Amateur Spectroscopy: How to Take the Temperature of a Star

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Stand out in the sunshine on a bright summers day and our star, the Sun, certainly feels hot but how hot? It is an obvious question to ask but is it a sensible question and if so how is it answered? Before we can attempt to answer this question, whether it be for the Sun or some other distant star, we must think very carefully about what it is exactly that we are asking.

The Question

Ignoring as yet undetected gravitational radiation, stars emit energy into space in the form of particles and electromagnetic radiation, here at the surface of the earth we humans only "feel" directly the effects of the Sun via electromagnetic radiation in the wavelength range from infrared to ultra violet. This radiation leaves the Sun from its reasonably uniform photosphere so we can refine our original question down to "what is the temperature of the Sun's (or other star's) photosphere"? We are therefore not interested directly in the core temperature or the coronal temperature both of which run to millions of degrees Kelvin.

Our refined question is not yet answerable however, as no physical thermometer is going to survive long enough to get anywhere near a star's photosphere to make a measurement. We must therefore sense the temperature remotely by relating the intensity of light emitted as a function of wavelength in our range of interest to some single "effective" temperature. To do this we need to spread the light from a star's photosphere out into a spectrum and then employ a bit of physical theory to relate the general shape of the spectrum, ignoring absorption lines, to an effective temperature. The relevant area of Physics is that of "Black Body Radiation" and luckily, over the wavelength range of interest, most single stable stars are reasonable approximations to a "Black Body". Multiple stars with a dominant component should also yield a believable result.

But what is a "Black Body"? .... it is an idealised object that has no preference for absorbing, or emitting, radiation at any particular wavelength. The best, almost realisable, example of such a black body would be a vast, hot cavity with thin and perfectly insulating walls. In one wall there would be a small hole, it is this hole that would represent the black body. Any radiation passing in via the hole would enter the cavity unimpeded, it would then bounce around inside the cavity for a long time exchanging energy with the hot interior walls until the whole system reached a state called "thermal equilibrium" which can be characterised by a single temperature value. Thus any radiation leaving the hole would be characteristic of the temperature of the interior of the cavity. This model is used by Physicists to calculate the spectrum of radiation emitted by a "Black Body" and the resulting spectrum takes the form of a "Planck curve":-

$$P(\lambda) = \frac{2\pi hc^2}{\lambda^5}\frac{1}{\left(exp\left(\frac{hc}{\lambda kT}\right)-1\right)} \qquad (1)$$

where:- λ is wavelength, h Planck’s constant, k Boltzmann’s constant, c the speed of light, T is the temperature of the black body in Kelvin and $P(\lambda)$ is the wavelength intensity spectrum. Figure 1 shows the shape of such Planck spectra for two temperatures 7500K and 5000K. In general Planck curves for typical stellar temperatures show an increasing intensity as the wavelength reduces from the far infrared reaching a maximum and then rapidly decreasing as wavelength decreases further. The position of the maximum intensity moves to shorter wavelengths as the temperature increases.

