

PROJECT

3

COLOUR IN ASTRONOMY

Objective: Explain what colour means in an astronomical context and its relationship with the temperature of a star. Learn how to create colour-colour diagrams and how to use these diagrams to distinguish between different types of objects. Introduce Wein's Displacement Law.

Observations:

- BVR observations of a blue star and a red star. Make sure that the field of view contains at least one star with known BVR magnitudes. This star will be used as a 'secondary standard' or 'comparison star'
- BVR observations of a Messier object to create three-colour images
- FLAT-FIELD and BIAS frames

Theory topics: colour of a star, colour index, colour and temperature, blackbody radiation, Planck's and Wien's laws.

Analysis: obtain magnitudes and colours of different type of stars, create of temperature versus peak wavelength, derive Wien's constant, make three-colour image.

Contents: Colour in Astronomy

1. Apparent magnitudes
2. Colour of a star
3. Colour and Temperature

Colour in Astronomy

1. Apparent magnitudes

The first step is to obtain instrumental and absolute BVR magnitudes. This is accomplished by observing at least one standard star with known magnitudes on the standard system along with your night's data and using it to determine the transformation equations. Often the standard star is not in your science images, so you have to take a set of calibration images that measure the standard star in your instrumental system. This usually requires calibration of the differing atmospheric transmission between the observations of the standard and science images, which changes with zenith angle and sky conditions. The procedure has been explained in detail in **Project 2**. However, there is an easier way *if one has a standard star in the science images*. In this case you can skip the atmospheric corrections, and go right to the transformation equations. You can calculate the transformation constant C simply as

secondary standard: $C = m_{\text{std}} - m_{\text{ins}}$

and then apply it to the target: $m_{\text{std}} = C + m_{\text{ins}}$

Exercise 1: Obtain the apparent BVR magnitudes for your programme stars.

Example: Let's assume that the programme and the secondary stars have

Band	Target ins	Standard ins	Standard
B	20.41	19.86	16.14
V	18.79	18.37	14.64
R	17.56	17.33	13.72

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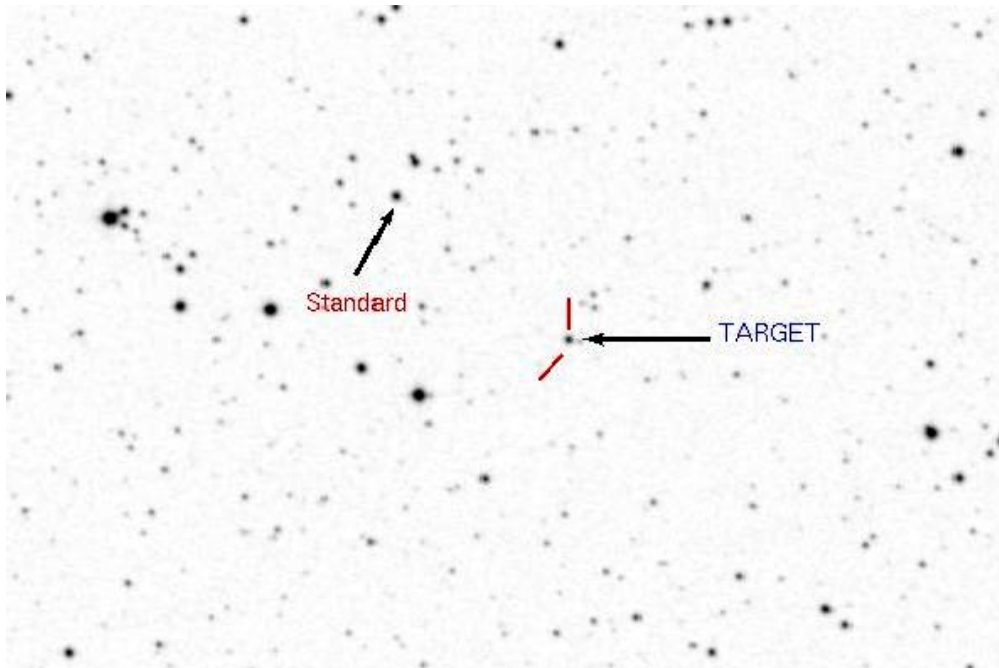


Fig. 1. Field of view showing the target and secondary standard.

