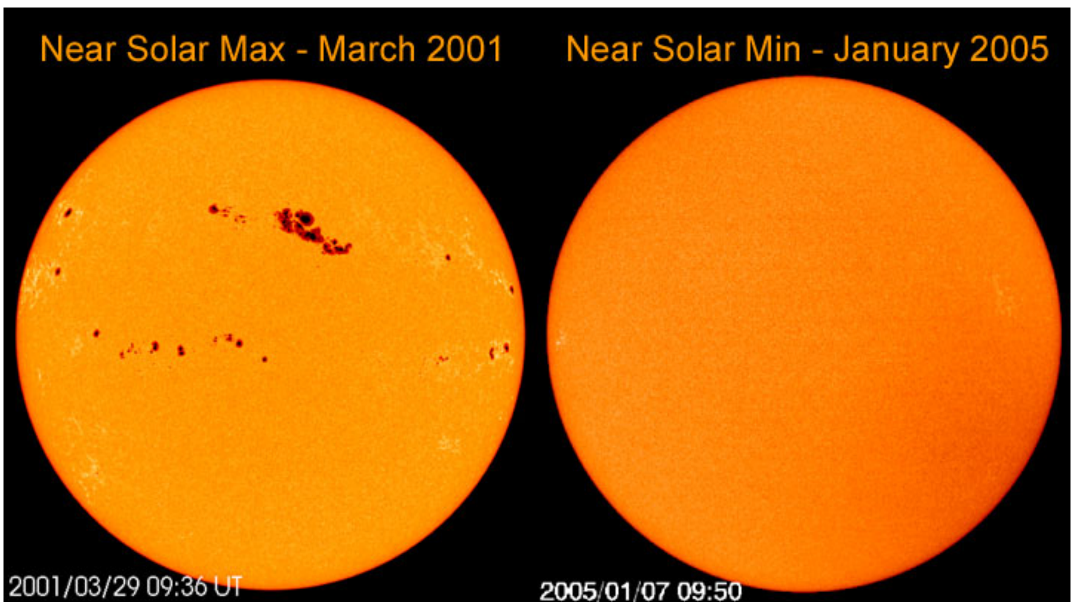
Astronomy 404
October 16, 2013

Main sequence stars
Eddington limit

The Sun's interior – radiation transport of energy from core up to ~0.7 $R_\odot$, then convection transport. The onset of convection is caused by the increased opacity from ionizing hydrogen.
Solar neutrino problem – caused by neutrino oscillation among three flavors (ν_e, ν_μ, ν_τ), only a fraction of ν_e produced in nuclear reactions is detected as ν_e.

The Solar Atmosphere



Sharp edge – from optically thin to optically thick in ~600 km, <0.001 times the solar radius of ~7×10^5 km.

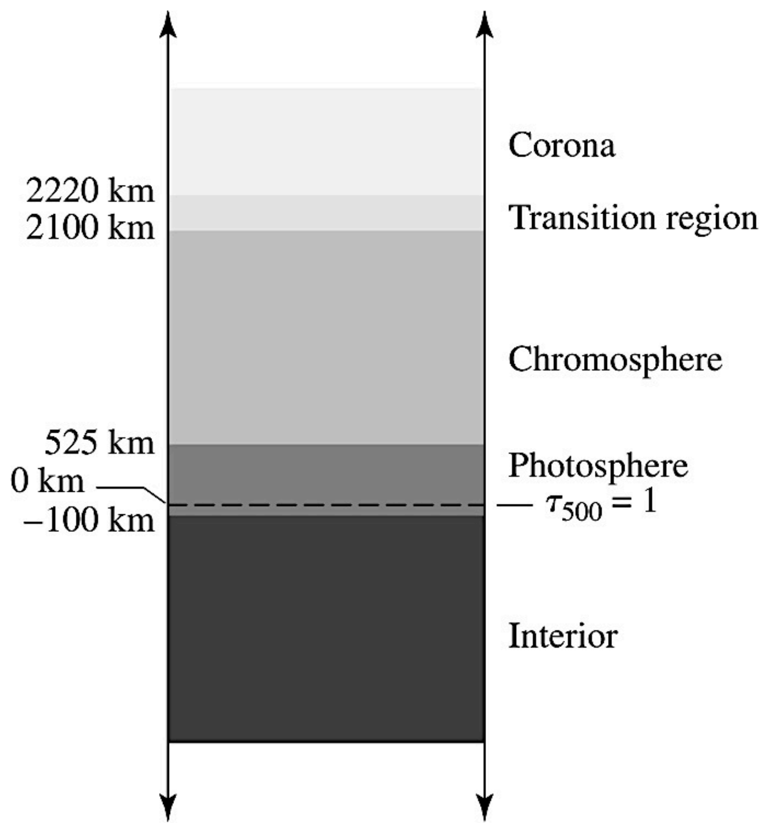
Limb darkening - $\tau = 2/3$ near the limb corresponds to upper parts of the atmosphere where T is lower.