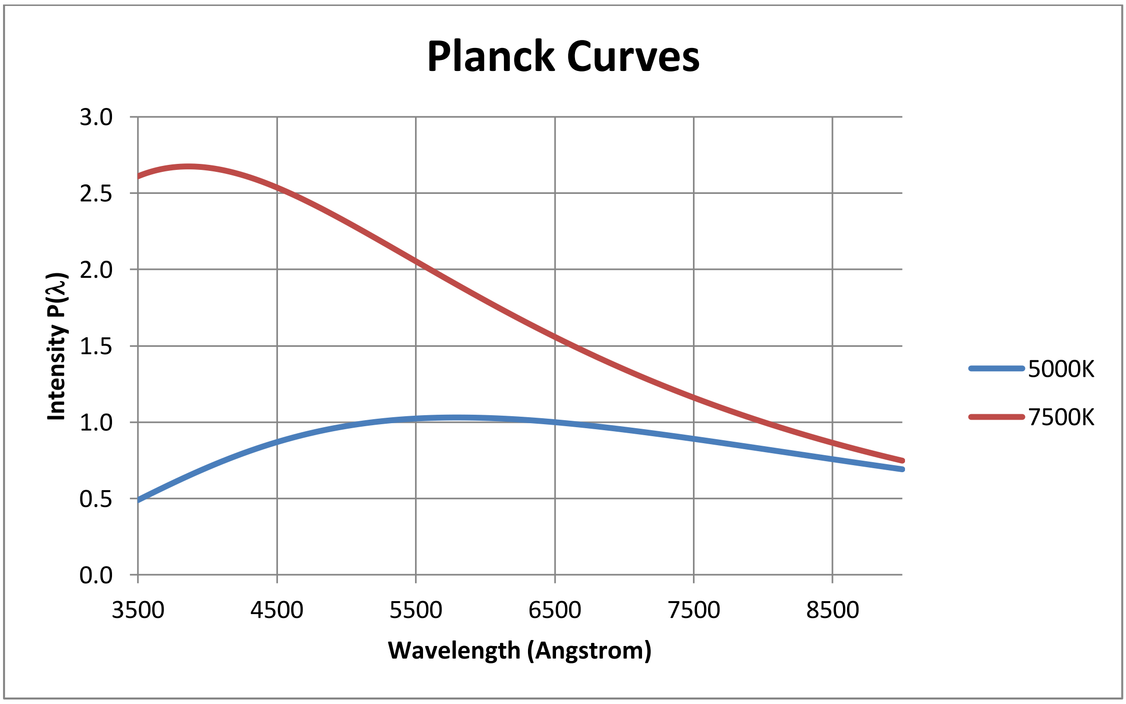

Figure 1: Planck curves for T=5000K and 7500K

So we are finally able to pose our question in a form that can be answered and that form is - "If I replaced the Sun (star) by a perfect black body of the same diameter as the Sun's (star's) photosphere to what temperature would I have to heat the black body so that when sitting in my deckchair on the beach (positioned a comfortable distance from the star) I would feel just as warm, see just as well and tan just as quickly as when under the real Sun (star)"?

The Answer

To answer our question we need to employ the measurement techniques of "Spectroscopy" because, as already described, we first need to spread the starlight out into a spectrum and then capture this data somehow for analysis.

Hardware

Fortunately amateur astro-spectroscopy is becoming increasingly popular with many hardware options coming onto the market ranging in price from Paton Hawksley's "Star Analyser" (less than £100) through Elliot Instrument's "CCDSPEC" (reviewed in Aug 2012 edition of AN and priced around £1200) to Shelyak's versatile "LHiresIII" (priced nearer £3000 if you include an additional low res 150 lines/mm grating). All three of these options are useable for estimating stellar temperatures as only low resolution spectra are required, however this equipment is in addition to that needed to obtain reasonable quality astro-images i.e. a tracking telescope, a CCD camera and software to capture and process the two dimensional CCD images.

Software

We also need to process the two dimensional CCD spectral images into graphs of intensity as a function of wavelength. Free software, written by very capable enthusiasts, is available on the web for example VSpec, though I personally prefer the more user friendly aspects of RSpec which is also available on the web at a cost in the region of $100. All analyses of spectra presented in this article were performed using RSpec.

Spectroscopic measurements

Figure 2 shows intensity vs wavelength spectra obtained from the two components of the binary star Alberio.