For the standard:

B-band: $C_B = m - m_{ins} = 16.14 - 19.86 = -3.72$

V-band: $C_V = m - m_{ins} = 14.64 - 18.37 = -3.73$

R-band: $C_R = m - m_{ins} = 13.72 - 17.33 = -3.61$

Therefore for our object

B-band: $B = m_{ins} + C_B = 20.41 - 3.72 = 16.69$

V-band: $V = m_{ins} + C_V = 18.79 - 3.73 = 15.06$

R-band: $R = m_{ins} + C_R = 17.56 - 3.61 = 13.95$

$$B - V = 1.63$$

2. Colour of a star



Fig. 2. Open cluster M50. Credit and Copyright: S. Kohle, T. Credner et al.

The photo above shows the open cluster M50. The variety of colours of the stars is obvious. Open clusters typically contain hundreds of stars, many of which are bright, young, and blue. In fact, most of the bright blue stars in the above picture belong to M50, but most of the dimmer, red stars do not. M50 lies about 3000 light-years from Earth and is about 20 light years across.

Magnitude is a number that measures the brightness of a star or galaxy. In magnitude, higher numbers correspond to fainter objects, lower numbers to brighter objects; the very brightest objects have negative magnitudes. In practice, astronomers measure the amount of light or *flux* in a restricted wavelength band. This can be done by letting the incoming beam of light go through a filter. The filters work by blocking out light at all wavelengths except those around the wavelength they are designed to see. Rather than just have one apparent magnitude, m measured across the entire visible spectrum we can use a filter to restrict the incoming light to a narrow waveband. If, for instance, we use a filter that only allows light in the blue part of the spectrum, we can measure a star's blue apparent magnitude, B . Similarly if we use a filter that approximates the eye's visual response which peaks in the yellow-green part of the spectrum we measure the magnitude V of a star. When you say that a star has a certain magnitude, you must specify the colour that the magnitude refers to.

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Colour is defined as the difference between the magnitude of a star in one filter and the magnitude of the same star in a different filter.

The physical property that magnitude actually measures is radiant flux - the amount of light that arrives in a given area on Earth in a given time. Remember that magnitude is a logarithmic quantity; a magnitude $m=4$ star emits 2.51 times as much light as a magnitude $m=5$ star. This allows you to define colour in terms of the amount of light given off by a star. Colour is a difference in magnitudes; B-V is the difference between a star's blue magnitude and the same star's green magnitude. Since magnitude is defined as

$$m = -2.5 \log(F_x/F_{\text{vega}})$$

where F_x is the observed flux in the band x , and F_{vega} is the flux of the star Vega. The star Vega, in the constellation of Lyra is used as a reference in the magnitude system. Vega has the arbitrary definition of zero magnitude at all wavelengths

$$U=B=V=R=I=0$$

This does not mean that Vega show the same brightness through all filters. It is an arbitrary decision taken by the astronomers who have agreed on taking Vega as the zero point for the magnitude scale.

Exercise 2: Spica and Antares are two well-known stars with colour indices (B-V)=-0.13 and (B-V)=+1.83. How many times more blue light (B band) do these objects emit, as compared to its green light (V band)?

Are your objects bluer or redder than the star Vega, which has B-V=0?

Spica is the brightest star in the constellation of Virgo and one of the brightest stars in the night-time sky. Spica is believed to be the star that provided Hipparchus with the data which enabled him to discover the precession of equinoxes. It has a colour of B-V=-0.13. Antares, the brightest star in Scorpius, has B-V=1.83.

In terms of radiant flux a colour index can be expressed as

$$B-V = -2.5 \log(F_{\text{blue}}) + 2.5 \log(F_{\text{green}}), \text{ which is equal to } -2.5 \log(F_{\text{blue}}/F_{\text{green}}).$$

So if a star has a B-V colour of -0.13, then

$$\log(F_{\text{blue}}/F_{\text{green}}) = +0.13/2.5,$$

which, by the definition of log, means that

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$$(F_{\text{blue}}/F_{\text{green}}) = 10^{(0.13/2.5)} = 1.13$$

In other words, a star with $B-V = -0.13$ emits 1.13 times as much blue-wavelength light as green-wavelength light.