Looking straight into the disk, $T_{\tau=2/3} = 5777$ K.

The Photosphere

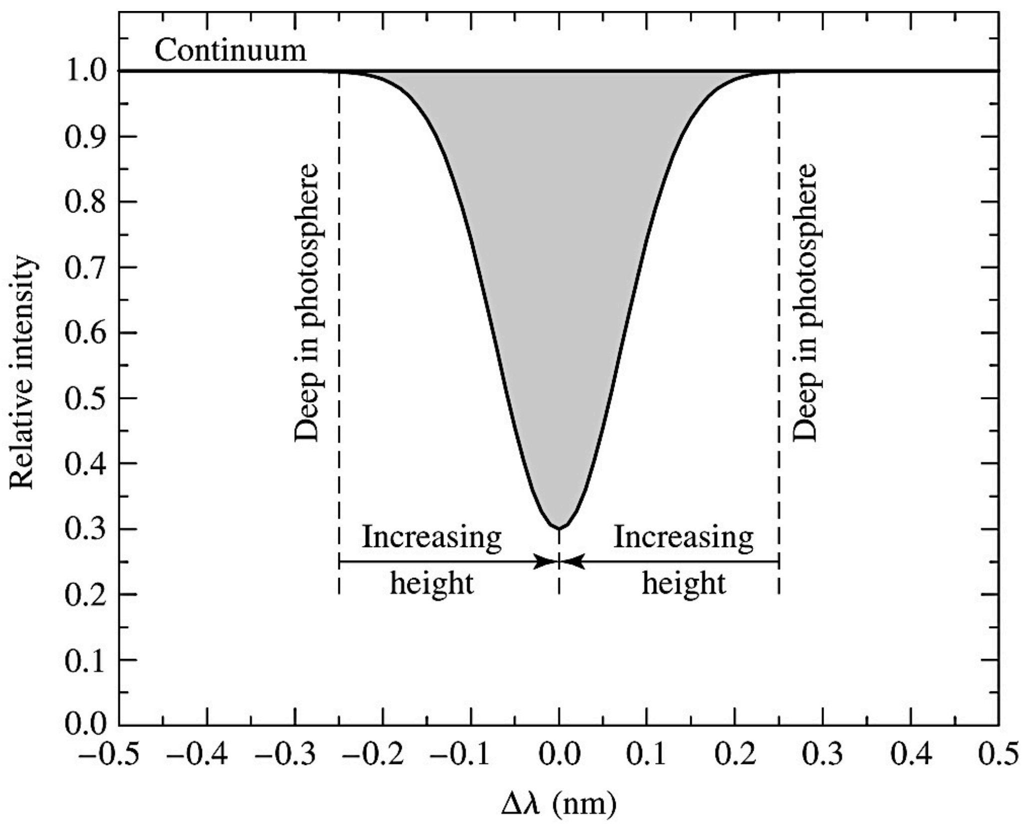
The base of the solar photosphere is *defined* to be 100 km below where the optical depth at a wavelength of 500 nm is unity, $\tau_{500}=1$. At the base of the photosphere, $\tau_{500} \sim 23.6$, and $T \sim 9400$ K.

The top of the photosphere is 525 km above $\tau_{500}=1$, where $T \sim 4400$ K. Beyond this point, T rises and the chromosphere starts.



