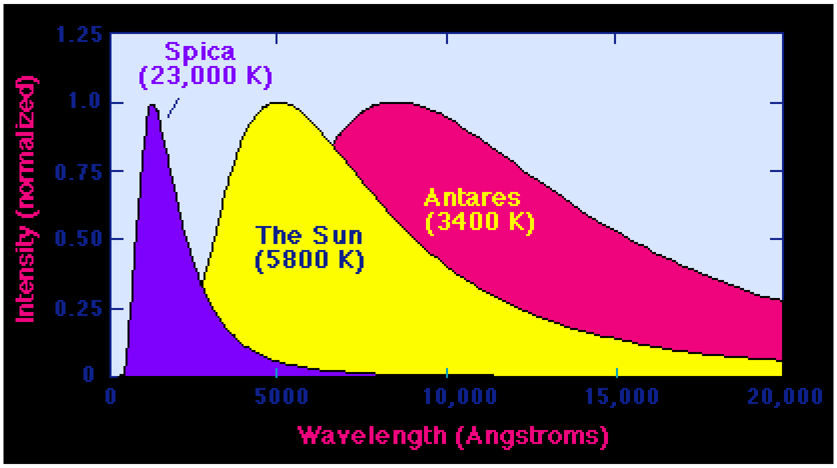
The solar spectrum

In the 17th century, the word “spectrum” was introduced into optics by Isaac Newton, referring to the range of colors observed when white light was dispersed through a prism.
Interestingly, in the year 1800, Sir William Herschel discovered the existence of the infrared (“beyond” the visible red color). As sunlight passes through a prism, the prism divides it into a rainbow of colors called a spectrum. A spectrum contains all of the colors which make up sunlight. Herschel was interested in measuring the amount of heat in each color. To do this he used thermometers with blackened bulbs and measured the temperature of the different colors of the spectrum. He noticed that the temperature increased from the blue to the red part of the spectrum. Then he placed a thermometer just past the red part of the spectrum in a region where there was no visible light and found that the temperature there was even higher. Herschel realized that there must be another type of light which we cannot see in this region. This light was called infrared.



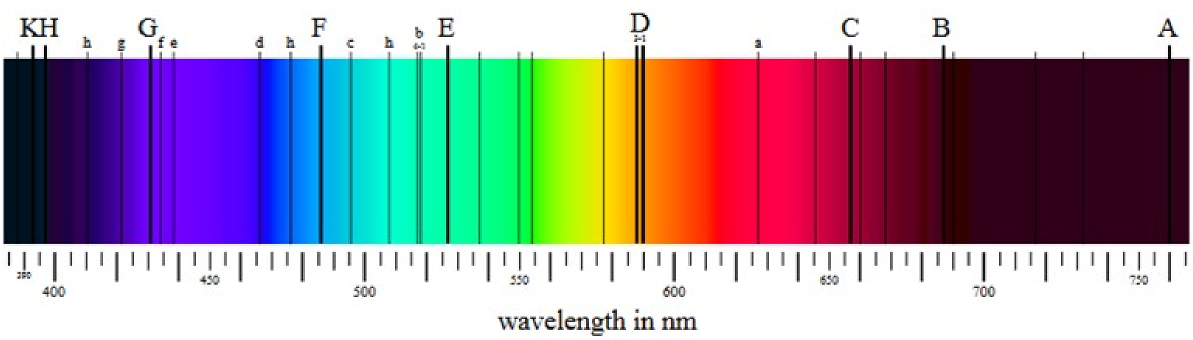


Over the years, the term “spectrum” was expanded to apply to other waves, eventually covering the entire electromagnetic spectrum, from radio wavelengths to the high frequency gamma and cosmic radiation. The visible spectrum is the part of the electromagnetic spectrum that can be seen by the human eye. The wavelength of visible light ranges from about 390 to 700 nm.
From the solar spectrum, one can actually deduce the temperature of the solar surface (about 6000 degrees). The Sun radiates maximum in the yellow-greenish part of the spectrum, indicating it is an average star. Cooler stars radiate mostly in the redder part of the spectrum, while hot stars are shining mostly in the bluish part.