For Antares, $(F_{\text{blue}}/F_{\text{green}}) = 0.18$ or $(F_{\text{green}}/F_{\text{blue}}) = 5.4$

Antares emits 5.4 times more green light than blue light.

By definition for Vega, $(F_{\text{blue}}/F_{\text{green}}) = 1$

For Spica, $(F_{\text{blue}}/F_{\text{green}}) > 1$

For Antares, $(F_{\text{blue}}/F_{\text{green}}) < 1$

Therefore, since Spica emits more blue light than Vega it will appear bluer than Vega. Antares, on the other hand, will appear redder than Vega.

3. Colour and Temperature

The colour of a star is primarily a function of its effective temperature. You should recall that a star approximates the behaviour of a black body radiator. As a blackbody gets hotter, its colour changes. If you were to heat a solid bar, it would first emit radiation in the infrared region. Further heating would see it glow a dull reddish colour. With more heating it could eventually glow orange, yellow, white and eventually blue-hot. Ultimately if it were hot enough a black body emits most of its energy in the ultraviolet region.

The colour that we see is usually an additive combination of the emissions from each wavelength. Hot stars appear blue because most energy is emitted in the bluer parts of the spectrum. There is little emission in the blue parts of the spectrum for cool stars - they appear red.

Exercise 3: Create a programme that obtains the blackbody energy distribution curve for a given temperature. A relatively easy way is to use a spread sheet (excel, oocalc, etc).

All you have to do is to define a range of wavelengths (100-30000 Å) in one column of the spread sheet. On the right column calculate the radiated power of a black body using the Power Density Planck law

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$$F(\lambda) = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

$$h = 6.626 \times 10^{-34} \text{ joule s}$$

$$k = 1.381 \times 10^{-23} \text{ joule K}^{-1}$$

$$c = 2.998 \times 10^8 \text{ m s}^{-1}$$

λ should be in meters. $F(\lambda)$ is in units of watts/m³

Let us look at two different stars, one with an effective temperature of 12,500 K and the other of 5,000 K. Each of these will produce a spectrum that approximates a black body curve. The diagram below shows these two curves on a normalized intensity plot, that is, we have divided each value of the flux by the maximum value of the flux (if we used a true intensity scale the plot for the 5,000 K star would be dwarfed by that for the hotter star). You can see that in the visible part of the spectrum the curve is sloping down to the right for the 12,500 K star whilst it slopes up for the cooler star. The two black lines represent the peak wavelengths for the B and V filters.

