Measuring the surface temperature of stars by analysing their spectra

(ESO Astronomy Camp Activity)

Age group
Secondary school students aged 16-18

Introduction
Wien's Law relates the wavelength of maximum emission, λ_{max}, of a black body to its temperature, T:

$$T= (2.9*10^7)/\lambda_{max}$$

where T is the temperature of the star in Kelvin (K), λ_{max} is in Angström (Å), and $2.9*10^7$ is the Wien's displacement constant.

Stellar spectra comprise two components: a continuum that covers the whole spectrum of emission, and dark lines superposed. You can find examples of stellar spectra in the other downloadable documents.

For this activity, we will neglect the dark lines and focus on the continuous component. As long as a star can be considered to be a black body (and this is *almost* true in most cases), we can use Wien's Law to work out its surface temperature by taking its spectrum and identifying the wavelength of maximum emission.

The spectra we acquired during the camp are in the range 4000–7000 Å, which spans almost the entire visible range. If we look at the maximum and minimum of that range, λ_{min} = 4000 Å and λ_{max} = 7000 Å, and apply Wien's Law, we get T = 7250 K and T = 4150 K, respectively (approximated to the nearest 50 K). This calculation implies that with the equipment available at the camp, we were able to measure the λ_{max} of stars whose temperature is included in this range, i.e. stars of classes F, G and K. Hotter and colder stars peak outside the limits of our instrumentation.

Hereafter we list the stars that were observed during the camp, including their spectral types and surface temperatures found in the literature.

Star	Spectral type	Surface temperature (in K)
Aldebaran	K5	4000
Bellatrix	B2	22000
Betelgeuse	M1,5	3600
Capella (*)	G8+G0	4900+5700
Dubhe	K0	4700
Pollux	K0	4800
Sirius	A1	9900

(*) Capella is a double star but its two components are similar; we can therefore expect to measure the average temperature of the two.

From this table and previous considerations, we see that Capella, Dubhe and Pollux are suitable stars to use for the proposed activity; Aldebaran is at the limit of our measurement capabilities; and Bellatrix, Betelgeuse and Sirius are too hot or cold for our instrumentation.

Further points to consider are:

- The spectra we acquired at the camp differ from the real ones because the Earth's atmosphere interacts with stellar light. This causes a so-called extinction that is much larger for the blue than for the red components of stellar light (also knwn as atmospheric reddening). Moreover, our sensor is more sensitive to red than to blue light: below about 5000 Å and moving towards 4000 Å, its sensitivity becomes poorer and poorer.
- Stars whose spectral types are between the last B types and the first F types (in particular, A stars) develop strong Balmer lines in the blue region that help to depress the spectrum in this area. This means that there is an intrinsic and important deviation from a black body curve that prevents any meaningful exploitation of Wien's Law for these stars.

These effects must be taken into account when attempting to precisely measure temperature; however, they will be neglected in this activity because a full treatment would require a university-level approach. Nonetheless, the results generated in this activity are still valuable and meaningful.

Materials
- The three downloadable documents with the stellar spectra, from the *Science in School* website:
  - the images of the spectra
  - the tables of the spectra with the result for the luminosity (only for the teachers)
  - the tables of the spectra without the result for the luminosity (for the pupils)
  The Stellar spectra of Aldebaran, Betelgeuse, Capella, Dubhe, Pollux, Sirius and Bellatrix were taken by the participants of the ESO Astronomy Camp.

- A computer with tabulation software (e.g. Excell).

Procedure
- Open the tables of the spectra without the result for the luminosity. Each tab contains the table for one star; each table shows:
  - Column 1: numbering of the pixels on the sensor, from left to right (in this context it shall be disregarded);
  - Column 2: wavelength on that particular pixel;
  - Column 3: number of incident photons at that particular wavelength detected during the exposure time.

- Calculate the ratio of number of photons to wavelength for each wavelength in the spectrum and enter the results in column 4. This ratio indicates where the maximum luminosity is in the spectrum.

The sensor of our instrumentation (as any charge coupled device sensor) measures the number of incident photons (shown in column 3) and not the incident energy. The energy of the photons at different wavelength is defined by the following equation:

E_{photon} = (Planck constant*speed of light)/wavelength

Luminosity is defined as the energy that arrives from the star per unit surface and time; in our case, the energy collected during the exposure time by the surface of the telescope. In other words, it is the sum of the energy of every single photon detected during the exposure time by the telescope:

Luminosity = $\sum E_{photon}$ = (number of photons) * [(Planck constant*speed of light)/ (wavelength)]

Since we are only interested in identifying the wavelength that emits the maximum luminosity, and not in the actual value of the luminosity, we can get rid of the constant values, and consider that the following ratio gives us an accurate estimation of the luminosity:

Luminosity = (number of photons)/(wavelength)

• Plot the luminosity (y axis) against the wavelength (x axis).
The graphic won't depict a smooth, black-body-like spectrum but rather an uneven profile because of spectral lines that are neglected in this treatment. In fact, as stellar spectra are not real black-body curves, astronomers had to figure out other methods to calculate the precise temperature of stars.

• Find the maximum value of the luminosity from the plot (it can also be calculated from the values in the table) and the corresponding wavelength.

• Use Wien's Law to work out the surface temperature of the star.

Considering the limitations and approximations of the model presented here, the activity provides valuable results and a good approximation of surface star temperature that can be easily understood by secondary school students.