**ChromaStar lab 1: The color-temperature relation**

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**Level:** High school to second yearUniversity

**Purpose:** To investigate the dependence of a star’s white-light color on its effective surface temperature, *T*eff, and to estimate *T*eff values from Hubble Space Telescope (HST) image data.

*Optionally*: To measure a star’s surface temperature from its spectrum.

**Background:** Stars are opaque objects that contain excess heat, so they glow with incandescent radiation (like the filaments of incandescent household lightbulbs), also known as thermal radiation, or *blackbody radiation* (the latter term is used because this is radiation that an object still emits on its own, even if there are *no other* light sources illuminating it). The *spectrum* (brightness at each *wavelength* of light, *λ*) of blackbody radiation has a characteristic shape in which the spectrum reaches maximum brightness at a particular wavelength, *λ*max. Although stars are gaseous, they have a visible, effective surface from which most of the blackbody radiation is emitted, and we can define an effective surface temperature, *T*eff, at this apparent surface. *T*eff and *λ*max have a *reciprocal (or inverse) relationship*: The larger the value of *T*eff, the smaller the value of *λ*max; *ie.* stars with hotter “surfaces” will glow with a spectrum that peaks in brightness at smaller *λ*max (*ie.* shorter wavelength). We do not have to record the star’s spectrum to notice this relationship – the star’s *white-light* color, as perceived with the unaided eye, depends on the value of *λ*max.

**Optional:** The spectrum of blackbody radiation is described by the Planck function, and *Wien’s displacement law* describes the inverse relationship between *T*eff and *λ*max:

*λ*max = (2.90x10-3 m \* K) / *T*eff (1)

where *T*eff is in expressed on the Kelvin (K) or absolute temperature scale and the *λ*max is in m. *Note* that the units of the constant in the numerator of equation (1) are “meters Kelvins”, not millikelvins!

A star’s actual spectrum is only approximately a blackbody spectrum (*eg.* there are *spectral lines* in the real spectrum), but the Wien displacement law is still valid to a high degree of accuracy.

Additionally, the value of a star’s color as defined with a standard set of three *photometric* color filters, the blue (*B*), yellow-green (or visual, *V*), and red (*R*) filters, will also depend on the value of *λ*max (the star’s brightnesses as seen through the *B*, *V*, and *R* filters can be combined to form the star’s white-light color). These three filters allow us to define two *color indices* that quantify the star’s color, or, equivalently, the shape of its blackbody spectrum:

*B-V = 2.5*log*10 (f*V*/f*B*) + C1* (2)

*V-R = 2.5*log*10 (f*R*/f*V*) + C2* (3)

Where *f*X is the *flux* (brightness energy) recorded through filter *X* (where *X* is one of *B*, *V*, or *R*), and the *C*n values are calibration constants. These indices are expressed on the *magnitude* scale that is used for stellar brightness, and do not have physical units.

**Apparatus:**

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

The image of the Sagittarius star cloud in the Hubble Heritage gallery (<http://heritage.stsci.edu/1998/30/index.html>) – be sure to click on the image to make it large. This image was made using photometric color filters a lot like the *B*, *V*, and *R* filters so as to record the white-light colors of the stars. (This “object” is not really a cloud – it is simply a particular direction in the southern sky with relatively little obscuration of starlight by interstellar dust, so it offers an especially good view of the stars.)

**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: Take note of the first dial on the left in the top-most panel (labeled “Stellar”) – it allows you to set the *T*eff value of the model star. By default, it should be set to 5777 K, the value for the Sun.

In the *Output* section: Take note of the upper left-most panel labeled “White light disk”. By default, it should look like the Sun.

**Optional:** In the banner with textual output just above the first row of output images, note that the values of the photometric color indices are displayed. There are actually *seven* of them that are formed from seven filters that extend from the ultraviolet (UV) band to the infrared (IR) band. In addition to the two in the visible band described above in the *Background* section, there are also *U-B*, *V-I*, *R-I*, *V-K*, and *J-K*, all of which are calculated with equations corresponding to Equations (2) and (3).

Make sure you are viewing the enlarged version of the Sagittarius star cloud.

**Procedure:**

1. Spend a few moments carefully studying the HST image of the Sagittarius star cloud. Because it was made with photometric color filters, it reveals something our unaided eyes are not sensitive to when viewing faint stars – namely that stars really do glow with an assortment of vibrant colors. Take note of all the colors you can discern. Are there some stars that have the same color as the Sun (WARNING: Do *not* look at the real Sun to find out-you’ll damage your eyes - compare to an on-line white light image of the Sun). Are there some stars whose color differs significantly from that of the Sun?
2. In ChromaStar, try adjusting the *T*eff dial up and down to various trial values, being sure to explore the full range, and hitting the “Model” button each time. Note the color of the “white light disk” image in the Output section each time.
3. Now, looking at the HST image, can you draw any conclusions about the approximate *T*eff values of any of the brighter stars in the image, relative to the Sun? Ie. can you identify stars that you are sure must be hotter than the Sun, or cooler than the Sun?

**Optional:**

1. Note the spectral energy distribution (SED) panel in the second row of output plots. This shows the shape of the star’s spectrum. We are not interested in all the fine details like the various spikes and jumps – only in the overall shape, which is approximately that of a blackbody. Note that the spectrum peaks in brightness at an intermediate wavelength – *λ*max. The vertical color bars indicate the locations of the photometric color filters *U*, *B*, *V*, *R*, *I*, *H*, *J*, and *K* – the *B*, *V*, and *R* filters are the ones that fall in the visible band and determine the star’s white light color, and they are indicated with the blue, green and red vertical bars.
2. Repeat Step 2, this time noting the values of the *B-V* and *V-R* color indices in the textual output panel *and* the *shape* of the SED – especially the value of *λ*max. Explore values of *T*eff from around the coolest stars (about 3600 K) to the hottest (about 40, 000 K). Note that to sample this *T*eff range sensibly, you will have to adjust the value in smaller increments (a few hundred K) at the lower end of the range, then in much larger increments (several thousand K) at the upper end – the star’s properties change significantly with changes in *relative* *T*eff, so we get “diminishing returns” from a *given* change as *T*eff increases. *How* do the *B-V* and *V-R* indices change as *T*eff *increases*?
3. Try setting the *T*eff dial to 9550 K (you can set the value precisely by typing it into the central box in the dial). What are the values of *B-V* and *V-R* at this *T*eff value? This is no coincidence – the values of *C1* and *C2*in equations (1) and (2) are *chosen to ensure* this outcome – that is how the color indices are *calibrated*.
4. Set the*T*eff dial to a value of your choice between 4000 and 6000 K, and note the value you have set. Now, estimate the value of *λ*max from the SED panel. Note that the x-axis is in units of nm (*nano*meters: 1 nm = 10-9 m – you will have to convert it to m before doing the next step.) In some web browers, you can do this by hovering with the mouse over the spectrum where it reaches maximum brightness – the first number in the brackets that appears below the plot is the value of *λ*max where the mouse is located – note this is the value in nm.
5. By re-arranging equation (1), calculate the *T*eff value of the star you have modeled in K. You have just used the SED as a *thermometer* to diagnose the star’s “surface” temperature the way astronomers do! How does this “measured” value of *T*eff compare to the “right answer” – ie. the *T*eff value you set with the dial?