PH20016 : Particles, Nuclei and Stars

Lecture 1: Introduction

Dr S R Davies

Overview

The final part of this course concerns some fundamental phenomena and problems in astrophysics which are relevant to particle and nuclear physics.

properties of stars — luminosities, magnitudes, colours

nucleosynthesis — creation of nuclei
... cosmic → in the Big Bang
... stellar → inside stars

fundamental forces — unification, GUTs

dark matter — exotic forms of fundamental particles

Cosmic Abundances

Roughly speaking, the Universe consists of H and He, with a little bit of everything else.

The Universe is observed to consist (by mass) of : ~ 74% H
~ 25% He
~ 1% the rest "metals"

If all of the He was produced by nuclear fusion reactions in the cores of stars:
... would predict He↓, metals ↑
... cosmic abundances largely set in the first few minutes after the Big Bang

The detailed predictions of Big Bang theories must satisfactorily account for the cosmic abundances that we observe.

Stellar Types

Observations of stars permit their ***masses***, ***radii*** and ***temperatures*** to be inferred.

Stars exhibit a range of temperature, brightness and size, but generally have very similar compositions.

Surface temperature : ~ 40,000 K - 2,500 K

Luminosity : ~ $10^6 L_\odot$ - $10^{-6} L_\odot$

Radius : ~ 40 $R_\odot$ - 0.05 $R_\odot$

In general, hot stars ... large, bright
cool stars ... small, faint

Most stars fit this pattern (***Main Sequence stars***), but there are some that do not :

Red Giants	– cool, but large, bright
White Dwarfs	– hot, but small, faint
Variable Stars	– brightness not constant
Novae	– sudden $\times 10^3$ in brightness
Supernovae	– " $\times 10^6$ " "

Brightness and Flux Density

We distinguish between:

Luminosity L (W) … total power output … rate at which energy is radiated

Flux F ($W.m^{-2}$) … energy per unit time, crossing unit surface area

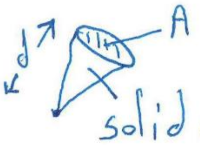
Flux Density F_ν ($W.m^{-2}.Hz^{-1}$) … flux per unit frequency interval $F_\nu = F/\Delta\nu$

$F_\lambda = F/\Delta\lambda$

Intensity (aka specific intensity, or spectral radiance or surface brightness or brightness) :

I_ν ($W.m^{-2}.Hz^{-1}.sr^{-1}$) for spectrum measured in frequency

I_λ ($W.m^{-2}.m^{-1}.sr^{-1}$) for spectrum measured in wavelength



solid angle, $\Omega = \frac{A}{d^2}$

$$I_\nu = \frac{F_\nu}{\Omega}$$

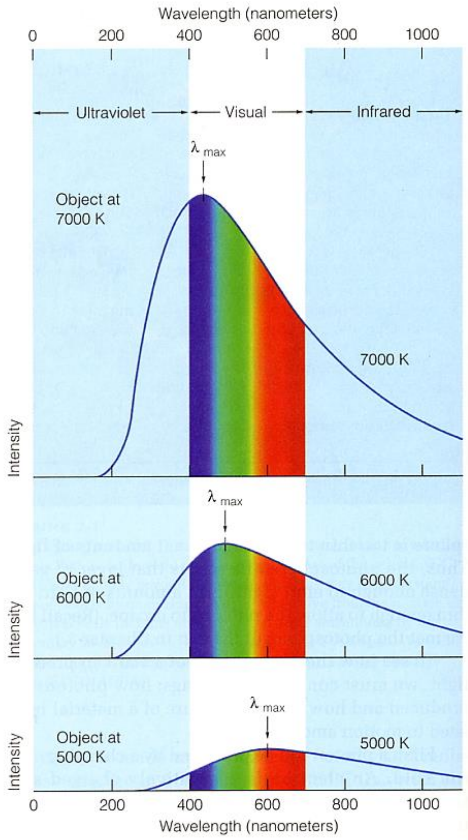
In this course, we will only be using parameters integrated over all solid angles.