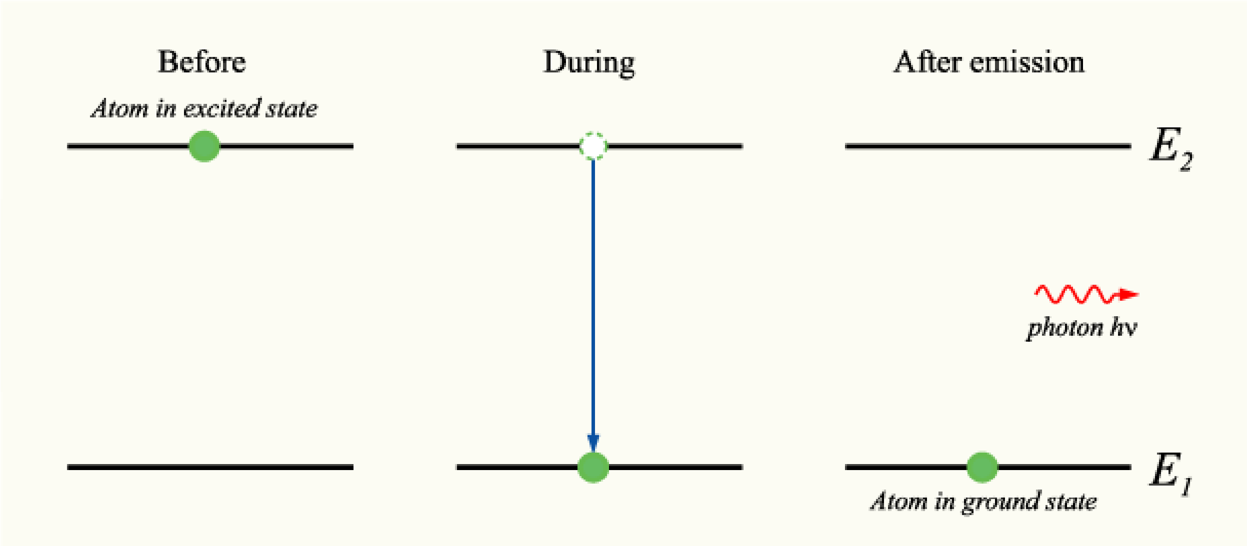
Absorption and emission lines in a spectrum

Looking closely at the solar spectrum one can see dark lines in the spectrum , called the Fraunhofer lines named after the German physicist Joseph von Fraunhofer (1787–1826). These spectral lines were originally observed as dark features (absorption lines) in the optical spectrum of the Sun. In 1802, the English chemist William Hyde Wollaston was the first person to note the appearance of a number of dark features in the solar spectrum. In 1814, Fraunhofer independently rediscovered the lines and began a systematic study and careful measurement of the wavelength of these features. In all, he mapped over 570 lines, and designated the principal features with the letters A through K, and weaker lines with other letters. Modern observations of sunlight can detect many thousands of lines.

