

# Stellar Spectra B. LTE Line Formation

Andreas Ellewisen

## 1. Stratification of the solar atmosphere

In this exercise we study the radial stratification of the solar atmosphere by using the FALC model by Fontela et al. (1993)

### 1.1. FALC temperature stratification

The first thing to do is import the data from the modelfiles, and take a look at how temperature varies with height. This can be seen in figure ??

### 1.2. FALC density stratification

I start by plotting the total pressure  $p_{total}$  against column mass  $m$ . See figures ?? and ?. We see that they scale linearly. From this we can conclude that we can write

$$p_{total} = Cm \quad (1)$$

where if one finds  $C$  for all pressures and column masses and then find the average  $C$ , I get  $C = g_{surface} = 27398.2 \text{ cm/s}^2$ .

Fontena et al. (1993) assumed complete mixing, so we check that this condition holds by plotting the ratio of the hydrogen mass density to the total mass density against height. Next we add the Helium as well and calculate the contribution of helium and hydrogen to the total. From the figure it seems that nearly all of the density is contributed from hydrogen and helium. However if one does the calculation one finds that the average fraction of the remaining elements (the "metals") contributes 0.002 (0.02%) of the total. This can be seen in figure ??

Next we plot the column mass against height. See figure ?. Note that the curve becomes nearly straight if we make the y-axis logarithmic in figure ?. This is caused by XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX.

The next quantity to look at is gas density. Gas density is plotted against height in figure ?.

We want to know the pressure scale height  $H_p$  in

$$\rho \approx \rho(0) \exp(-h/H_p) \quad (2)$$

This can be found from the definition

$$H_p = \frac{kT}{Mg} \quad (3)$$

where  $k$  is boltzmanns constant,  $T$  is temperature in K,  $M$  is the mean molecular weight, and  $g$  is surface gravity. If one assumes that most of the molecules in the photosphere is hydrogen we can set  $M = m_H$ . Inserting the values for the deep photosphere ( $h = -100$ ) then gives a scale height of  $H_p = 196.3 \text{ km}$ . This is not realistic. Assuming that the photosphere only contains helium gives a scale height  $H_p = 49.3 \text{ km}$ . The real number is somewhere between these two, but since we don't know the mean molecular weight this method doesn't really work in this case.

Another way to do this is to just mark the point where the density has fallen to  $1/e$  of its original value. In figure ?? this is marked with a line. The point the two lines cross gives  $H_p \approx 150 \text{ km}$ .

The next step is to compute the gas pressure and plot it against height. We also overplot the product  $(n_H + n_e)kT$ . See figure ?. There is some difference between the curves. Plotting the ratio between the curves shows this clearly (figure ?). Note however that the sun does not only contain hydrogen. Because of this we must include the hydrogen number density in the ideal gas law. By doing this we obtain figure ? which shows a curve that seems to be overlapping perfectly. Plotting the ratio between the two curves shows that it deviates only slightly at the fourth decimal place. See figure ?. From this we can conclude that the ideal gas law is a very good approximation.

With that done we want to look at the total hydrogen density. We should also include the electron density, proton density, and the density of the electrons that do not result from hydrogen ionization. The electron density, proton density and electron density can be read out of the FALC model. To find the density of the electrons not from ionized hydrogen we need to assume that all of the protons come from ionized hydrogen. This would indicate that  $n_H - n_p$  equals the number of neutral hydrogen atoms. And since each neutral hydrogen has one electron this would be the number of electrons still bound to hydrogen, e.g those not from ionized hydrogen. The density of these should then be

$$n_{be} = (n_H - n_p). \quad (4)$$

This is plotted against height in figure ?.

From the graph we see that the number density of protons is a little above 0 for very low heights. This indicates that the hydrogen gets ionized at this height. As the height increases this goes to zero indicating that the hydrogen remains neutral when height increases. Because of this it is only logical that the electron density goes to zero as well, and that the density of the electrons not from ionized hydrogen approaches the density of the hydrogen (since nearly all of the hydrogen is neutral hydrogen). Figure ? shows the same with a logarithmic

As the height increases the number density of everything approaches zero, which makes sense since we are looking at the atmosphere of the sun. At some point we should approach vacuum which has almost zero density.