The Sun radiates predominantly as a blackbody in the visible and IR, indicating a source of opacity that is continuous across the wavelength. This continuum opacity is provided by H^-, although only about 1 in 10^7 H atoms forms an H^- ion.

Although the Kirchhoff's laws require absorption lines to be formed in cooler gas in front of a continuum source of higher temperatures, the absorption lines are actually formed in the same layers where H^- produces the continuum.

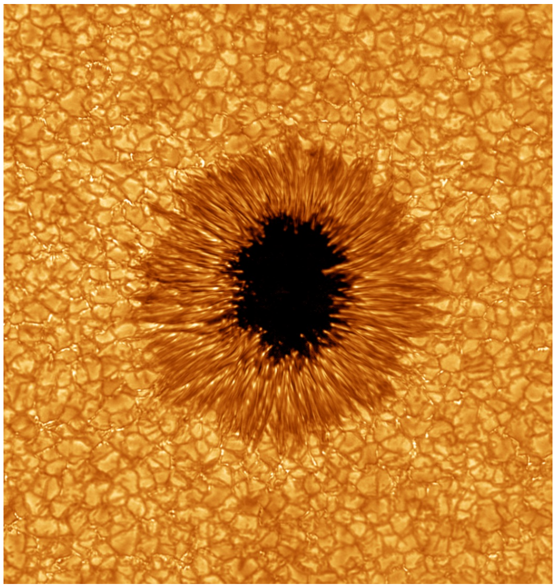


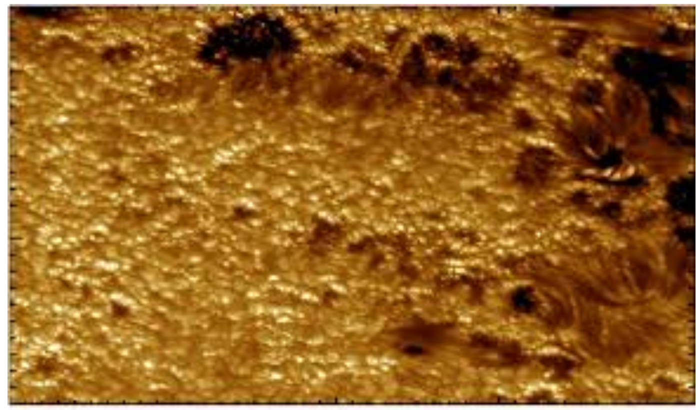
This can be understood as looking into the photosphere, but seeing only the continuum from the layer where $\tau = 2/3$.

As $\tau_\lambda = \kappa_\lambda \rho s$, when κ_λ is large, s would be small, i.e., we are seeing the upper part of the photosphere where temperature is lower.

The wings of an absorption line profile are formed deeper in the photosphere than the core of the line.

Solar Granulation





http://www.youtube.com/watch?v=gKTPB7_jTcE

The cells are ~700 km across.

Solar granulation originates from the top of the convection zone protruding into the base of the photosphere.

Hotter material rises in the lighter parts, cools, and sinks in the darker parts. Radial velocities are ~ 0.4 km/s.