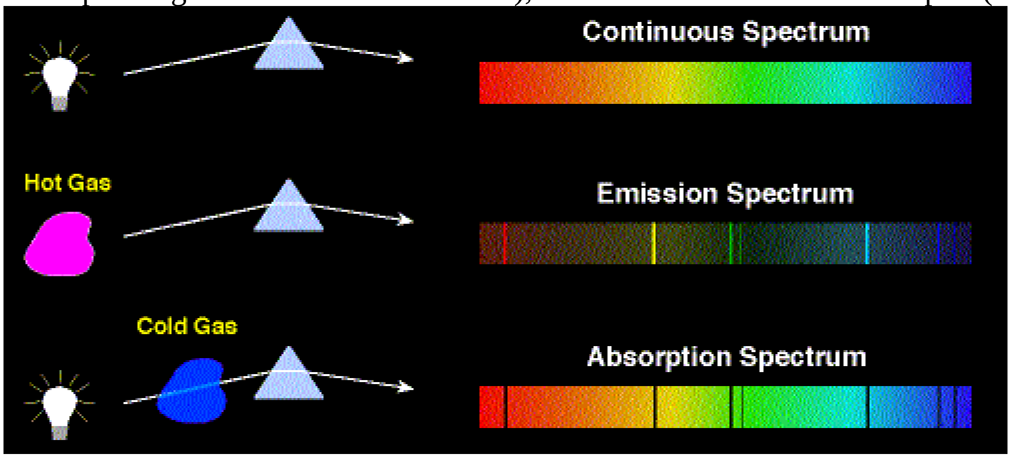


The solar spectrum needs to be corrected from the absorption lines imprinted when the light passes through the Earth's atmosphere (e.g. from water vapor). With the remaining lines, and by comparing against spectra from various elements taken in laboratories, astronomers were able to conclude that the Sun mostly consist of Hydrogen and Helium, with traces of other elements such as Calcium, Oxygen,… It also became clear that the Sun was much hotter than any other object in the solar system, as it had a surface temperature of about 6000 degrees. The Sun is a star!

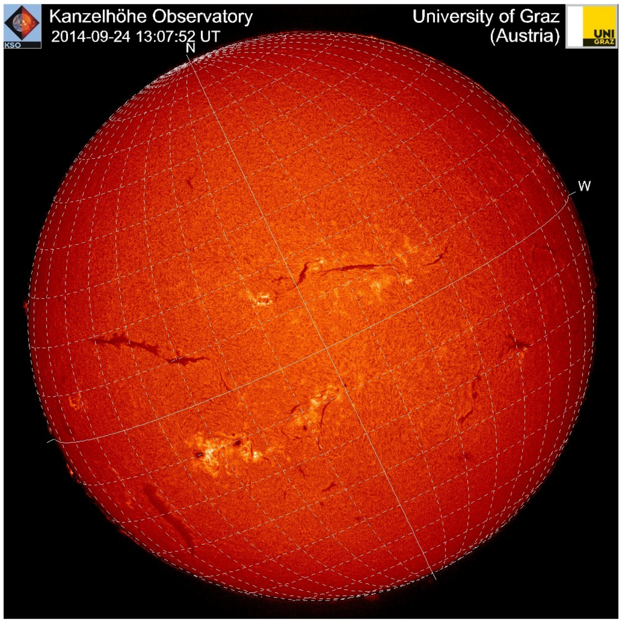
The absorption "lines" exist due to the fact that electrons can only take discrete orbits when going around the atom's nucleus. The energy needed to go one level up, or released when coming one level down, is called a quantum (a tiny package of energy). Thus, the lines are related to very specific local conditions determined by temperature, pressure, density, and so on.



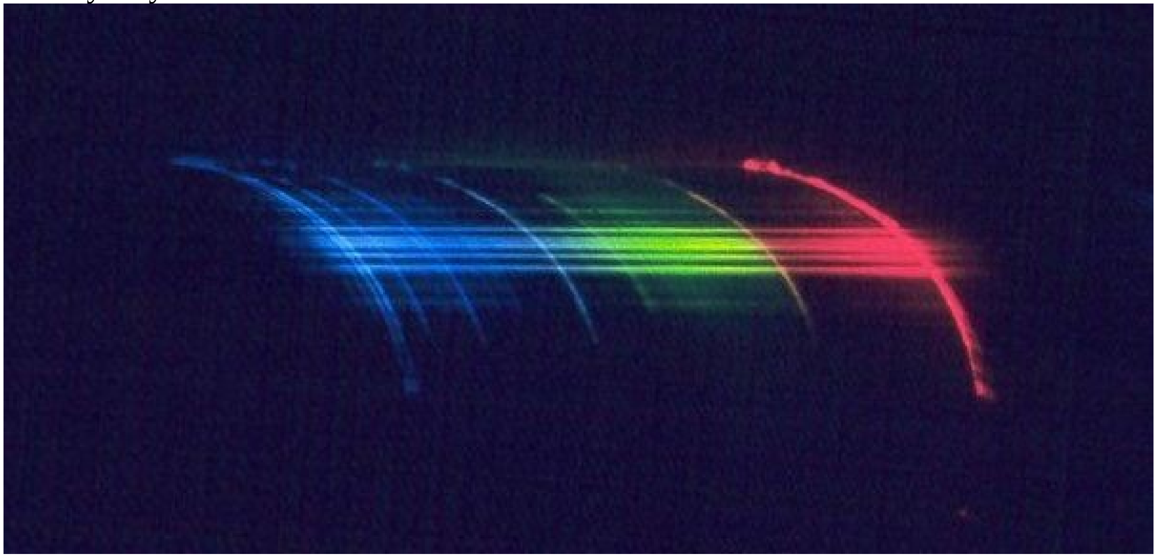
Hence, absorption lines exist because the light from the solar surface passes through layers which are colder than this surface. The particles take away a very specific amount of energy from the solar light. This tiny amount of energy corresponds to a certain wavelength in the spectrum. At that location, the spectrum becomes darker and produces an absorption line. Typical lines are those from Hydrogen (e.g. Hydrogen alpha at 656.28 nm in the red part of the solar spectrum, corresponding to Fraunhofer's "C " line), and from Calcium in the blue part (384 nm).



