The Sun's Atmosphere and its Magnetic Field

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Photosphere

The photosphere is what you see through your sunglasses. It's the top of the solar convection zone. Things to notice:

- Yellowish-white color
- Sharp edge, $R_\odot = 6.96 \times 10^{10}$ cm
- Limb darkening

ESAC Astronomy Club

Effective Temperature

The solar luminosity $L_\odot = 3.84 \times 10^{33}\,\mathrm{erg/s}$ is due almost entirely to continuum radiation from the photosphere. This isn't quite a blackbody spectrum, but we can derive some of the basic properties by treating it as such:

$$L_\odot = 4\pi R_\odot^2\, \sigma T^4.$$

Stefan's constant is $\sigma = 5.67 \times 10^{-5}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,K^{-1}}$. This results in an effective temperature

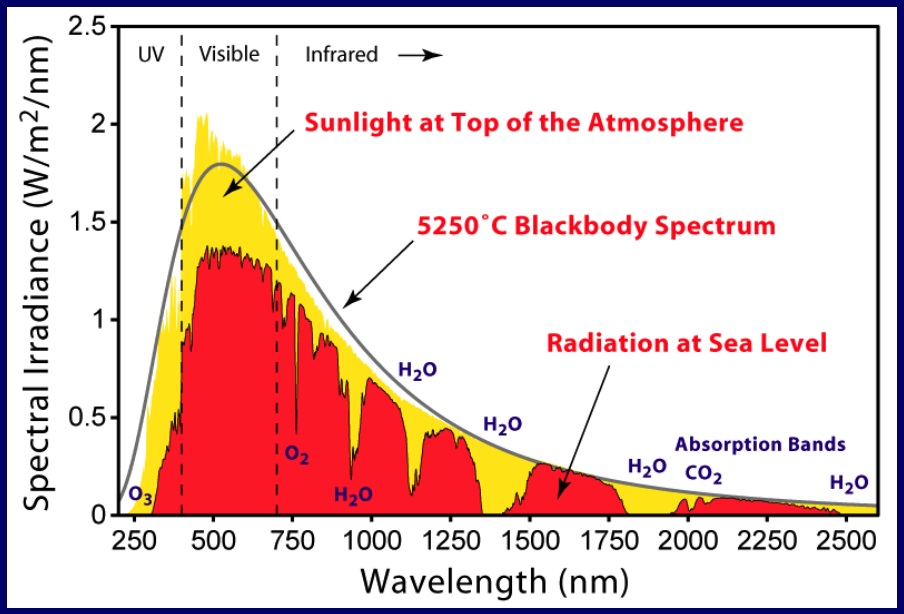
$$T_{\mathrm{eff}} = 5775\,\mathrm{K}.$$

Wien's law puts the maximum of the Planck function at

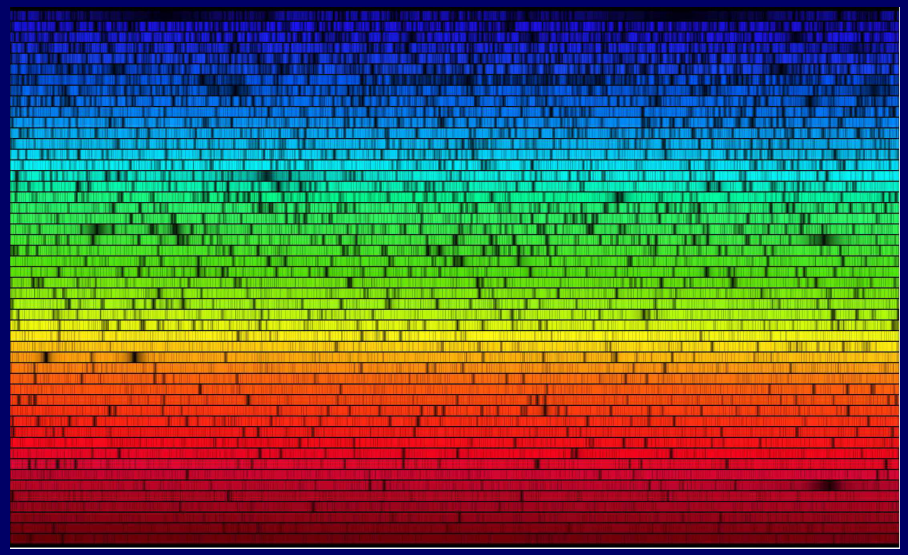
$$\lambda_{\mathrm{max}} = \frac{2.90 \times 10^6\,\mathrm{nm\,K}}{T_{\mathrm{eff}}} = 502\,\mathrm{nm}.$$

We shouldn't take this number too seriously, but it is consistent with a spectrum peaked in the visible.

