Lecture 8 – Chromospheres

Stars have hot outer envelopes. In the Sun, the chromosphere and corona which have small amounts of mass with relatively high temperatures. These are dynamic, complex environments, so all we can is present simple models.

Evidence for the existence of hot outer gas comes from ultraviolet and X-ray emission lines. There are also reversals in the central cores of the H and K lines of calcium and emission in Hα and sometimes other lines. Some stars display gigantic flares as seen in radio or even optical light.

One way to study the Sun's outer atmosphere is from the radio emission (Marsh & Hurford, 1982, Ann Rev. Astron. Ap., 20, 497; Zirin, Baumert & Hurford 1991, ApJ, 370, 779). In this very simple model, the chromosphere is taken to have a constant, uniform temperature, T_{chrom}, of 11000 K. The corona is an optically thin, isothermal slab of $T = 10^6$ K, base density of 3.2×10^8 cm^{-3} and scale height, H, of 5×10^9 cm. In this model, the radio brightness temperature, T_b, is

$$T_b \;=\; A\nu^{-2.1} \,+\, T_{chrom} \tag{1}$$

The fit to the data is given by $A = 140{,}000$ if ν is in GHz. This value of A can then be used to determine the emission measure of the corona. They estimate $T = 10^6$, $n_e = 3 \times 10^8$ cm^{-3} and $H = 5 \times 10^9$ cm. This can be derived from the formula in Spitzer (1978, Physical Processes in the Interstellar Medium) that in units of cm^{-1}:

$$\kappa_\nu \;=\; 0.173\left(1 \,+\, 0.130\log\frac{T^{3/2}}{\nu}\right)\frac{Z^2 n_e n_i}{T^{3/2}\nu^2} \tag{2}$$

This high temperature agrees with values derived from X-ray emission and the observed pronounced outer extension of the corona. From these conditions, the quiet Sun X-ray luminosity and mass loss rate can be computed.

The chromosphere can be studied by its ultraviolet emission. It is complicated because it depends upon the level of magnetic activity and is patchy over the Sun. A good discussion of recent chromospheric models is in Fontenla et al. (2006, ApJ, 639, 441). The most important emission line from the chromosphere is Lyman α; it carries over half of the total surface flux which is about 2×10^5 erg cm^{-2} s^{-1}; about 10^{-5} of the radiative flux (σT_e^4) of 6.3×10^{10} erg cm^{-2} s^{-1} from the photosphere. The emergent flux in this one line varies during the solar cycle by perhaps a factor of 2 (Krivova et al. 2006, A&A, 452, 631).

At line center, the flux at the Earth in the Lyman α line is about 3.2×10^{11} photons cm^{-2} s^{-1} Å^{-1} or 2.6×10^{-12} erg cm^{-2} s^{-1} Hz^{-1}. The emission profile of Lyman α is complex because of radiative scattering of photons in the chromosphere. The line is self-reversed and has a FWHM of 0.8 Å (Combi & Smyth 1988, ApJ, 327, 1044). The observed intensity in the line from the disk is about 2.6×10^{-8} erg cm^{-2} s^{-1} Hz^{-1} ster^{-1} or 5.3×10^4 erg cm^{-2} s^{-1} Å^{-1}. Theoretical models (Table 10 in Fontenla et al. 1991) can reproduce this result. Incidentally, this intensity corresponds to a brightness temperature of 7400 K, this is only a formal result.

The total luminosity in Lyman α is about 1.2×10^{28} erg s^{-1} or about 3×10^{-6} of the Sun's bolometric luminosity.

According to Fontenla et al. (1991), the temperature where the bulk of the Lyman α emission is produced is 40,000 K. Since the number of absorbers varies as:

$$n(V)\,dV \propto e^{-mV^2/2kT} \tag{3}$$

Then if λ_0 denotes the wavelength of Lyman α, we expect that:

$$\lambda_{FWHM} \;=\; \frac{\lambda_0}{c}\left([4\,\ln 2]\,\frac{kT}{m}\right)^{1/2} \tag{4}$$

This predicts a FWHM of 0.12 Å, appreciably less than the observed value of 0.8 Å. The difference is explained because the line is in non-LTE and scatters multiple times before escaping from the chromosphere. Evidence that the FWHM is not thermally broadened comes from a comparison with the Lyman β emission which has a FSWM of 0.5 Å. Thus, $\Delta\lambda/\lambda$ for Lyman β is only about 0.5 of the value for Lyman α. Lyman α carries about 70 times as much energy as does Lyman β (Lemaire et al. 1978, ApJ, 223, L55).