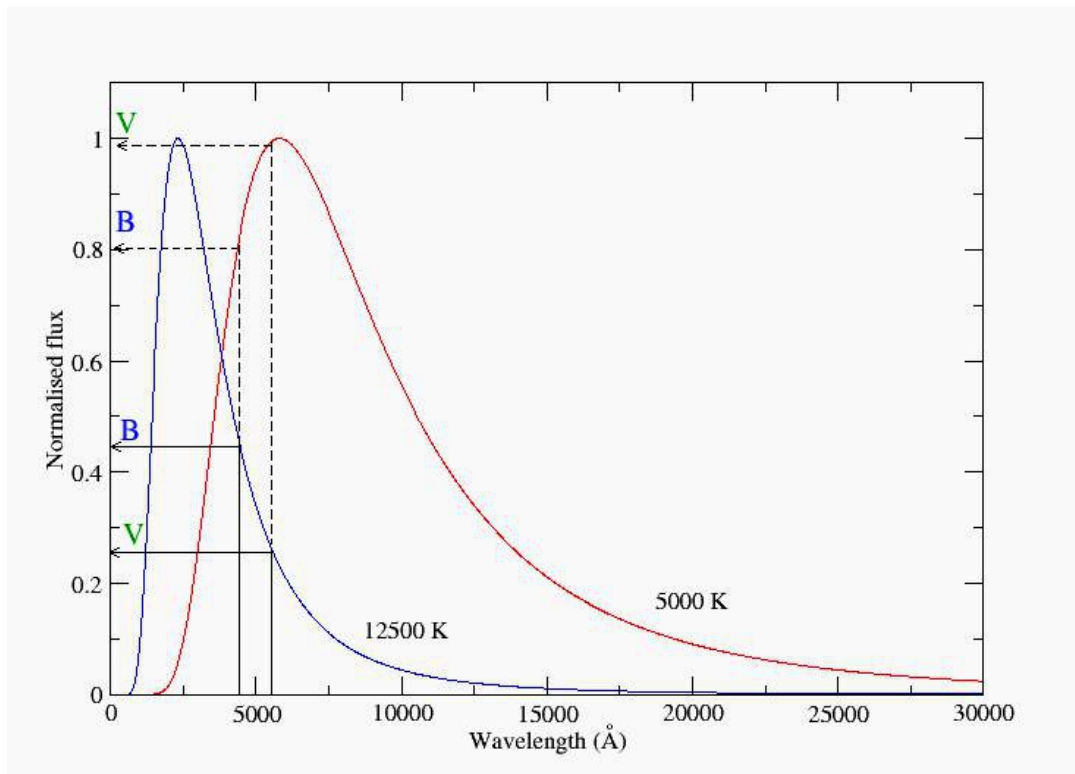


Fig. 3. Comparison of the B-V colour for a 'hot' and a 'cold' star.

The blue curve represents the 12,500 K star. It emits more energy in the B waveband

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than in the **V** waveband. This means that it is brighter in **B** than in **V**, therefore its apparent magnitude **B** will be **lower** than apparent magnitude **V**. The colour Index is $B - V$, so for this star it will be < 0 , that is, **negative**. The red curve represents the 5000 K star. For this $B-V$ is **positive**.

Exercise 4: Create several blackbody energy distribution curves for 9 different temperatures ranging from 3000K to 20000K (do not forget the curve that corresponds to $T=9790$ K, Vega's effective temperature). Taking into account the effective wavelengths for the various filters given below, annotate the flux values for each filter and each curve and create a (B-V)-temperature plot. What do you observe?

Which end of the line in your graph corresponds to hotter stars? Which corresponds to cooler stars? How do you know?

Calculate the temperature of Spica and Antares and compare the values that you get with those found in precise measurements. Why are your values of the temperature lower than the real ones? In other words, why are they redder than they should be?

	U	B	V	R	I
λ	3650	4400	5500	7000	9000
$\Delta\lambda$	700	1000	900	2200	2400

In terms of flux

$$B - V = -2.5 \log \left(\frac{F_B}{F_V} \frac{F_V^{vega}}{F_B^{vega}} \right)$$

If you calculate the $B-V$ colour index for each curve and represent the blackbody temperature as a function of the colour you should get a plot like this

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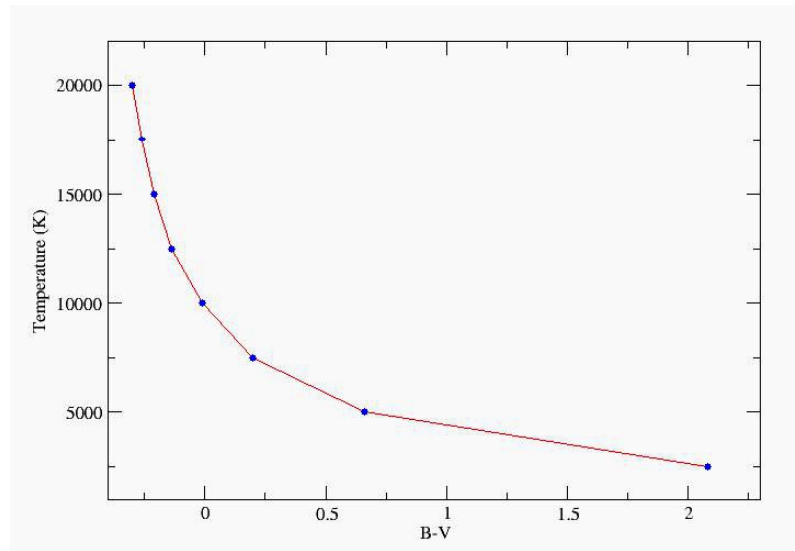


Fig. 4. Relationship between colour and temperature obtained from the blackbody theoretical curves.