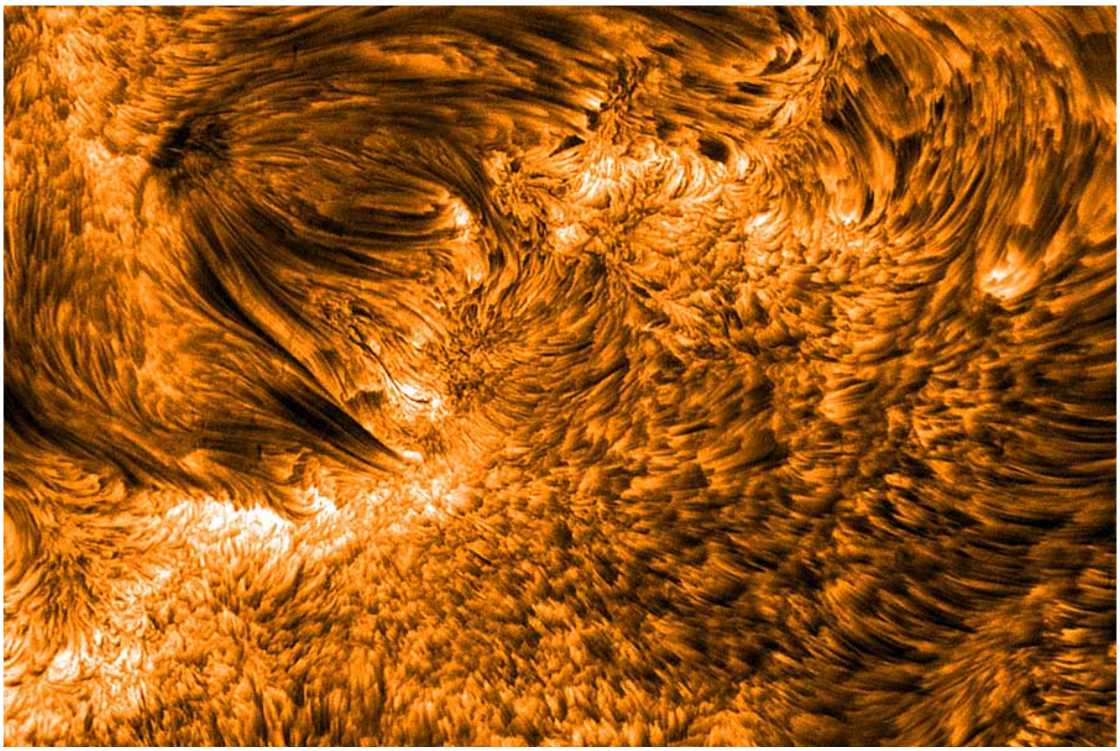
The Chromosphere

The chromosphere extends upward for ~1600 km from the top of the photosphere. The density decreases by more than a factor of 10^4, but the temperature increases from 4400 K to 10,000 K.

He II and Ca II H & K lines are formed in the chromosphere.

Lines can appear in absorption or in emission. Emission lines in UV or IR can be detected more easily; optical emission lines can be observed during solar eclipses.

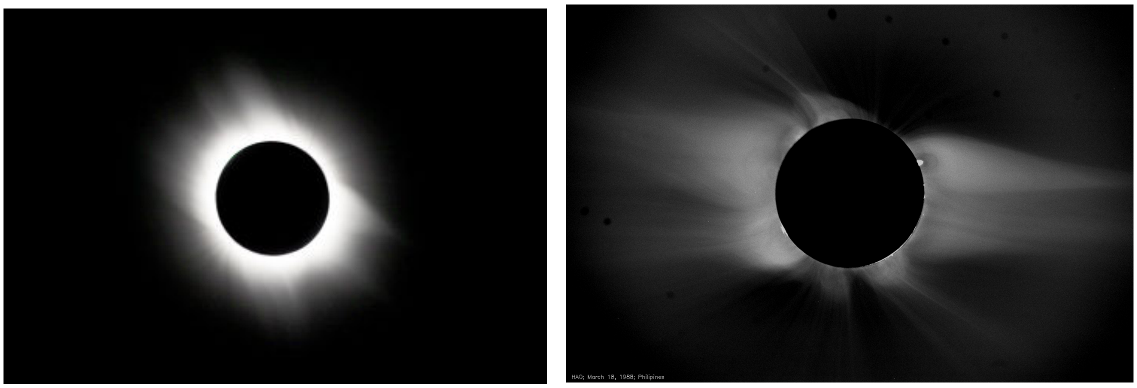
Hα emission line from the chromosphere can show **supergranulations** on a scale of 30,000 km. It can also show **spicules**, vertical filaments extending upward from the chromosphere for 10,000 km. An individual spicule may have a lifetime of ~15 min; the material moves outward at ~15 km/s. (see the Hα image below)