Note that "dark" doesn't mean "nothing". If one removes the rest of the solar spectrum, this line would actually be bright. This is why astronomers study the Sun with big telescopes: The Sun obviously produces enough light, but one needs as much light gathering area as possible in order to study the Sun in that particular absorption line. For example, observing the Sun using H-alpha filters or in the Calcium H or K line, allows the study the physical processes in the lower atmosphere of the Sun.



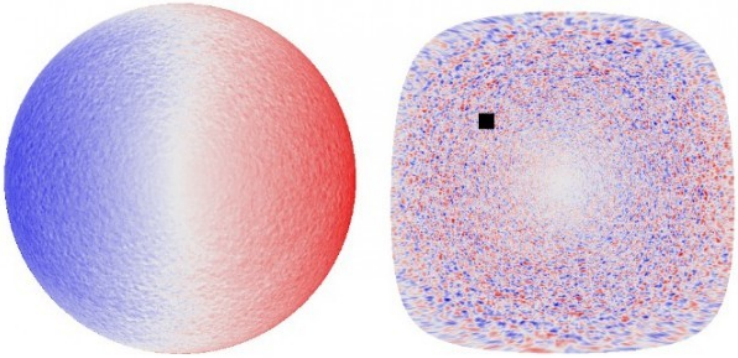
Interestingly, during the solar eclipses in 1868-1869, it was observed that the normal absorption spectrum changed into an emission spectrum when the Moon completely covered the solar disk, i.e. during the few minutes of totality. Lines in emission mean that they stand out bright against a rather dark background spectrum. We now know that this is because the light goes through a layer that is hotter than the area underneath it. It was not until 1940 that Bengt Edlén identified a green line (530.3 nm) as that related to thirteen times ionized Iron (Fe XIV, Fe^{13+}), which can only at very high temperatures. So it became clear that the Sun's upper atmosphere (the corona) was much hotter than the solar surface, resp. several million degrees versus about 6000 degrees. The mystery of the hot corona is still not solved.



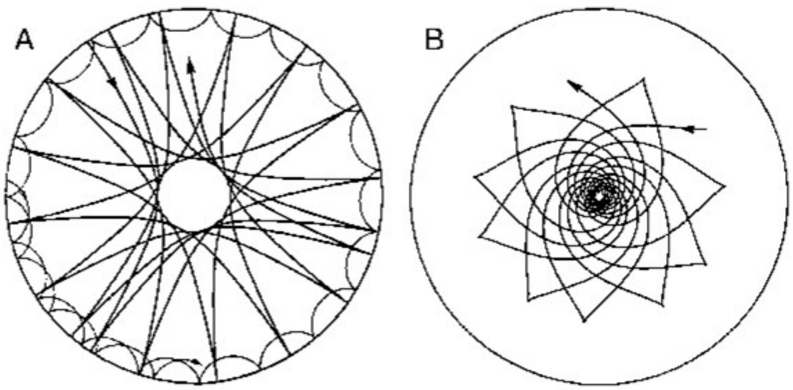
Helioseismology

The Doppler effect is best known from the varying change in pitch from an ambulance's sirene: As the ambulance is approaching, the pitch is higher (higher frequency), and when it is moving away, the pitch is lower (lower frequency). This Doppler effect is also visible in a spectrum, where objects moving towards the observer produce spectral lines that are blue shifted (towards