Which you can compare with this plot using real data

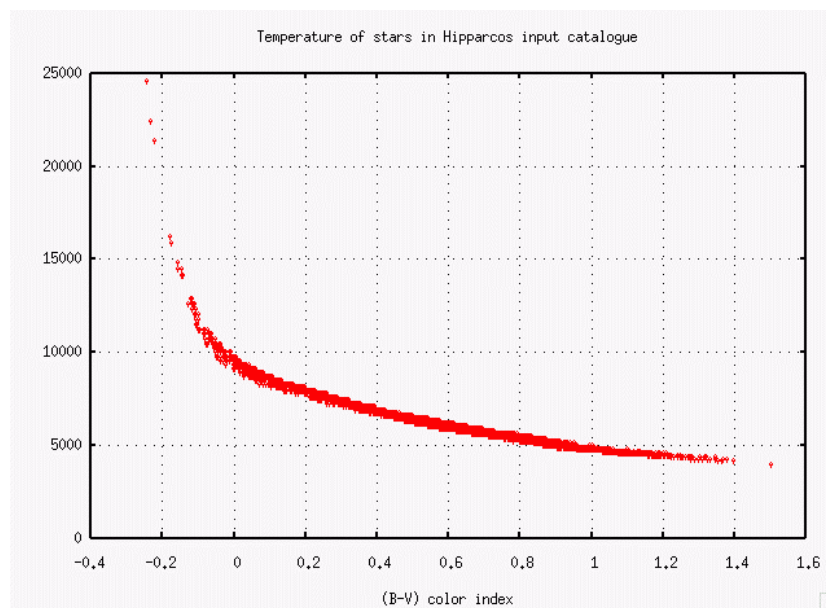


Fig. 5. Relationship between colour and temperature obtained from real data.

Spica has $(B-V) = -0.13$ and Antares $(B-V) = 1.83$. From Fig. 3 we can deduce approximately the temperatures: 3000 K for Antares and 12300 K for Spica. The real temperatures of Antares and Spica are 3400 K and 18000 K, respectively.

The main reason for the discrepancy in the temperature is that only the peak wavelength has been used to derive the B and V magnitudes, without taking into account the transmission curves of each filter.

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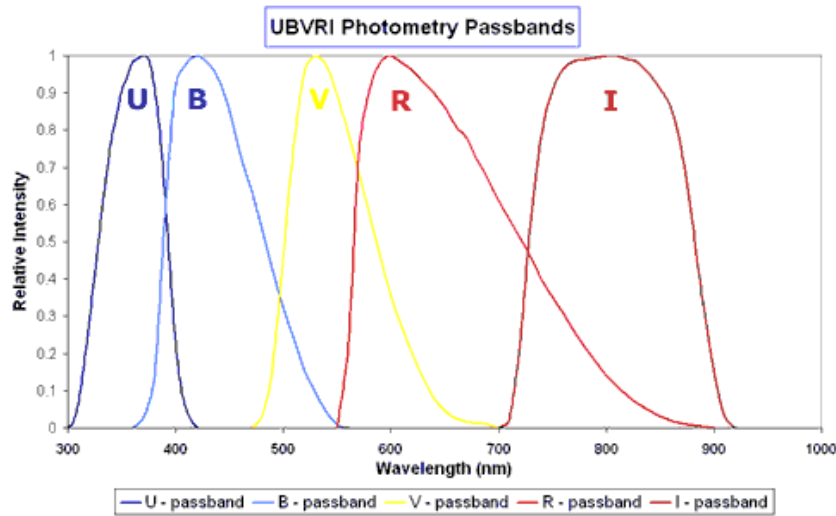


Fig. 6. Normalized intensity plot showing the response of the five filters.

Another reason why you obtain lower temperatures is that the Interstellar space is not a perfect vacuum. The interstellar medium (ISM) comprises cold neutral gas (H I at ≈ 70 K), warm neutral gas (H I at 6,000 K) and hot ionised plasma (H II at 10^6 K) primarily located in the plane of the galaxy in the spiral arms. Cosmic dust is made up of small grains of silicates, iron, carbon, frozen water and ammonia ice 0.1 to 0.01 microns (μm) in size. Although this cosmic dust only makes up 1% of the mass of the ISM, it absorbs and scatters light from stars. This means that light from a distant star is reduced in intensity so that the star appears dimmer than it would be if there was no intervening material. Termed *extinction*, this effect can be estimated if the distance to the star and its position relative to galactic arms and molecular clouds is known. In general more distant stars suffer greater extinction or reduction in brightness than nearby stars. Extinction is inversely proportional to wavelength so red light is less affected than blue light. Distant stars thus appear redder than they actually are. This *interstellar reddening* must be compensated for in trying to determine the true colour and brightness of a star. However, interstellar extinction is not expected to affect the colour of Spica and Antares because they are 'near-by' objects.