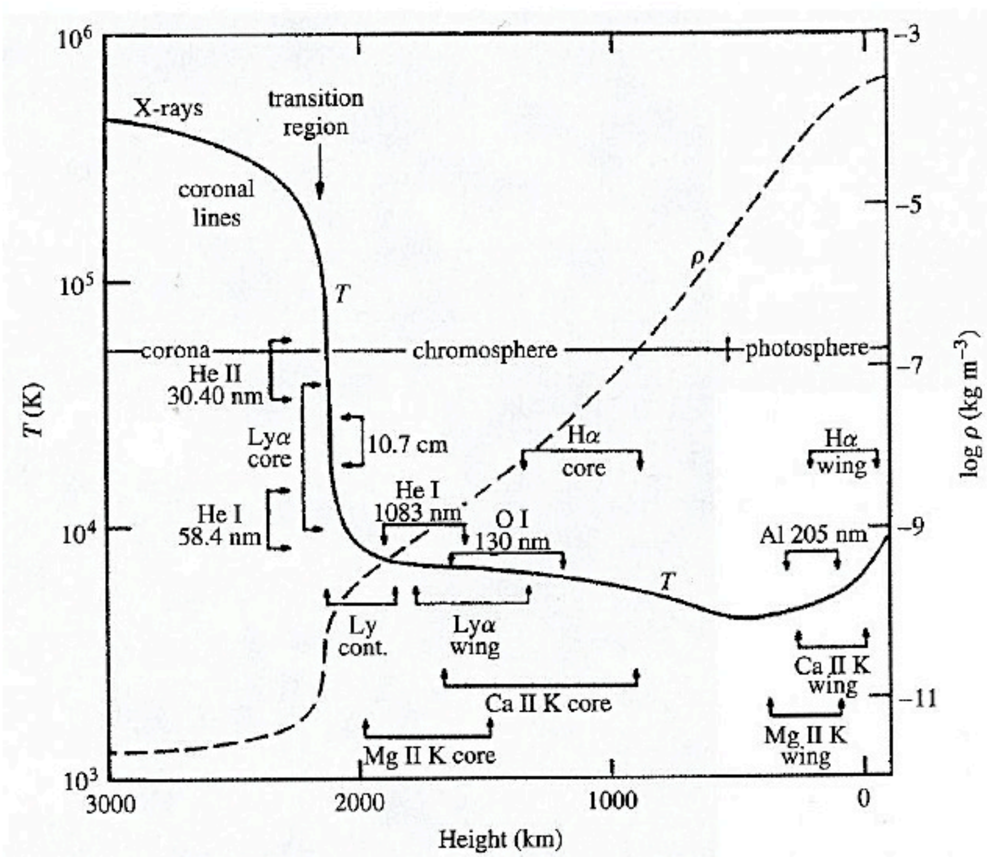
Above the chromosphere is a transition zone then the corona.