Solar Spectrum



Wikipedia



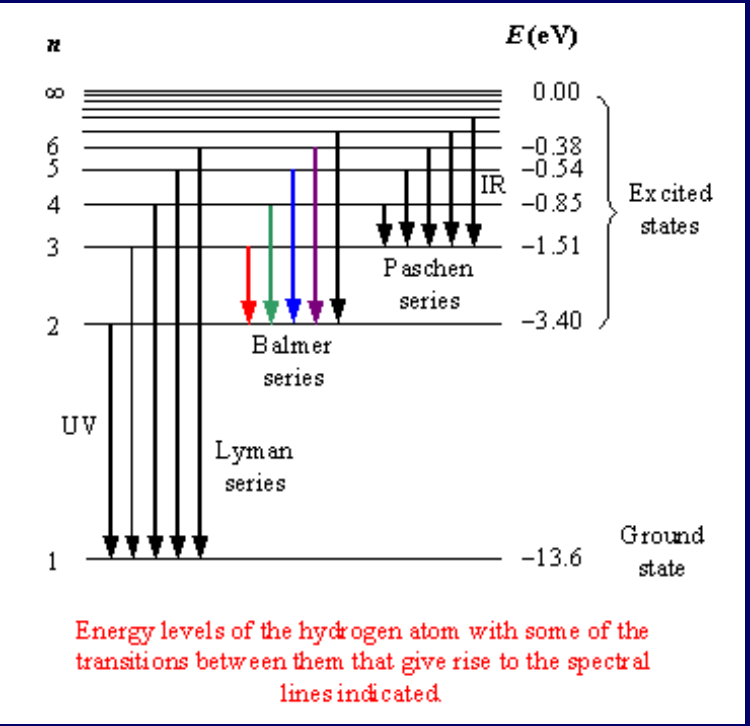
R. Kurucz, CfA

This is what the solar spectrum really looks like.

Back up the train!

Q: What is the Sun made of?

You know about atoms. Hydrogen for example:

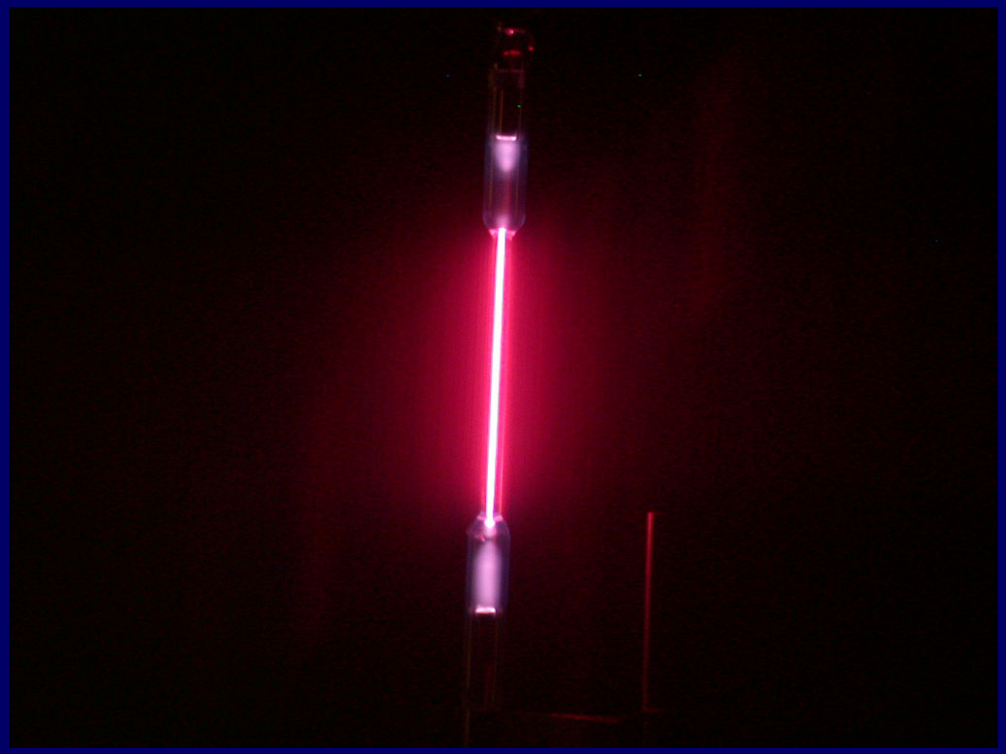


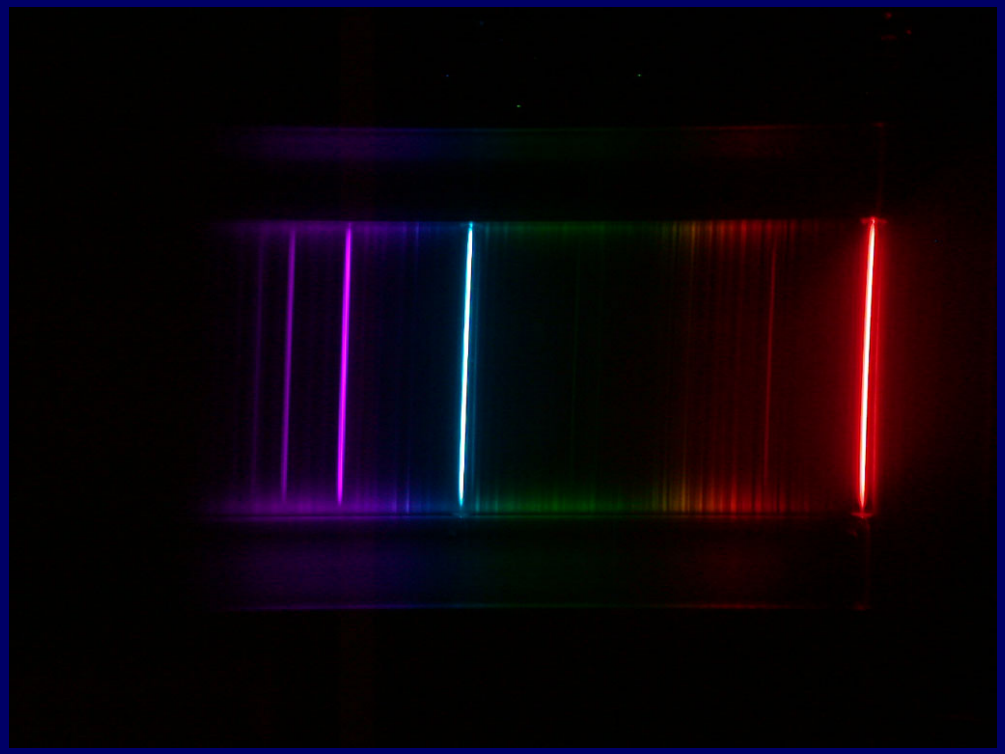
Energy levels of the hydrogen atom with some of the transitions between them that give rise to the spectral lines indicated.

Encyclopedia of Science

Atoms

Perhaps you've seen an experiment like this in class:





Brian K. Niece, Assumption College

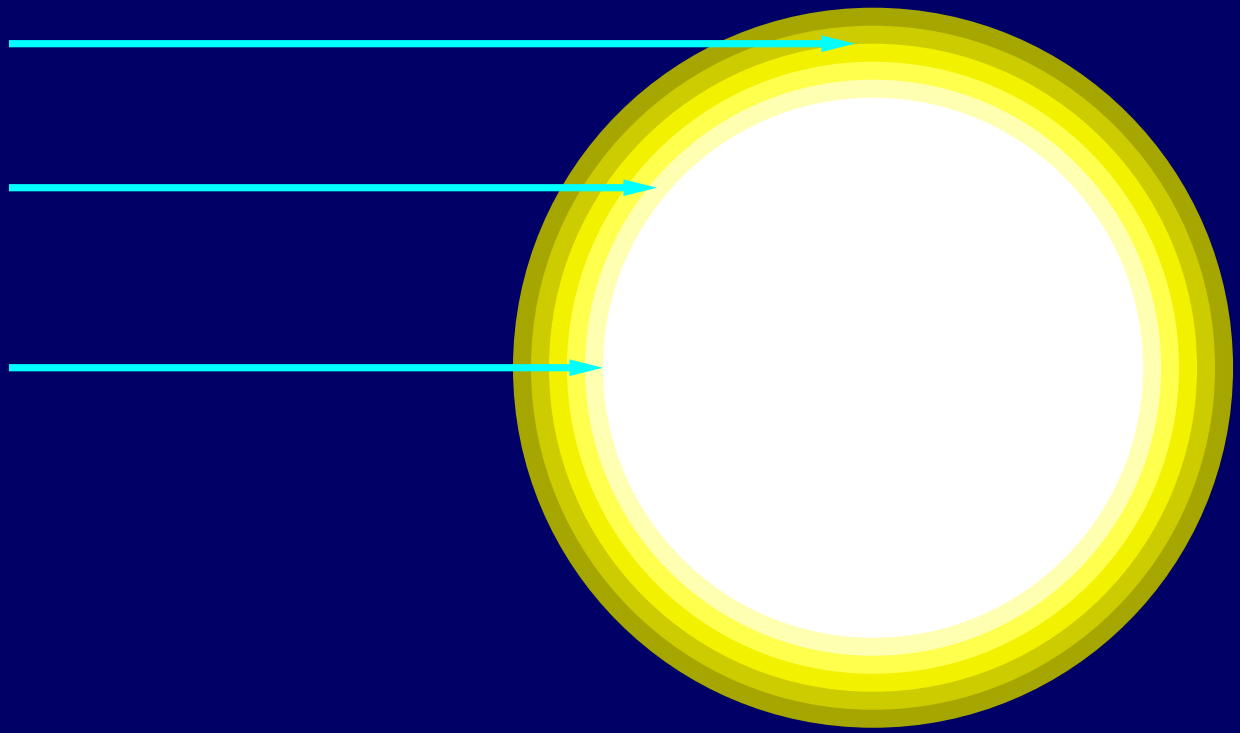
Why doesn't the solar spectrum look like this?