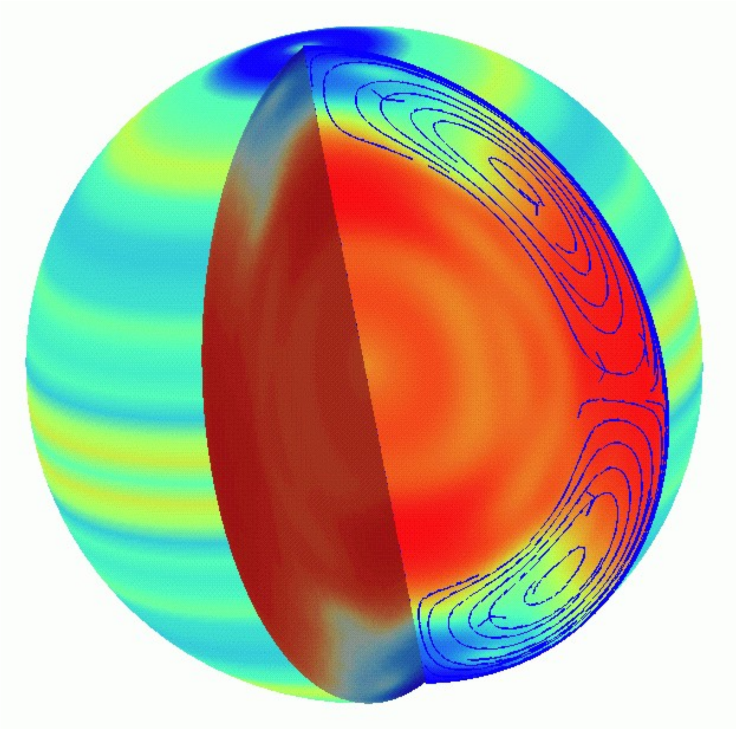
higher frequencies), and objects moving away can be recognized from the red shifted spectral lines (towards lower frequencies).
The solar surface is not solid, but consists of various irregular 1000 km wide cells (the size of France), called granules. These granules rise and descend back to the solar interior as they radiate their heat into space. In the second half of the 20th century, astronomers discovered that this up and down movement of the granules creates waves in the solar interior.



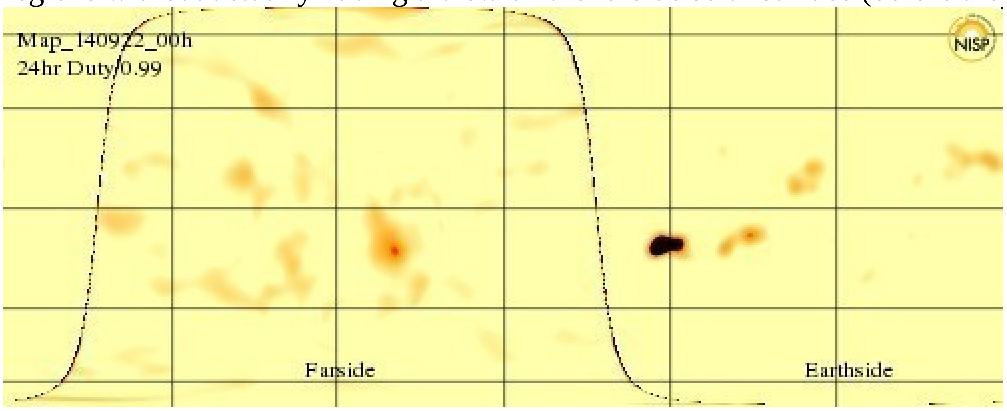
Some of these waves may actually reinforce themselves, other dampen out (a bit like organ pipes). Certain frequencies are amplified by constructive interference. In other words, the turbulence "rings" the sun like a bell. These are called sunspot oscillations, and are best observed by measuring the Doppler shift of photospheric absorption lines.



Changes in the propagation of oscillation waves through the Sun reveal inner structures and allow astrophysicists to develop extremely detailed profiles of the interior conditions of the Sun – which is very similar to using earthquakes to learn something from the Earth’s interior. This area of research is aptly called “Helioseismology”. Studied parameters include temperature, density, rotation speed, … at the various depths, and indicate that the standard solar model agrees very well with the observations, except for small deviations in more turbulent regions such as the solar core and the transition region between the radiation and the convection zone of the Sun. The latter is called the tachocline, is located about 200000 km under the solar surface, and is believed to be the seat of the solar magnetism.