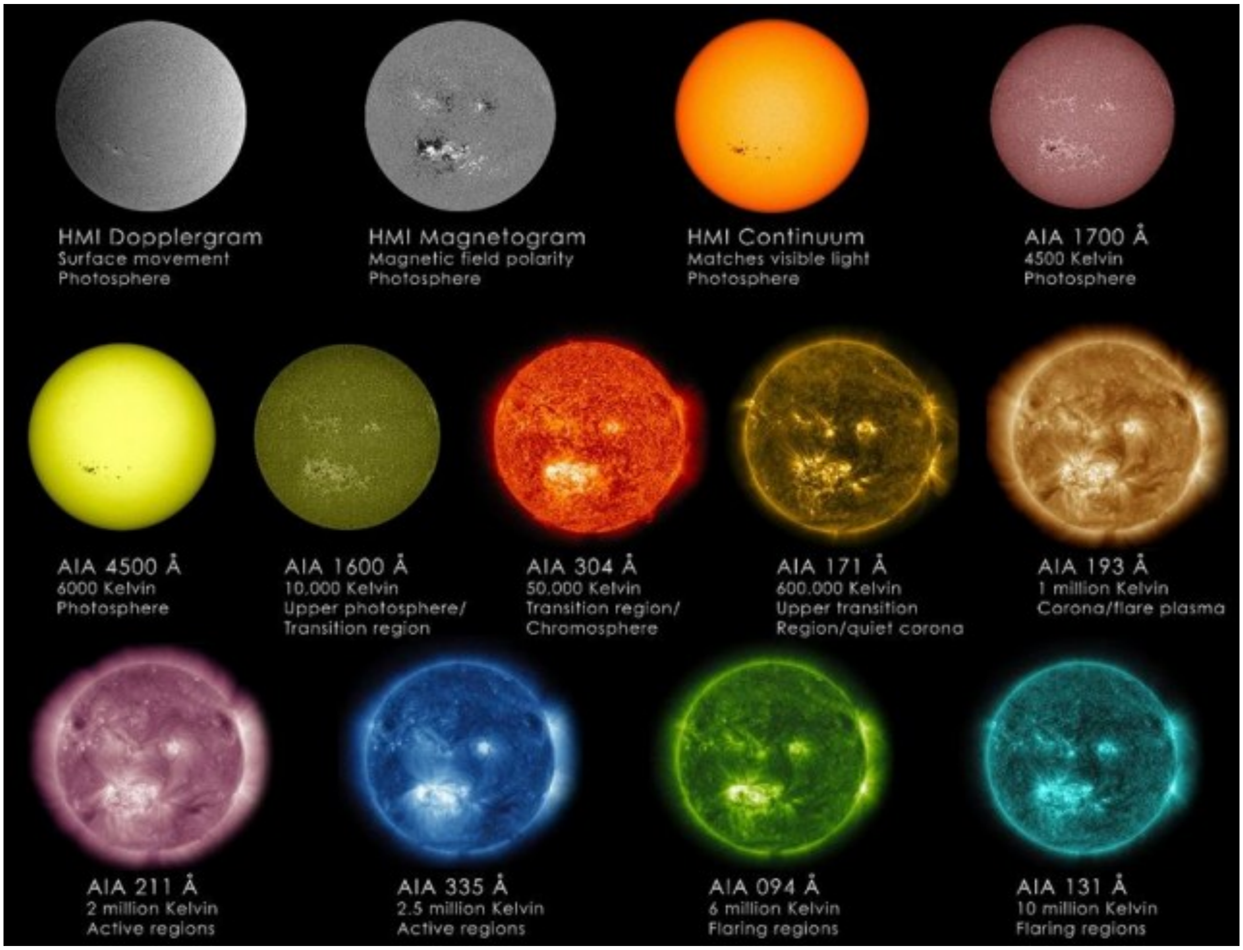
The Corona

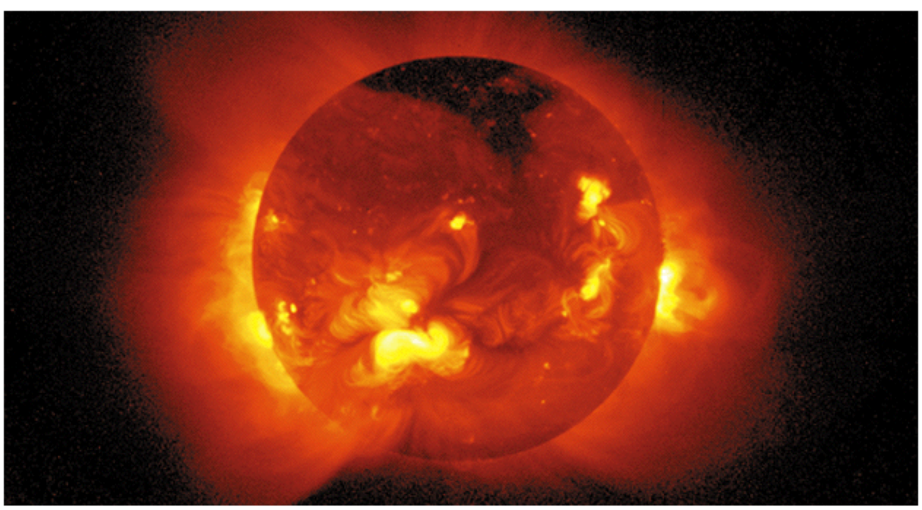
K corona (R = 1-2.3 $R_\odot$), F corona (R > 2.3 $R_\odot$), and E corona. The E corona, the source of emission lines of highlyionized atoms, overlaps with both K and F coronae.