Radiative Transfer

- Astrophysical objects like the Sun are large. There's a lot more hydrogen there than in your discharge tube in the lab.
- The mean free path of the light is *much* smaller than the Sun.
- Light is scattered countless times before it escapes the photosphere.
- Each scattering event shifts the wavelength (why?)
- The outcome is a continuous spectrum. If the gas were all one temperature, we'd see a blackbody spectrum.

Appearance of the Limb

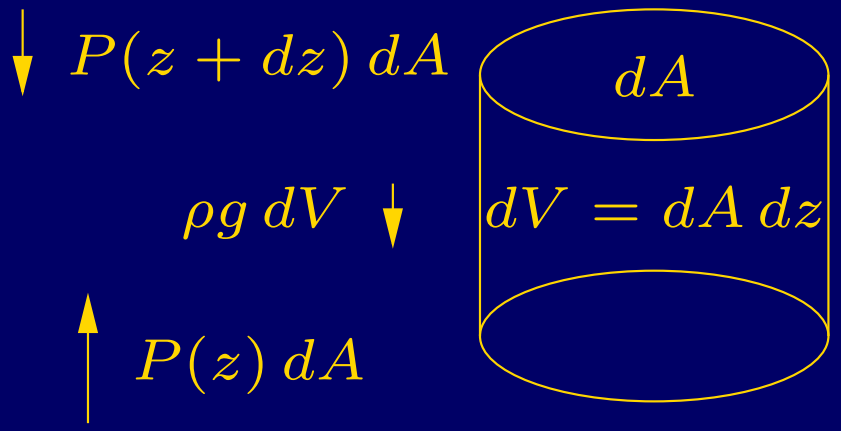
- We are looking into an opaque ball of gas.
- Our line of sight takes in a range of temperatures.
- What does that imply as we observe from center to limb?



But why does the limb appear so *sharp*?

Scale Height

Force balance on a volume element of gas:



$$P(z) - P(z+dz) - \rho g\,dz = 0$$

$$\frac{dP}{dz} = -\rho g$$

$$kT\,\frac{dn}{dz} = -nmg$$

$$n = n_0\,e^{-z/L}$$

where $L = \dfrac{kT}{mg}$

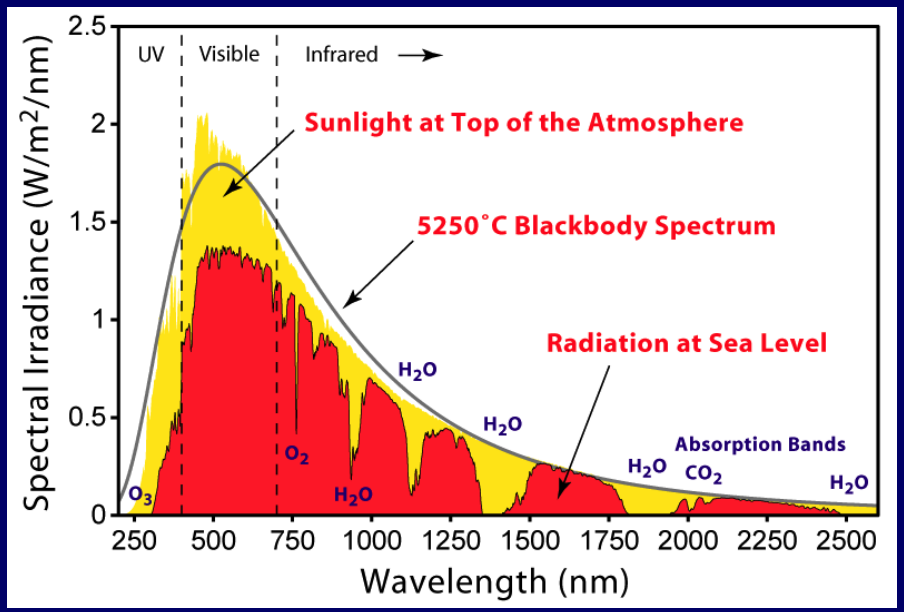
$$g_\odot = \frac{GM_\odot}{R_\odot^2} = 2.74 \times 10^4\,\mathrm{cm\,s^{-2}} = 28\,g_\oplus.$$