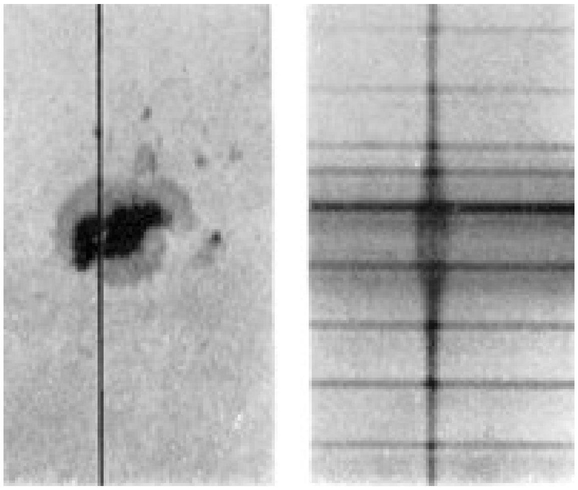


The same principle also allows to image the backside of the Sun, and to get an idea of any active regions without actually having a view on the farside solar surface (before the STEREO era).

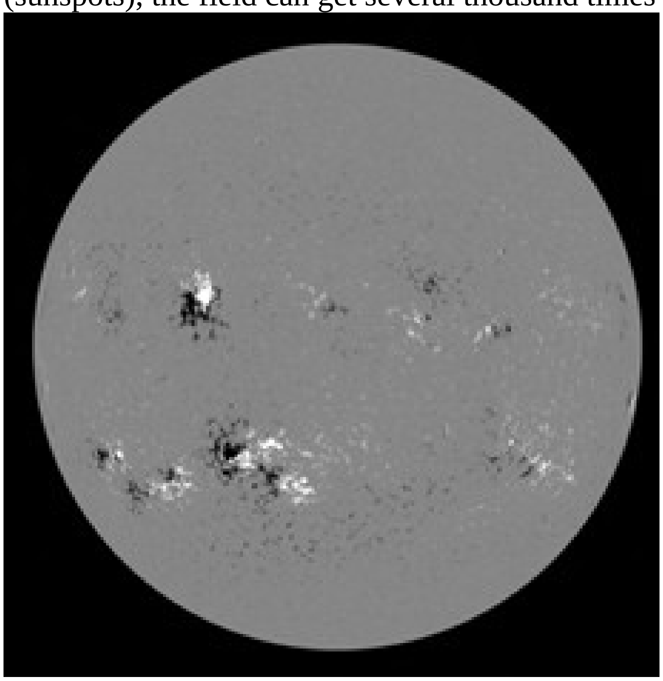


The Zeeman-effect

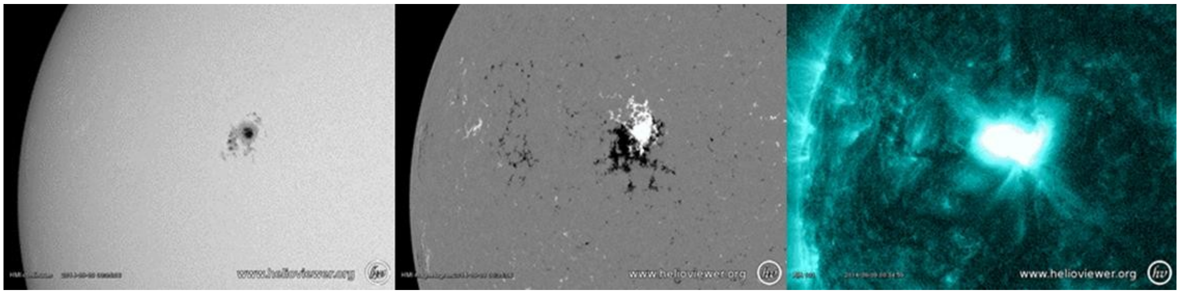
In 1896, the Dutch scientist Zeeman found that when light passes through a strong magnetic field, spectral lines that normally appear as single lines, may double or even triple. This is due to the interaction between the magnetic field and the inherent magnetic moment of the atom, ion, or molecule. A deeper discussion of the effect would require a college-level quantum physics course. The stronger the field, the more obvious the splitting.