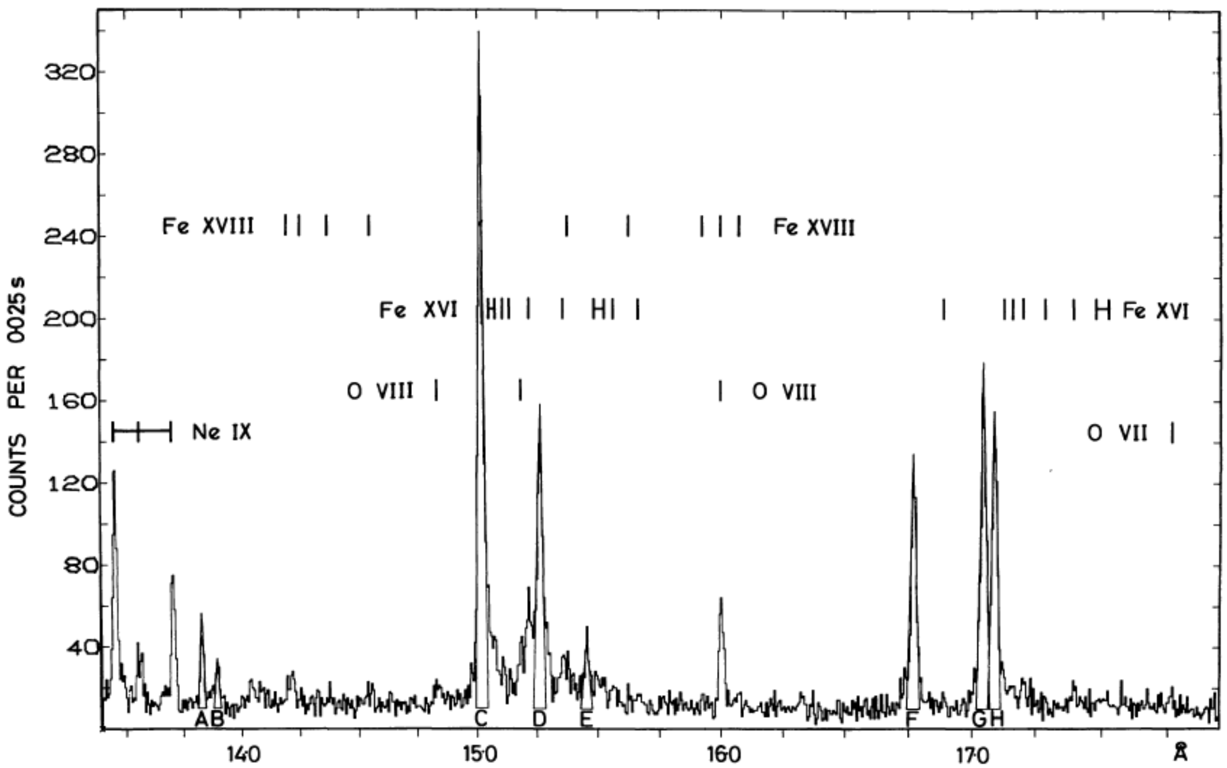
Optical images of the Sun during eclipses, showing a quiet corona and an active corona, respectively.







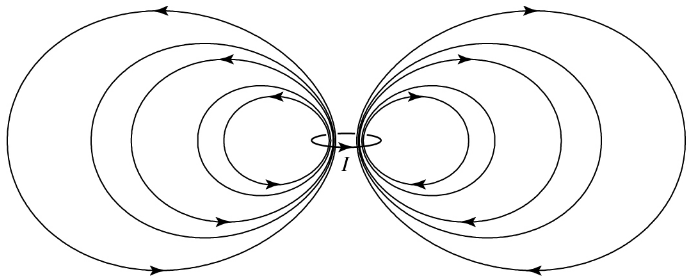
An X-ray image of the Sun obtained by the Soft X-ray Telescope on the Yohkoh Solar Observatory. See the coronal hole at the top of the image.