If we let $m = m_p$ (mainly hydrogen) and $T = T_{\mathrm{eff}}$, then

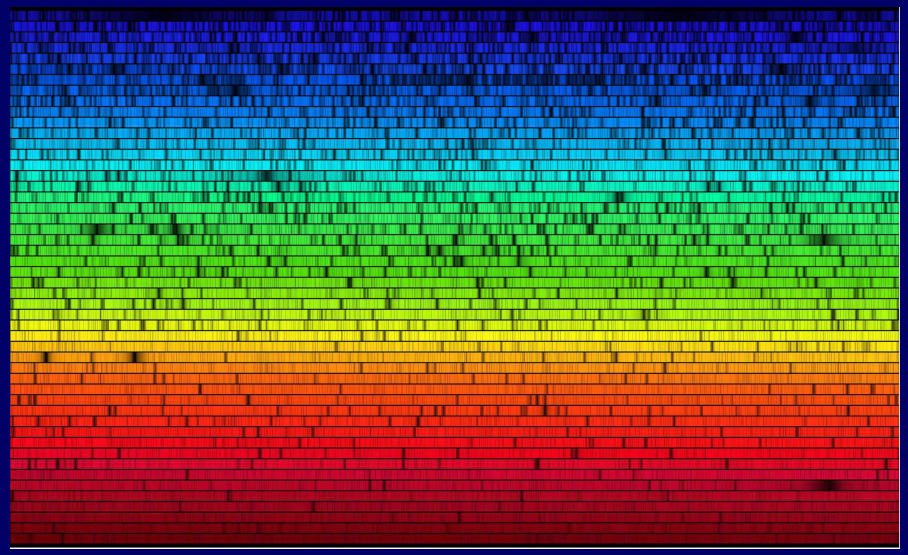
$$L = 1.8 \times 10^7\,\mathrm{cm} = 2.5 \times 10^{-4}\,R_\odot.$$

Solar Convection (Granulation)

Solar Spectrum



Wikipedia



R. Kurucz, CfA

The Fraunhofer absorption lines (right) indicate that there is something in the foreground. What is it?

$\rightarrow$ Form an image in one of the more prominent absorption lines...

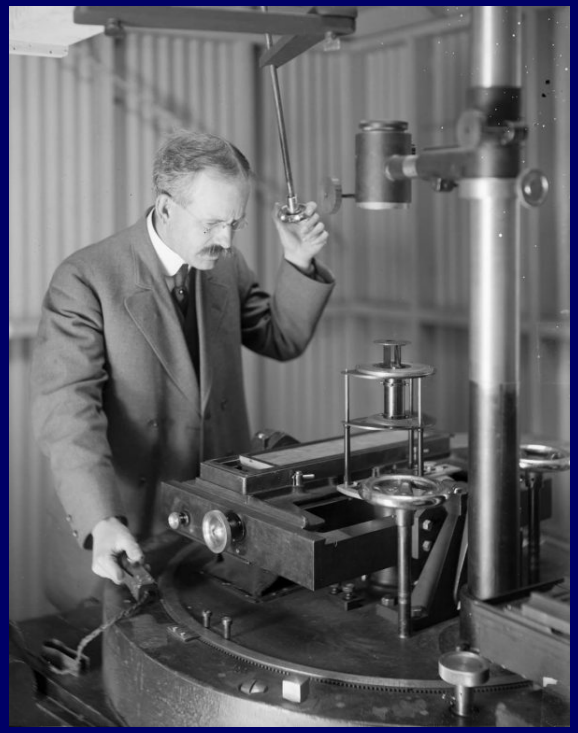
Chromosphere (H Balmer α)

Chromosphere (Ca II H)