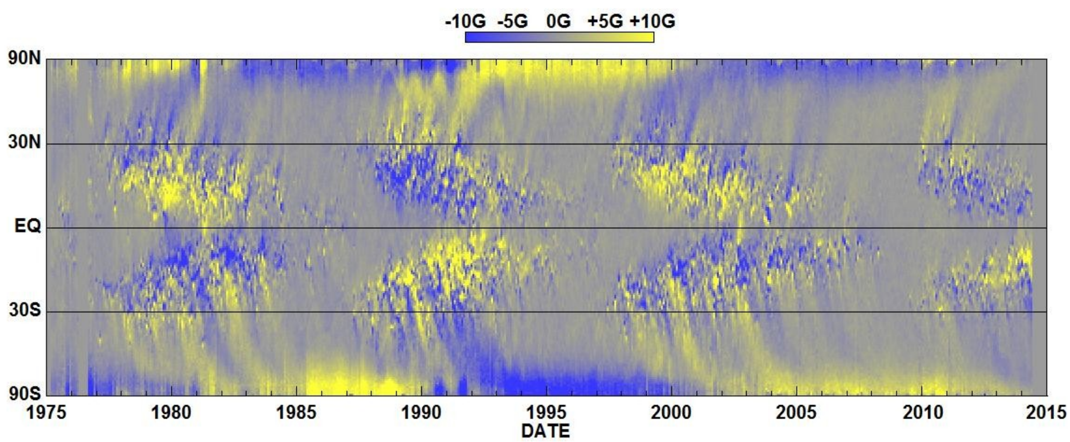
George Ellery Hale was the first (in 1908) to notice the Zeeman effect in the solar spectra, indicating the existence of strong magnetic fields in sunspots. Such fields can be quite strong, on the order of 2000-3000 Gauss or higher (compare to the Earth's poles: about 0.65 Gauss). Today, the Zeeman effect is used to produce magnetograms showing the variation of magnetic field on the sun. By convention, when the magnetic field lines come out of the solar surface, it is displayed in a white color ("positive"), and when it returns to the Sun, it gets a black color ("negative"). The average magnetic field on the Sun is not very strong (1-2 Gauss), about two or three times the strength of the Earth's magnetic field at the poles. However, very locally (sunspots), the field can get several thousand times stronger.



It is known that when opposite magnetic fields come very close together on the Sun, a reconnection can take place releasing vast amounts of energy. This is called a solar flare. The extra radiation from such a flare can have a strong effect on communication and navigation systems here on Earth, as part of the so-called "space weather". As such, space weather forecasters meticulously study the solar magnetograms to make their flare predictions as accurate as possible.



Another important application related to the magnetograms is the study of the global magnetic evolution of the Sun as the solar cycle unfolds. Indeed, as sunspot regions emerge ever closer to the solar equator, their trailing magnetism gets carried towards the solar poles by the currents on the Sun (meridional current). There they replace the magnetic field of the previous cycle with the opposite polarity field of the ongoing cycle. This happens during the period of the maximum of the solar cycle. This polar field reversal is about finished for the ongoing solar cycle (SC24). Some prediction methods use the maximum strength of these polar fields at solar cycle minimum to predict the strength of the next solar cycle.



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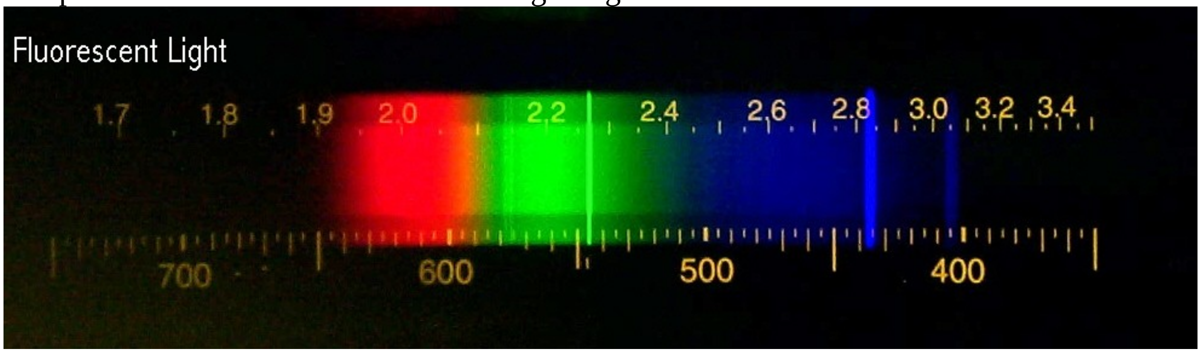
How does a spectroscope work?