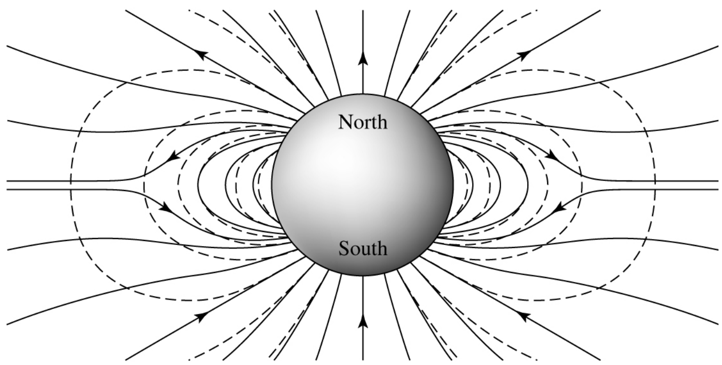
X-ray spectrum of the solar corona. The wavelength is in units of Å (0.1 nm). Figure 11.21 in the book has incorrect horizontal axis. The O VIII line at 16 Å corresponds to 775 eV, the n=3 to n=1 transition of the H-like oxygen ion.

Similar kind of coronal X-ray emission is observed in late-type stars with convection envelopes. The X-ray luminosity is up to $\sim 10^{-4}$ times the bolometric luminosity of the star.

The plasma in the solar corona move in the magnetic field of the Sun.

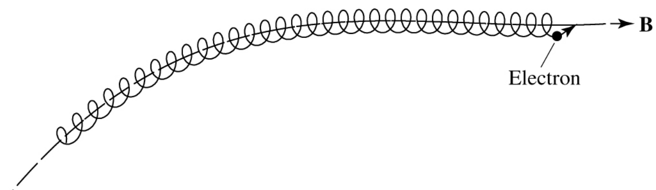


(a)



(b)

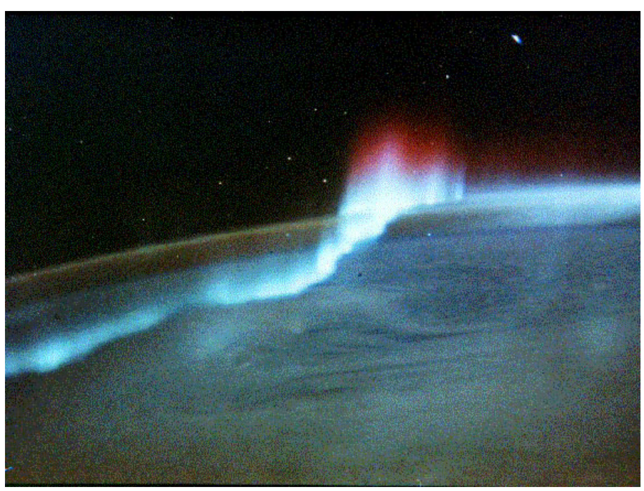
Charged particles cannot cross magnetic field lines because of the Lorentz force: $\mathbf{F} = q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$. So, charged particles spiral around the magnetic field lines:



For closed magnetic field lines, charged particles are trapped in the magnetic field loops. For open magnetic field lines, charged particles can escape, resulting in lower density and hence lower emission (coronal holes). The escaped particles form the **solar wind**.

Comet Mrkos shows a dust tail (curved and fanning out) and a straight ion tail. The dust tail is pushed out by radiation pressure, and the ion tail is straightened by the solar wind.

When the solar wind reaches the Earth, the charged particles will spiral around the Earth's magnetic field lines. The only regions where solar wind particles can slam into the upper atmosphere are the north and south poles, forming the aurora borealis and aurora australis.



http://www.physicschick.com/pole/20120511/dsl_aurora.gif

The solar wind has a speed of ~750 km/s. Some slow solar wind at ½ of the speed can also originate from the streamers in the corona associated with closed magnetic fields.

What's the mass loss rate of the solar wind?

Considering a sphere of radius *r*, the solar wind that passes through this sphere in *dt* will be

$$dM = \rho\, dV = (n m_H)(4\pi r^2\, v\, dt),$$

The mass loss rate *dM/dt* is then:

$$\frac{dM}{dt} = 4\pi r^2\, n m_H v = 4\pi r^2\, \rho v.$$

For a solar wind velocity of 500 km/s, r = 1 AU, and $n = 7\times10^6$ protons m^{-3}, the mass loss rate is:

$$\dot{M}_\odot \simeq 3 \times 10^{-14}\ M_\odot\ yr^{-1}$$

This mass loss rate is so small that it does not affect the Sun's evolution.