**ChromaStar lab 6: Ionization equilibrium and MK spectral class**

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**Level:** Second year University

**Purpose:** To investigate the variation with *T*eff of the *relative* *strength* of spectral lines of species that are adjacent ionization stages, *k* and *k+1*, of a chemical element, *Z*. To relate this variation to the MK spectral classification of class G and K stars. You will be using *equivalent width*, *W*λ, as the measure of spectral line strength.

**Background:** TheMorgan-Keenan (MK) spectral classes (main classes OBAFGKM(LTY)) are known to correlate with a star’s effective temperature, *T*eff. The fundamental reason is that the strength of a spectral line of a chemical species, *k*, due to one of its atomic transitions (*i→j*) depends mostly on the number density, *n*i, of absorbing particles of *k* that are in the lower atomic energy level, *i*, of the transition. The value of *n*i depends on *two* things:

1. *T*he *ionization equilibrium* of the corresponding chemical element, *Z* - that isthe ratio, *N*k+1*/****N*k**, of *Z* in the ionization stage *k+1* to that in the adjacent lower stage *k* (and/or, similarly, the ratio ***N*k***/N*k-1), as described by the *Saha equation*, *and*
2. The *excitation equilibrium* of ionization stage (*ie.* species), *k* – that is the fraction, *n*i*/N*k, of *k* in the lower energy level *i*, as described by the *Boltzmann equation*.

Both of these equilibria depend on the star’s *T*eff value – the larger the *T*eff value, the larger the *ionization temperature*, *T*ion, in the Saha equation, and the larger the *excitation temperature*, *T*exc, in the Boltzmann equation. In this lab we will be studying the *ionization* equilibrium (*N*k+1*/N*k) effect *only*.

**Apparatus:**

The ChromaStar stellar atmospheric modelling WWW application: ([www.ap.smu.ca/OpenStars/](http://www.ap.smu.ca/~ishort/OpenStars/GrayStar3/GrayStarV4.html) )

 A spreadsheet application: (OpenOffice Calc (free!), MS Excel, …). You must be able to ‘Save’, ‘Export’, or ‘Print’ the file in a platform-independent format such as PDF – you might have to submit it electronically.

**Initial set-up:**

Make sure you are starting with a fresh ‘reload’ of ChromaStar so that all the input parameters have their default values (among other things, the stellar parameters will default to solar values - if you think that some values are not reverting to default, try clearing your browser’s history with all optional data types checked, and ‘reload’ again).

In the “Input:” section, open the optional input panel titled “Show/hide spectral line” – you won’t have to change anything manually in this panel, but you’ll need to take note of it.

Open the optional input panel titled “Show/hide samples” – you’ll be working with the lowest row of radio buttons labeled with the identities of important MK classification lines (a chemical species name and either a wavelength or a letter).

In the “Output:” section, under “Plots:”, check the box for “High resolution spectral line” – this displays two optional figures: A plot of the spectral line for which we will be studying the strength, and a diagram of the corresponding atomic energy levels and transition. *Note* that the value of *Wλ* is displayed in picometers (1 pm = 10 mA) in this plot, as well as in the textual output banner just above the graphical output.

In a spreadsheet application open a new document and save it with the filename “YourLastName-TeffLab”. At the top of the sheet, enter a meaningful *title*, the *date*, and your *name*, and the *course name*. You *might* have to submit the spreadsheet electronically.

**Procedure:**

1. In ChromaStar, in the “Samples” input panel, check the radio button labeled “Ca I 4227” (this refers to the Ca I spectral line at 422.7 nm – an important MK classification diagnostic for class G and K stars). Hit the “Model” button – ChromaStar is now modeling this spectral line for the Sun. You should *confirm* this – in the “spectral line panel” the “Line center wavelength (*λ*o)” text box should now contain a value close to 422.7 nm, the text box “Stage I ground state ionization E (*χ*I)” and that for Stage II (*χ*II) should now contain the ground state ionization energies for Ca I and II in eV, respectively (look them up and check if you’re worried!), and the “Particle mass” box should now have the isotopic average of the atomic *mass* (*A*) of Ca (about twice the atomic *number* (*Z*) of Ca - 40 amu). Note that the “Excitation E” of the lower level of the transition (*χ*i) is 0.0 eV – that means that the Ca I 4227 transition arises from the *ground state* of Ca I. Also note that the “*A*12 Number density” box now has the value of the total Ca abundance for the Sun (6.34). Finally, in the “Spectral line profile” plot, the value of *λ*o should be about 422.7 nm, and you should see a *saturated* line with broad line *wings*.