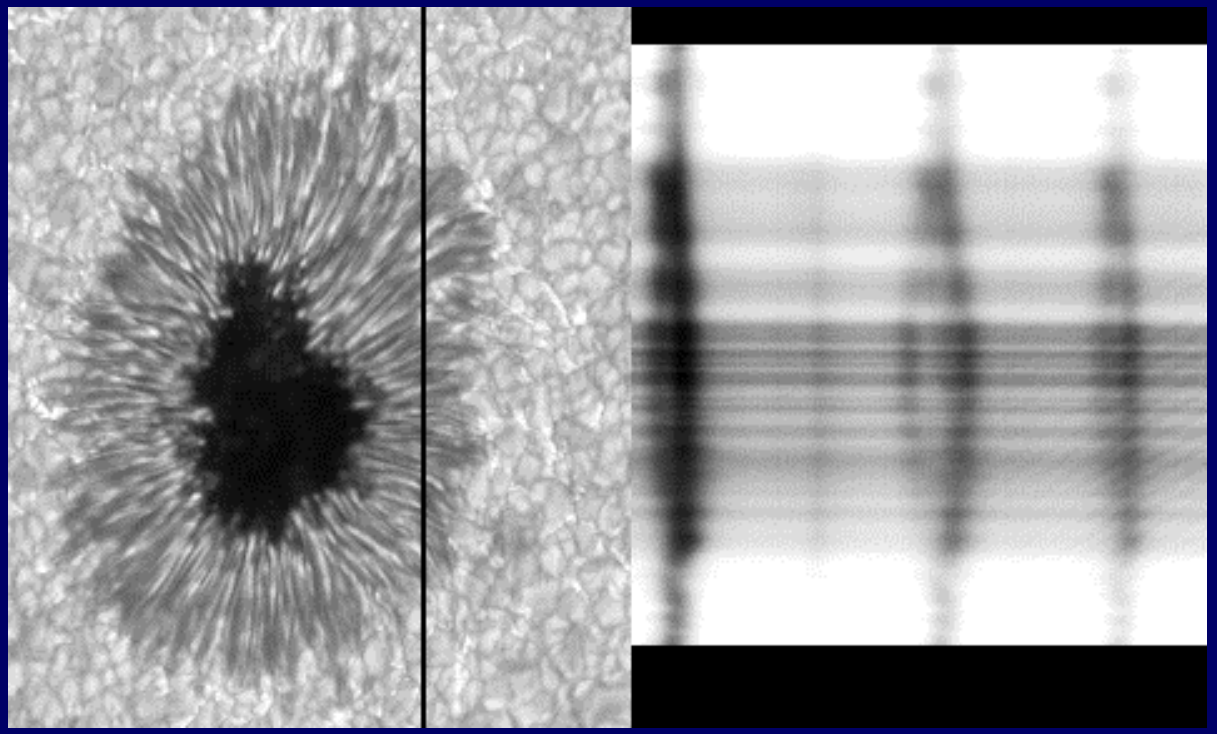
Hinode / Solar Optical Telescope, 2006-11-20 07:15 UT

- IRIS mission: `http://iris.lmsal.com`

Hale's Discovery (1908)



George Ellery Hale at the Mount Wilson Obervatory.