In optics, a dispersive prism is a type of optical prism, usually having the shape of a geometrical triangular prism. It is the most widely known type of optical prism, although perhaps not the most common in actual use. Triangular prisms are used to disperse light, that is, to break light up into its spectral components (the colors of the rainbow). This dispersion occurs because the angle of refraction is dependent on the refractive index of a certain material which in turn is slightly dependent on the wavelength of light that is travelling through it. This means that different wavelengths of light will travel at different speeds, and so the light will disperse into the colours of the visible spectrum, with **longer wavelengths (red, yellow) being refracted less than shorter wavelengths (violet, blue).**

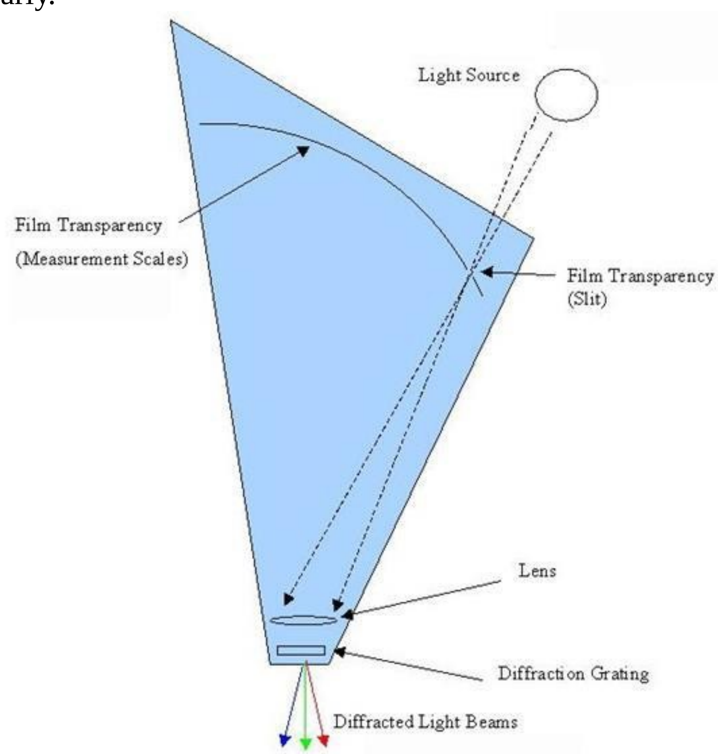
A diffraction grating is an optical component with a periodic structure, which splits and diffracts light into several beams travelling in different directions. Diffraction creates the "rainbow" colors reflected from a compact disc. A grating has many closely spaced parallel lines, while a CD has a spiral of finely-spaced data tracks.

The principles of diffraction gratings were discovered by James Gregory, about a year after Newton's prism experiments, initially with artifacts such as bird feathers. The first man-made diffraction grating was made around 1785 by Philadelphia inventor David Rittenhouse, who strung hairs between two finely threaded screws. This was similar to notable German physicist Joseph von Fraunhofer's wire diffraction grating in 1821.



The Project STAR spectrometer is a very simple yet useful device made from cardboard or plastic containing a diffraction grating, a strip of phototransparency film, and a lens. You are looking at spectrographic images taken using the spectrometer, the scales are the phototransparency film, and the rainbow is caused by the diffraction grating.

The optical system is very simple for such a useful device. Light enters the spectrometer from a clear slit in the transparency. The thin beam of light travels the length of the housing until it reaches a lens, which collimates the beam (or focuses it to infinity). The diffraction grating is located just after the lens, and you place your eye up close to the grating as you look through it. The grating disperses the different wavelengths of light, because the diffraction angle is a function of wavelength. The resulting rainbow image appears to be located at optical infinity, superimposed on the scales. The markings on the scales are actually transparent too, so that rear illumination allows you to see them clearly.



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