With that done we plot the ionization fraction of hydrogen against height. The ionization fraction of hydrogen fraction is simply

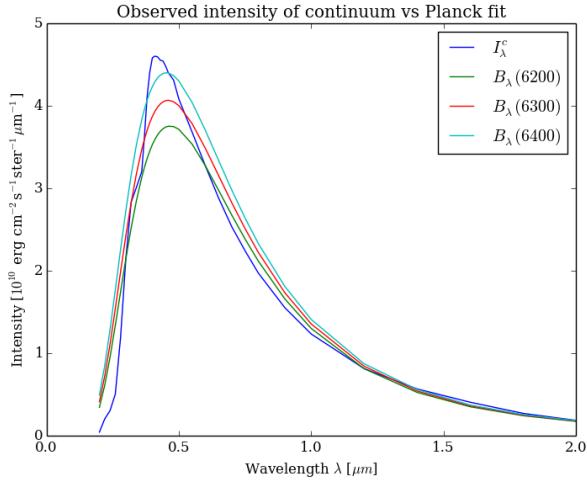
$$n_{HII} = \frac{n_p}{n_H} \quad (5)$$

See figure ?. Note the logarithmic scale. There is a clear resemblance to the temperature plot (see figure ?). XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX EXPLAIN WHY THAT IS AND WHY IT IS TILTED XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

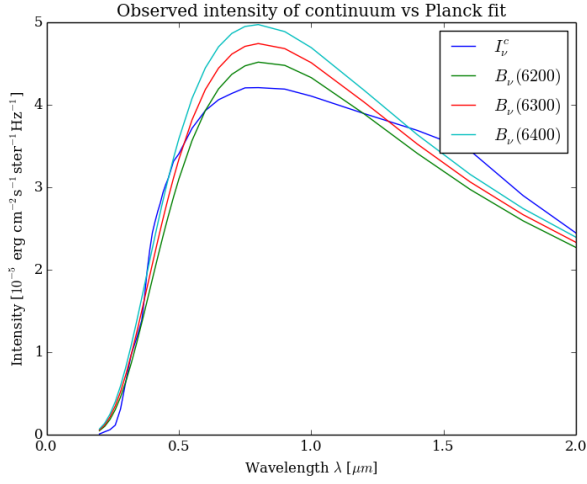
The next thing one should do is compare the photon density to the particle density. If one assumes thermodynamic equilibrium the photon density  $N_{phot}$  in photons per  $\text{cm}^3$  is given by

$$N_{phot} \approx 20T^3 \quad (6)$$

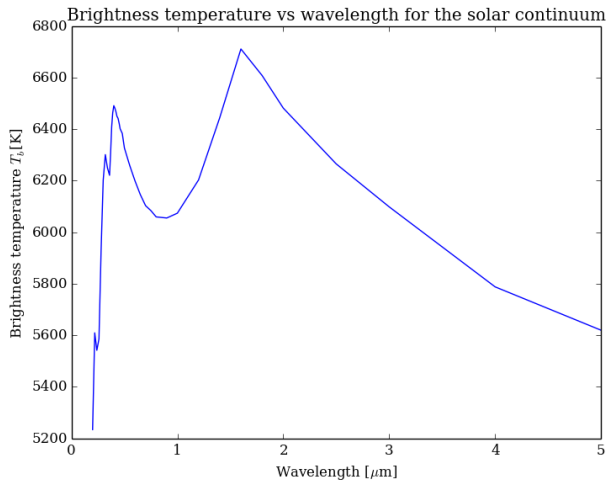




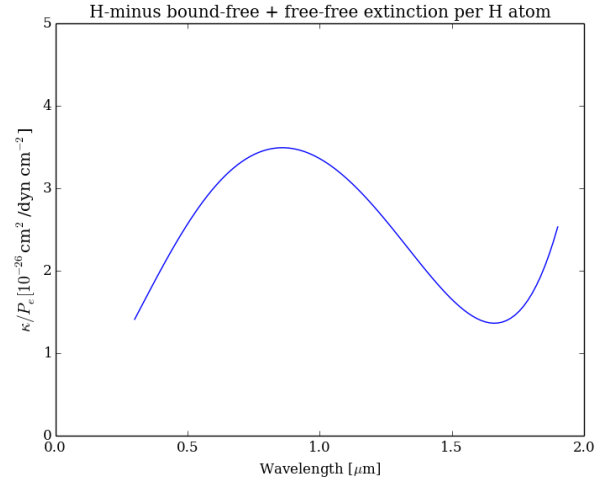
**Fig. 1.** The solar continuum with three attempts to fit a planck function to it.



**Fig. 2.** The solar continuum with three attempts to fit a planck function to it.



**Fig. 3.** Brightness temperature of the solar continuum.



**Fig. 4.**  $H^-$  extinction for FALC parameters at surface of solar atmosphere, normalized with the electron pressure  $P_e = n_e kT$

even higher than the violet one. That peak is also a wider one which would indicate that more energy is transported through infrared radiation than visible light.

## 2.2. Continuous extinction

Now we aim to reproduce figure 5 in the project text. We are provided with a function that evaluates polynomial fits for  $H^-$  extinction that are given on page 135 ff of Gray (1992). This function takes delivers the total  $H^-$  extinction in units of  $cm^2$  per neutral hydrogen atom. Plotting the values corresponding to the electron density and temperature at the surface of the solar atmosphere results in figure 4

## 3. References

Rutten, R. J.: 1991, The Generation and Transportation of Radiation, Sterrekundig Instituut Utrecht, The Netherlands