*Caution*: If you “reload” the ChromaStar page for any reason during the procedure, the Ca I 4227 “sample” line will become de-selected, and you will have to select it again!

1. In your spreadsheet, below the header information you’ve already entered, *log* the three stellar parameters from the “stellar” input panel that will remain *fixed* – log *g*, mass and metal content (they should be the default solar values!). This involves logging both the *name* of the parameter as it appears in the ChromaStar panel, and the corresponding *value*. Note that you will be *varying* *T*eff - it should *not* be logged in the header.
2. In your spreadsheet, below the fixed parameters you have logged, leave several blank rows and establish a data table that will have three columns. Give columns 2 and 3 the super-heading “W (pm)” indicating equivalent width data. On the next row, give column 1 the heading “Teff”, column 2 the heading “CaI4227”, and column 3 the heading “CaIIK”.
3. In the “stellar” input panel, find the control for the *effective temperature* , *T*eff , and change the value from the default (5778 K) to 3600 K (use the central text box to set the value precisely). Click the “Model” button and model your first spectral line. In the graphical output section, check the appearance of the line in the “Spectral line profile” plot – at this low *T*eff value you should see a line much stronger than that for the solar *T*eff value that you checked earlier. Log the input value of *T*eff in column 1 of your data table, and the output value of *Wλ* in column 2.
4. Repeat step 4) for a range of input *T*eff values from 3600 to 6400 K (mid-M to mid-F class stars) with a sampling, *ΔT*eff, of 200 K. This will lead to a substantial data table with 16 rows. Be sure to visually inspect the spectral line profile plot periodically - as *T*eff increases you should see the spectral line *weaken*. Also, periodically inspect the direct image labeled “Visual spectrum” – you should see the absorption feature labeled “CaI 4227” *weaken* and the one labeled “CaII K” *strengthen* as *T*eff increases.
5. Repeat step 1), this time selecting the “Ca II K” line in the “samples” panel. In the “line profile” panel the boxes for the ionization energies (*χ*I and *χ*II), the particle mass, and the *A*12 solar Ca abundance should all be the same as before, of course – it’s still Ca! The *λ*o value should now be close to 393.34 nm, and the excitation energy of the lower level of the transition (*χ*i) should now be *slightly* larger than the Ca I ionization energy (*χ*I), indicating that the K like arises from the ground state of Ca II. Repeat steps 4) and 5) for the Ca II K line, completing column 3 of your data table. This time, the strength of the line should *increase* as *T*eff  increases from 3600 to 4200 K – check this in the spectral line profile plot from time to time as you proceed.
6. Have the spreadsheet application make a “line plot” or a “scatter plot” (*ie.* symbols with no connecting lines) of *Wλ (y*-axis) *vs* *T*eff *(x*-axis) and plot up the relation for *both* spectral lines. (This will involve “selecting” the entire data table and then opening the “Data” tab in the spreadsheet menus. Note that the default plot type is probably something inappropriate (like “bar chart”) and you’ll have to choose something that looks like a line plot or a scatter plot.) Make sure the plot is big enough for you to mark on it when doing the analysis below. Give the plot a meaningful *title*, and the axes the correct *labels* and add information in the plot, or nearby in the spreadsheet, indicating which plot symbols (or line) are for which spectral line.
7. Print out your spreadsheet with the graph. You will need to mark on it in the analysis below, and hand it in with your submission.

**Analysis & Discussion:**

1. According to your graph, the strength of Ca I 4227 decreases as *T*effincreases, indicating that the number density of Ca I, *N*I, is decreasing. Where are all these Ca I particles going (*ie.* what’s happening)? Is there any *evidence* for your explanation in the graph? *Explain!*
2. According to your graph, at about what value of *T*effare the Ca I 4227 and Ca II K line equally strong? State the value here, and also indicate the point on your graph. Before proceeding to step 3), what would you *guess* the value of *N*II*/N*I, for Ca to be, approximately, at this *T*effvalue? Briefly *explain* the reasoning for your guess.
3. According to the *Saha equation*, what is the *actual* value of *N*II*/N*I for the temperature you found in step 1)? *Show* the formula, input quantities, and all steps of the calculation!
4. Can you think of at least *two* reasons for why the *T*eff value at which the *W*λ values for the two lines are equal does *not* correspond to equal amounts of *N*Iand *N*II? (*Hints*: What is the significance of some of the other quantities in the “spectral line” input panel? What is the temperature that should be used in the Saha equation?)
5. Based on your graph, explain why the Ca I 4227 and Ca II K line strengths, *when* *compared to each other*, are good *MK classification diagnostics* – *ie.* why do they help distinguish among the spectra of the subclasses of G and K stars?