The pressure in the chromosphere at 10,000 K is about 1 dyne cm^{-2} which implies a hydrogen density (for mostly neutral gas) of 7×10^{11} cm^{-3}. The scale height of this material, H, is:

$$H \;=\; \frac{k\,T}{m\,g} \tag{5}$$

Therefore, $H \approx 400$ km. Thus, the column density of neutral hydrogen is $\sim 3 \times 10^{19}$ cm^{-2}. In the damping wing of the line, we can write that

$$\tau \;=\; \frac{\pi e^2}{m\,c}\,f\,\frac{N}{(\Delta\nu)^2}\,\frac{A}{4\pi^2} \tag{6}$$

For the 1s-2p transition of atomic hydrogen, we take $f = 0.416$ and $A = 6.265 \times 10^8$ s^{-1}. Thus in this portion of the chromosphere, $\tau = 1$ at $\Delta\nu = 2 \times 10^{12}$ Hz or $\Delta\lambda \approx 1$ Å. Although the real chromosphere is more complex, it can be understood why the FWHM of the line is considerably broader than the thermal width.

The temperature in the chromosphere increases with height. In a very simple model, the physics is described by hydrostatic equilibrium:

$$\frac{dp}{dz} \;=\; -\rho\,g \tag{7}$$

the ideal gas law:

$$p \;=\; \frac{\rho}{\mu}\,k\,T \tag{8}$$

and an equation to relate density and temperature. A simple model is a constant heat flux, F, (erg cm^{-2} s^{-1}) is balanced by radiative cooling so that:

$$F \;=\; \int q\, dz \tag{9}$$

where q is the local radiative cooling (erg cm^{-3} s^{-1}):

$$q \;=\; n_e\, n\, g(T) \tag{10}$$

For Lyman α cooling, Fontenla et al. (1991) adopt:

$$q \;=\; h\nu\, n_e\, n(H)\, C_0 \gamma\, T^{-1/2}\, e^{-h\nu/kT} \tag{11}$$

with $C_0 = 4.3 \times 10^{-6}$ cm^3 s^{-1} and γ between 0.7 (T = 10,000 K) and 1.0 (T = 40,000 K). At lower pressures, the temperature rises to balance the heating. (As the hydrogen becomes more and more ionized, then other lines besides Lyman α dominate the cooling.) Note that $C_0\, \gamma\, T^{-1/2}$ is roughly given by $\sigma\, V_e$ where σ is the geometric cross section of the hydrogen atom and V_e is the thermal velocity of an electron. [Take $\sigma \approx 10^{-16}$ cm^2 and V_e = $(8\, k\, T/\pi\, m_e)^{1/2}$ or 6 $\times$ 10^7 cm s^{-1} at T = 10,000 K. Thus $\sigma\, V_e$ is $\sim 10^{-8}$ cm^3 s^{-1} while $C_0\, \gamma\, T^{-1/2}$ is $\sim$3 $\times$ 10^{-8} cm^3 s^{-1}.]

Main-sequence stars exhibit a wide variety of chromospheric activity. As discussed in the next lecture, there is a correlation between $V \sin i$ and the level of activity for stars later than about mid-F. Stars as old as the Sun are relatively inactive and display Maunder minima (Baliunas et al. 1995, ApJ, 438, 269). A-type stars exhibit very little chromospheric activity (for example, Simon et al. 1994, ApJ, 428, 319).

Much of the energy flux is carried by conduction. Thus:

$$F \approx K\, \frac{dT}{dz} \tag{12}$$

where K is the coetficient of conductivity.

A more complete treatment is to include turbulence and magnetic fields in the gas pressure. Thus, for example, one could include (see Fontenla et al. 2006, ApJ, 639, 441)

$$p \;=\; p_{gas} \;+\; \frac{1}{2}\rho\, V_A^2 \tag{13}$$

where V_A, the Alfven velocity is:

$$V_A^2 \;=\; \frac{B^2}{\pi \rho} \tag{14}$$

Chromospheric emission in the ultraviolet has been observed for large numbers of stars. A difficulty in observing Lyman α is that the Earth's geocoronal emission is often very bright. The Earth loses a small amount of hydrogen, typically 1 kg s^{-1}, and there is a cloud of neutral gas around us. This cloud scatters Lyman α emission from the Sun into any Earth-orbiting telescope.

The Lyman α flux is important in heating the Earth's upper atmosphere and photo-processes in comets. For example, water is vaporized from a comet's nucleus and then is photodissociated by the process:

$$h\nu \ + \ H_2O \rightarrow OH \ + \ H \tag{15}$$

This process is followed by:

$$h\nu + OH \rightarrow O \ + \ H \tag{16}$$