Exercise 5: Using the blackbody curves obtained in the previous exercise, annotate the wavelength at which the flux is maximum. What do you observe?

Create a plot of temperature as a function of the λ_{peak} using a logarithmic scale. What do you observe?

Fit a function (straight line) to the data and calculate Wien's constant.

The Sun has a peak wavelength of thermal radiation of 5300 Å. What is the Sun's average temperature? And for the Polar star which has $\lambda_{\text{peak}}=3500$ Å.

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A star's color can give clues to an important property of a star: its average temperature. Physicists have found that every object in the universe emits thermal radiation. So of course, thermal radiation is emitted by stars. The curves show that hotter stars give off more thermal radiation. The curves also show that the peak wavelength of the thermal radiation moves to shorter wavelengths as the temperature increases.

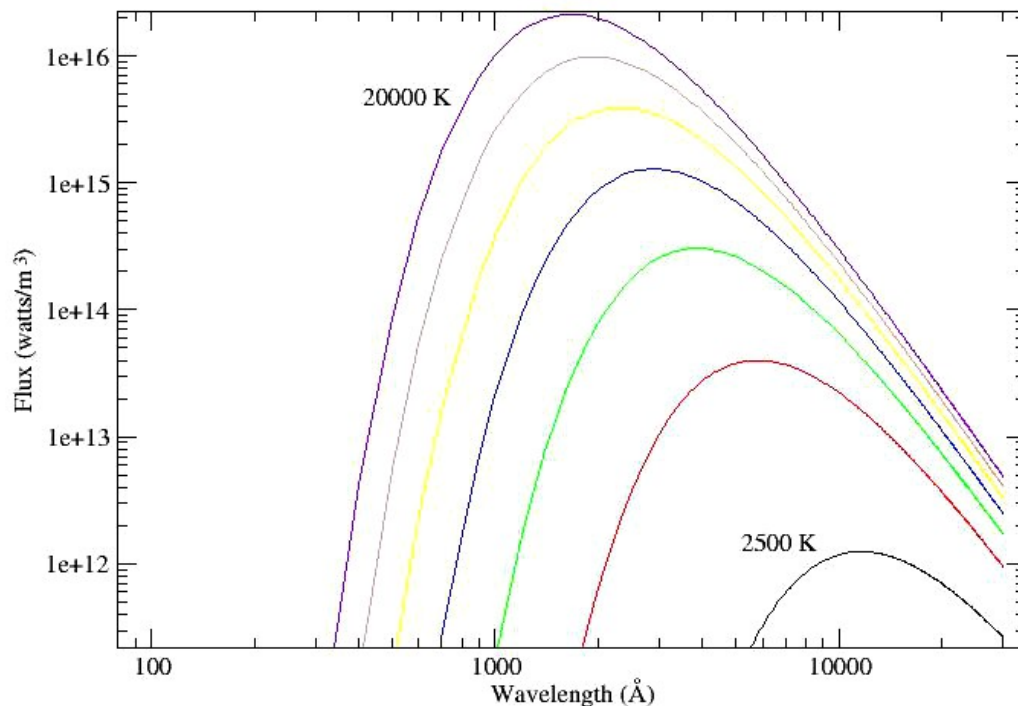


Fig. 7. Blackbody curves for thermal bodies at different temperatures.

- **Temperature and Peak Wavelength (Wien's law):** Wien's Law tells us that objects of different temperature emit spectra that peak at different wavelengths.

- Hotter objects emit most of their radiation at **shorter** wavelengths; hence they will appear to be **bluer**.
- Cooler objects emit most of their radiation at **longer** wavelengths; hence they will appear to be **redder**.

Furthermore, at any wavelength, a hotter object radiates more (is more luminous) than a cooler one. You can understand this by the size of the area that encloses each curve.