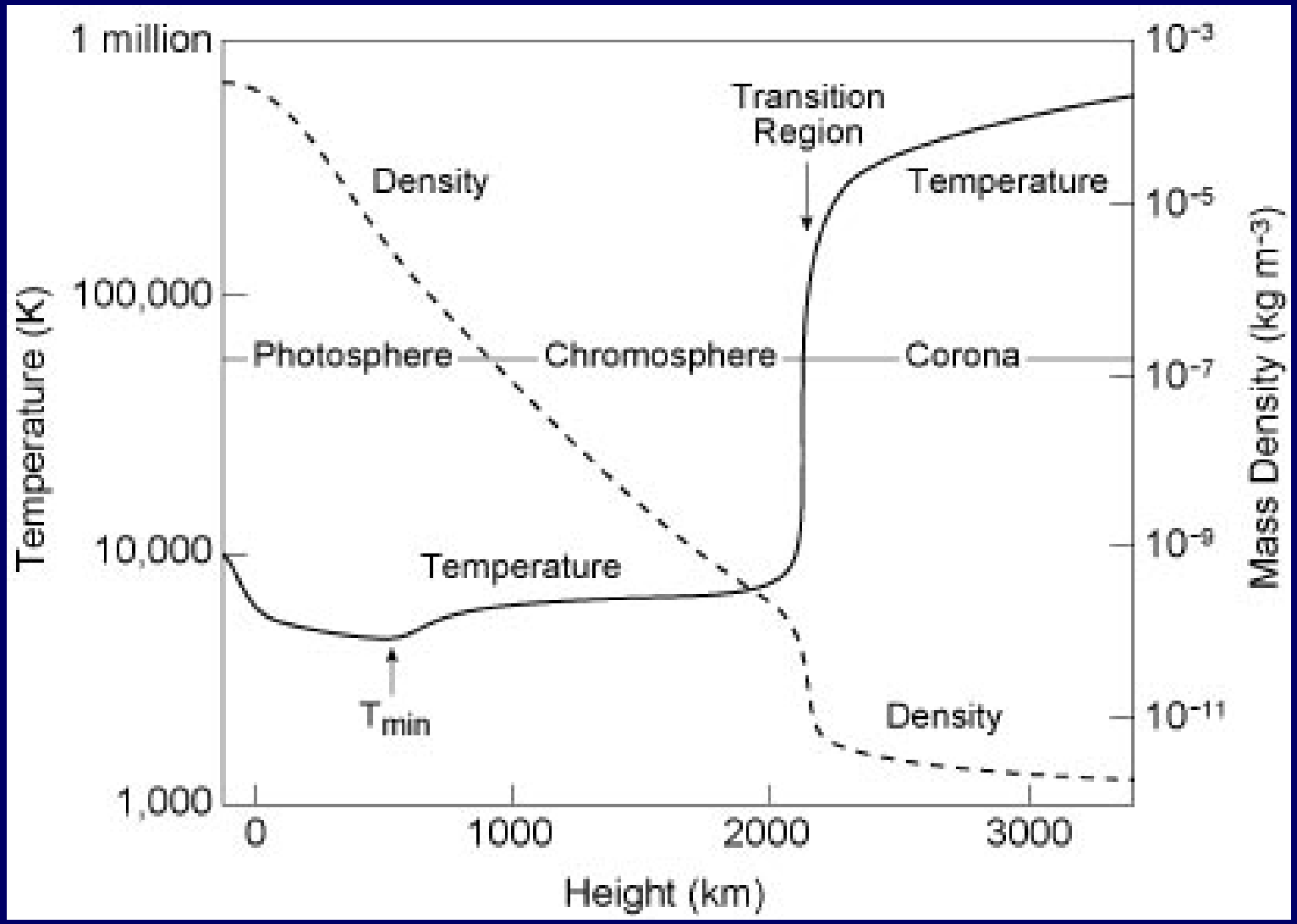
Zeeman splitting in a sunspot reveals its magnetic nature.

Solar Magnetism

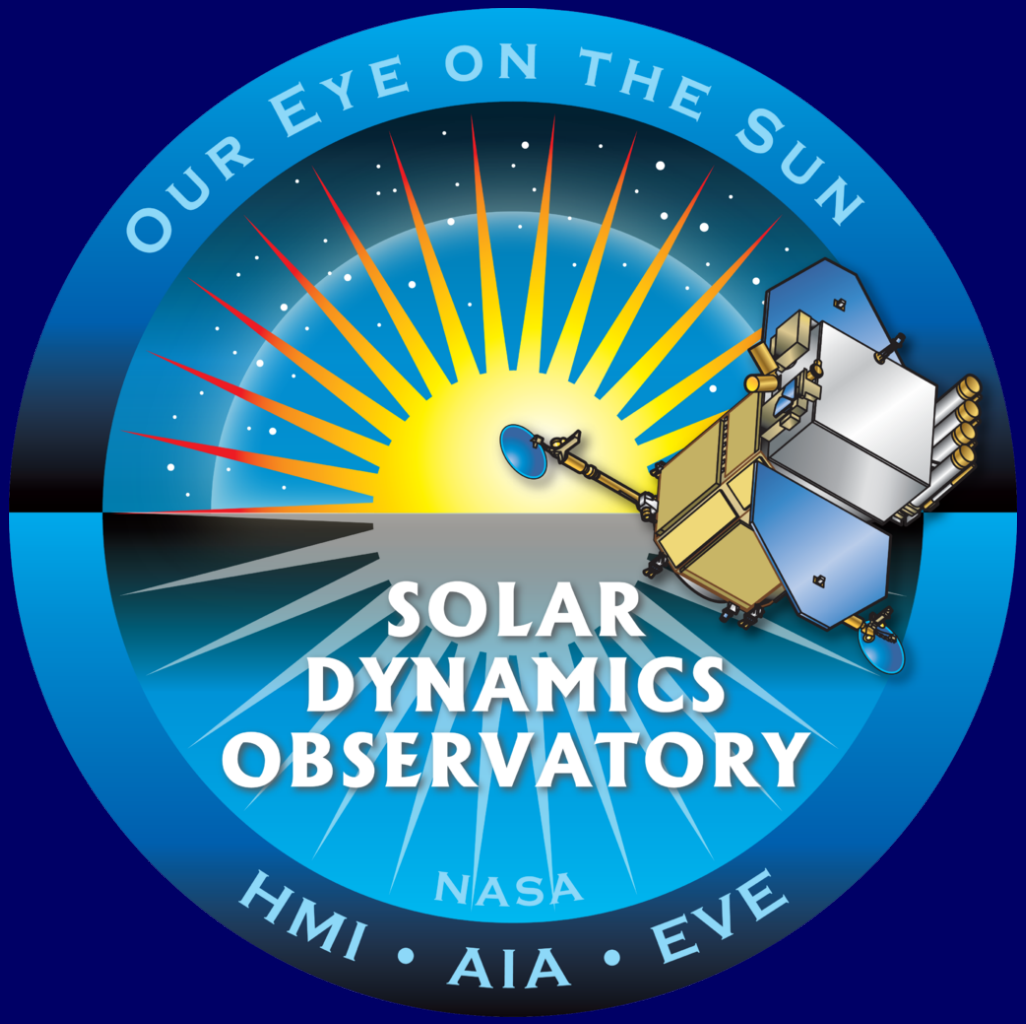
Beyond the Chromosphere...