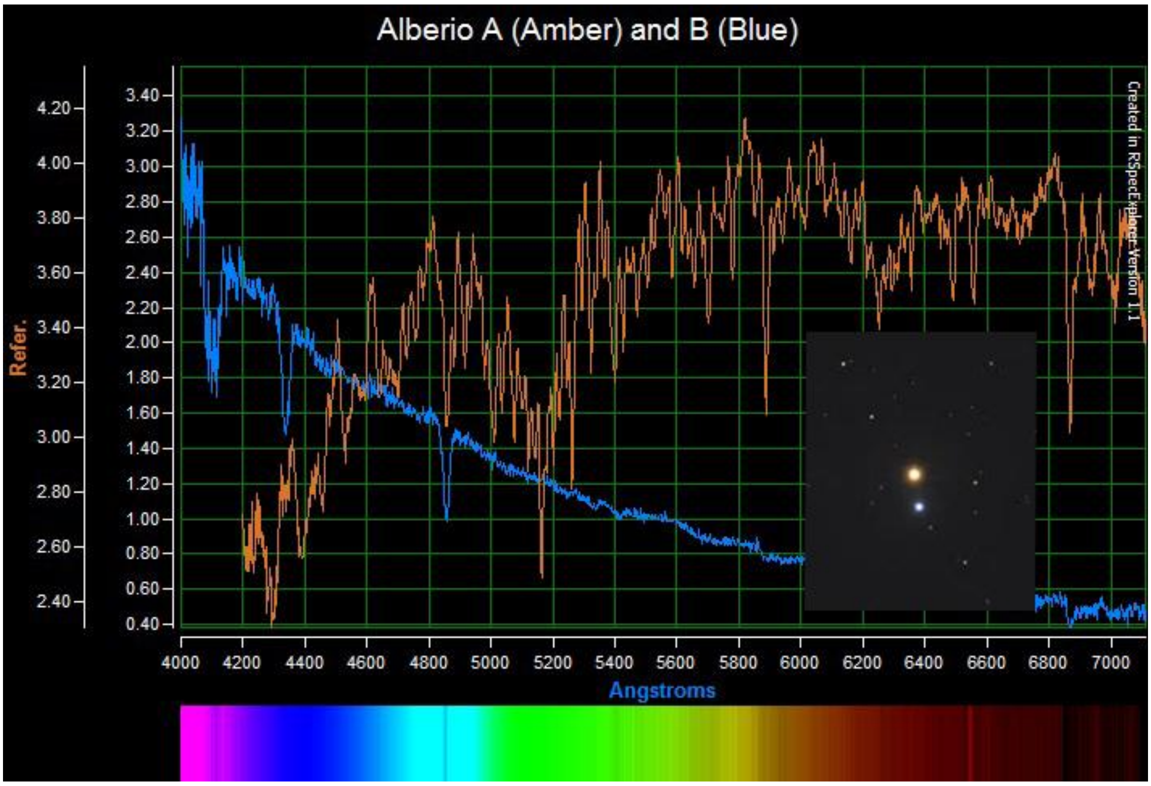

Figure 2: Calibrated low resolution spectra of the Alberio A and B components (pictured in the inset).

The raw spectra (intensity as a function of pixel number) were calibrated to intensity as a function of wavelength by identifying known spectral lines and calculating a pixel to Angstrom ratio. A value of 2.1 Angstrom/Pixel was obtained for my particular setup of LHiresIII spectrograph with a 150 lines/mm grating and an Atik314L+ camera.

The data presented in Figure 2 has been corrected for atmospheric and instrument absorption, the process is very well described in the video tutorials that accompany the RSpec software. Essentially a hot star at similar altitude to the target star is used as a calibration star and a, professionally measured, library spectrum of that type of star is used to deduce the correction. In this case Alberio

B (a hot B8 star) is the perfect calibration star to use when producing a fully calibrated spectrum of Alberio A.

Calculating the Temperature

We have our spectra (Figure 2) it is now merely a matter of generating Planck curves from equation (1) at various temperatures and determining which one most closely resembles the target spectrum. I have produced software to do this that is available via the RSpec user group and the latest version of VSpec includes an "Auto Planck" function. Note we are only trying to fit the overall shape of the spectra ignoring all the individual absorption lines.

My software works by dividing, at each wavelength, the target spectrum by the corresponding intensity value of the particular Planck curve being trialled. The ideal result would be a straight line of constant intensity independent of wavelength, in reality a mean resultant intensity is calculated together with an RMS deviation from that mean. The best fit Planck curve is that one that produces the smallest RMS deviation value.

Alberio B

Figure 3: RMS deviation as a function of temperature for Alberio B

Alberio B is a B8 type star with a photosphere temperature in the range 11000K < T < 25000K. Figure 3 shows how the RMS deviation varies as a function of temperature when dividing the measured spectrum by trial Planck curves. The minimum RMS value occurs at a temperature of 18025K as indicated in the figure and this is our desired "effective temperature" for Alberio B, this value is consistent with the B8 designation. It can be seen however that the minimum is not very distinct and this is because, at such high temperatures, the peak emission is moving to the far ultra violet outside the range of wavelengths we can detect sitting as we are at the bottom of an ultra violet absorbing atmosphere. When the emission peak is out of the picture the Planck curves become independent of temperature and so a temperature measurement is not possible for the hottest stars using amateur equipment.