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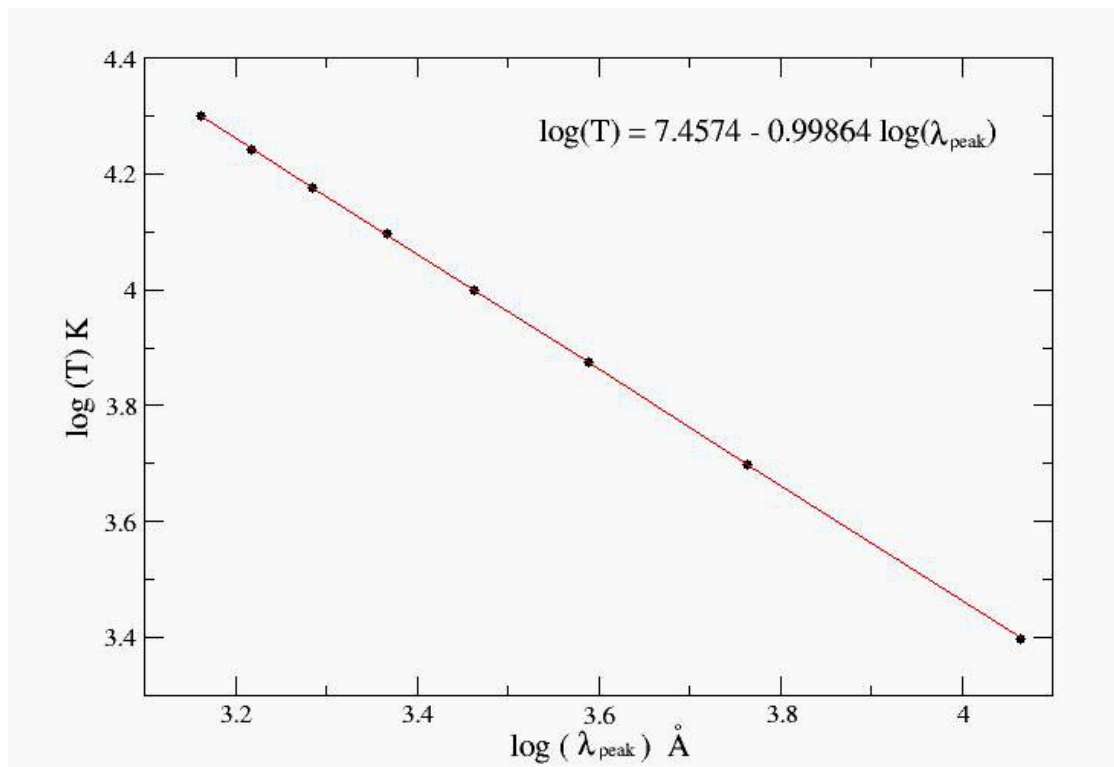


Fig. 8. Temperature as a function of the peak wavelength.

The best-fit is

$$\log(T \text{ K}) = 7.4574 - 0.9986 \log(\lambda_{\text{peak}} \text{ \AA})$$

thus

$$\lambda_{\text{peak}} T = 10^{7.4574} = 28668171.9 \text{ \AA K}$$

The Wien's constant in units of the International System that we find from our data is

$$2.867 \times 10^{-3} \text{ m K}$$

which can be compared with the carefully measured relationship between temperature and peak wavelength of thermal radiation

$$\lambda_{\text{peak}} T = 2.897 \times 10^{-3} \text{ m K},$$

where λ_{peak} is measured in meters and T is measured in Kelvin.

The Sun's peak wavelength is 5300 Angstroms. Convert this length to meters

$$1 \text{ meter} = 10^{10} \text{ Angstroms}$$

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5300 Angstroms ($1 \text{ m} / 10^{10} \text{ Angstroms}$) = $5.3 \times 10^{-7} \text{ m}$.

Insert this length into the peak wavelength equation:

$$\lambda_{\text{peak}} T = 2.897 \times 10^{-3} \text{ m K}.$$

to get: ($5.3 \times 10^{-7} \text{ m}$) $T = 2.897 \times 10^{-3} \text{ m K}$. Now, solve for T

$$T = (2.897 \times 10^{-3} \text{ m K}) / (5.3 \times 10^{-7} \text{ m}) = 5460 \text{ K}$$