The **corona** is a million degree ionized plasma sitting on top of the chromosphere, glowing in X-rays!!

Atmospheric Profile



Solar Atmosphere Tour: SDO/AIA



We'll proceed through the channels on the Atmospheric Imaging Assembly (AIA) in order of increasing temperature...

450 nm, Continuum; 5000 K

NASA Solar Dynamics Observatory / Atmospheric Imaging Assembly

170 nm, UV Continuum; 10^4+ K?

NASA Solar Dynamics Observatory / Atmospheric Imaging Assembly

160 nm, CIV + Continuum; $10^4 - 10^5$ K?

NASA Solar Dynamics Observatory / Atmospheric Imaging Assembly

30.4 nm, He II; 5×10^4 K

NASA Solar Dynamics Observatory / Atmospheric Imaging Assembly

13.1 nm, Fe VIII, XX, XXIII; $4 \times 10^5, 10^7, 1.6 \times 10^7$ K

NASA Solar Dynamics Observatory / Atmospheric Imaging Assembly

17.1 nm, Fe IX; 6.3×10^5 K

NASA Solar Dynamics Observatory / Atmospheric Imaging Assembly

19.3 nm, Fe XII, XXIV; $1.2 \times 10^6, 2 \times 10^7$ K

NASA Solar Dynamics Observatory / Atmospheric Imaging Assembly

21.1 nm, Fe XIV; 2×10^6 K

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33.5 nm, Fe XVI; 2.5×10^6 K

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9.4 nm, Fe XVIII; 6.3×10^6 K

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13.1 nm, Fe VIII, XX, XXIII; $4 \times 10^5, 10^7, 1.6 \times 10^7$ K

NASA Solar Dynamics Observatory / Atmospheric Imaging Assembly

SDO/AIA Channels Summary

AIA Wavelength Channel	Source[15]	Region of solar atmosphere	Characteristic Temperature
White Light	continuum	Photosphere	5000 K
170 nm	continuum	Temperature minimum, photosphere	5000 K
30.4 nm	He II	Chromosphere & transition region	50,000 K
160 nm	C IV + continuum	Transition region & upper photosphere	10^5 & 5000 K
17.1 nm	Fe IX	Quiet corona, upper transition region	6.3×10^5 K
19.3 nm	Fe XII, XXIV	Corona & hot flare plasma	1.2×10^6 & 2×10^7 K
21.1 nm	Fe XIV	Active region corona	2×10^6 K
33.5 nm	Fe XVI	Active region corona	2.5×10^6 K
9.4 nm	Fe XVIII	Flaring regions	6.3×10^6 K
13.1 nm	Fe VIII, XX, XXIII	Flaring regions	4×10^5, 10^7 & 1.6×10^7 K

1. Why are the wavelengths not inversely proportional to temperature?
2. Why are there no coronal H or He lines?
3. Why is the corona hotter than the photosphere?

Solar Atmosphere Summary

- Photosphere
  - Convection zone is dense and opaque, with a well-defined surface.
  - Energy to escapes at the photosphere as continuum radiation.
  - Spectrum at a given depth depends mainly on temperature (LTE).
  - To first approximation, can ignore magnetic field.
- Corona (& Transition Region)
  - Optically thin (transparent).
  - Ionization (and therefore source spectrum) determined by temperature.
  - Magnetic field confines plasma to 1D atmospheres (loops).
- In the Chromosphere, everything matters:
  - Neither opaque nor transparent. Messy radiative transfer.
  - Non-LTE (radiation field out of equilibrium with temperature).
  - Magnetic field competes with hydrodynamic forces.