AlberioA

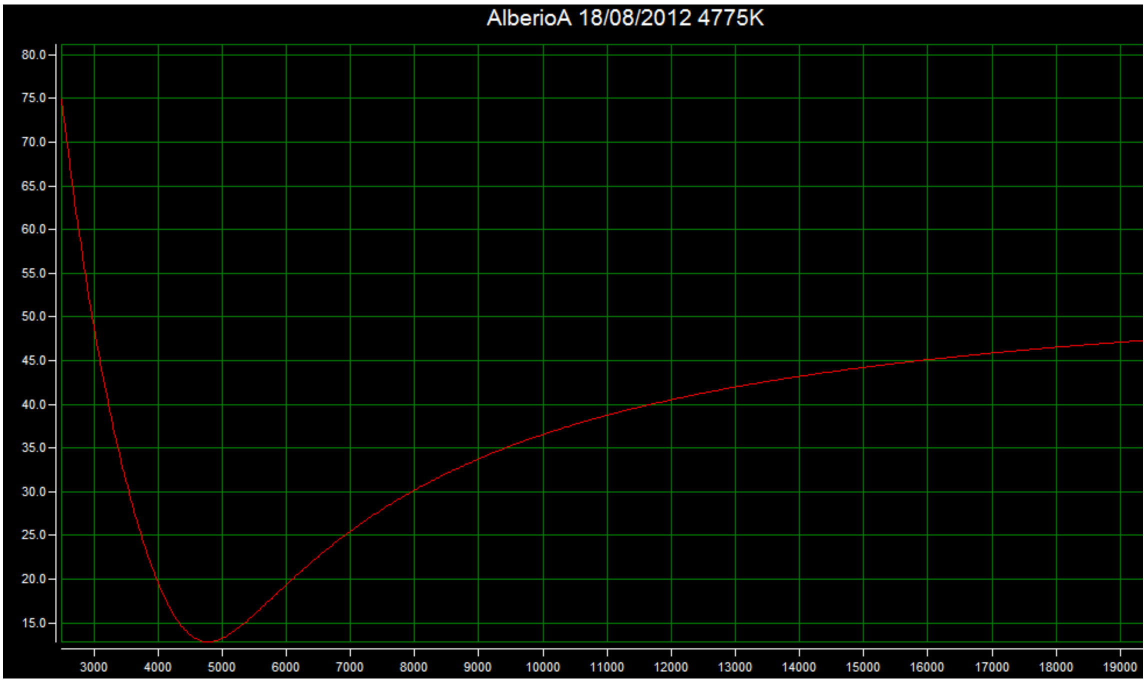

Figure 4: RMS deviation as a function of temperature for Alberio A

Alberio A is a K3 type star with a photosphere temperature in the range 3600K < T < 5100K. Figure 4 shows how the RMS deviation varies as a function of temperature for Alberio A. The minimum RMS value occurs at a temperature of 4775K again indicated in the figure and this is our desired "effective temperature" for Alberio A. This value is consistent with the K3 designation and In this case the minimum in the RMS curve is quite distinct as the emission peak is well within our measurement window.

Conclusions

The answer to our question "what is the temperature of a star" may not have any great practical value, at least until we discover (and are able to visit) planets with sandy beaches orbiting other stars. But, in the process of determining an answer, a lot of fun can be had capturing and processing data, learning more about spectroscopy along the way.

Spectroscopic equipment is becoming affordable and can lead to many more project areas, for example:-

1. Investigate the chemical elements presents in objects (stars, nebulae, comets, planets).
2. Determine stellar B-V colour indices as well as temperatures
3. Measure line of sight velocities via Doppler shift of spectral lines
4. Detect spectroscopic binaries again via Doppler shifts
5. Planetary rotation.

The above list is by no means exhaustive but it should be noted that whilst the least expensive, low resolution, hardware can be used for many interesting projects high resolution capability opens the door to many more possibilities.

Another exciting aspect of amateur spectroscopy is that there are many Pro-Am collaborations that you can get involved with which means you could contribute data of real scientific interest. These collaborations mostly require the more expensive high resolution hardware but it you can afford it it's well worth the investment in both time and money in my opinion!