Blackbody Radiation and Spectral Lines

In general, a star's spectrum consists of a continuous blackbody curve with superimposed absorption lines at certain wavelengths. Photometry at several wavelengths samples the blackbody spectrum, allowing an estimate of the surface temperature to be made. Spectroscopy reveals the shape of the spectral lines, providing information on the energy states of the atoms and ions present in the atmosphere of the star.

To first order, the surface of a star has an output spectrum that is essentially that of a blackbody radiator. The shape of an ideal blackbody spectrum is determined by the temperature of its surface as predicted by Planck's Radiation Law:

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{\exp(hc/\lambda kT) - 1} \qquad (1)$$



where *B* is the ***specific intensity***, or ***spectral radiance*** of the light. The spectral radiance, at a given wavelength λ, is the energy emitted per second, from unit surface area of the blackbody at temperature *T*, per unit wavelength, per unit solid angle through which the radiation propagates. For a spectrum measured in wavelength, the units of *B* are (W $m^{-2}m^{-1}sr^{-1}$), where a steradian (sr) is the unit of solid angle. Planck's constant, $h = 6.626 \times 10^{-34}$ Js, Boltzmann's constant, $k = 1.38 \times 10^{-23}$ J K^{-1} and *c* is the speed of light.

A ***hotter*** blackbody emits a greater proportion of its radiation at ***shorter*** wavelengths than a cooler body.

A ***hotter*** blackbody emits ***more*** radiation at ***all frequencies*** than a cooler body.

The peak in the blackbody curve occurs at a wavelength given by Wien's Displacement Law:

$$\lambda_{max} = \frac{2.898 \times 10^{-3}}{T}, \quad \text{where } \lambda_{max} \text{ is in m, for } T \text{ in K.} \qquad (2)$$

Integrating eqn. (1) over all wavelengths and all (solid) angles results in an expression (the Stefan-Boltzmann Law) for the total power radiated from unit cross-sectional area of the ideal blackbody at temperature *T*:

$$F = \varepsilon\sigma T^4, \quad \text{where} \quad \sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \qquad (3)$$

The emissivity has a value $0 < \varepsilon < 1$; for an "ideal" blackbody, then $\varepsilon = 1$.

The Stefan-Boltzmann law can also be expressed in terms of ***energy density*** :

$$u = \varepsilon a T^4, \quad \text{where} \quad a = {}^{4\sigma}/_{c} \qquad (4)$$

Thus, if a star is assumed to be spherical, with radius R, having a surface of uniform temperature T, presumed to behave as an ideal blackbody, the total power output radiating from the surface of the star, the *absolute luminosity*, L, will be

$$L \;=\; 4\pi R^2\,\sigma T^4\,. \tag{5}$$

We see emission lines (e.g. Balmer series) and continuous spectra (e.g. BB radiation) in all parts of the EM spectrum.

continuum spectrum

e.g.   blackbody radiation

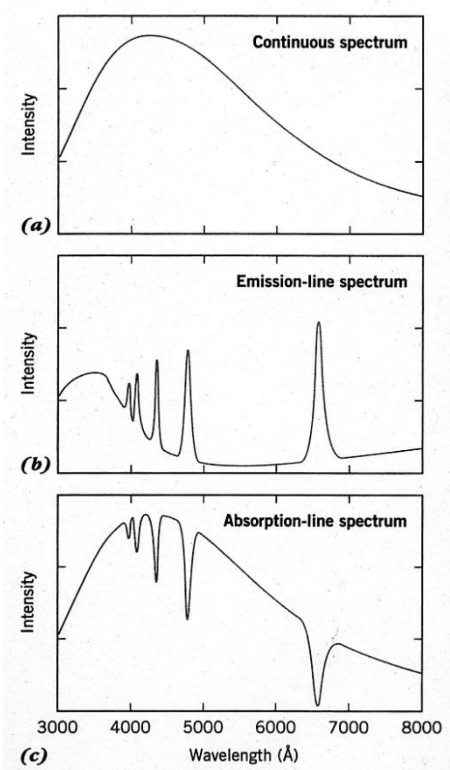
Both absorption and emission lines may also be present, often superimposed on top of a BB spectrum

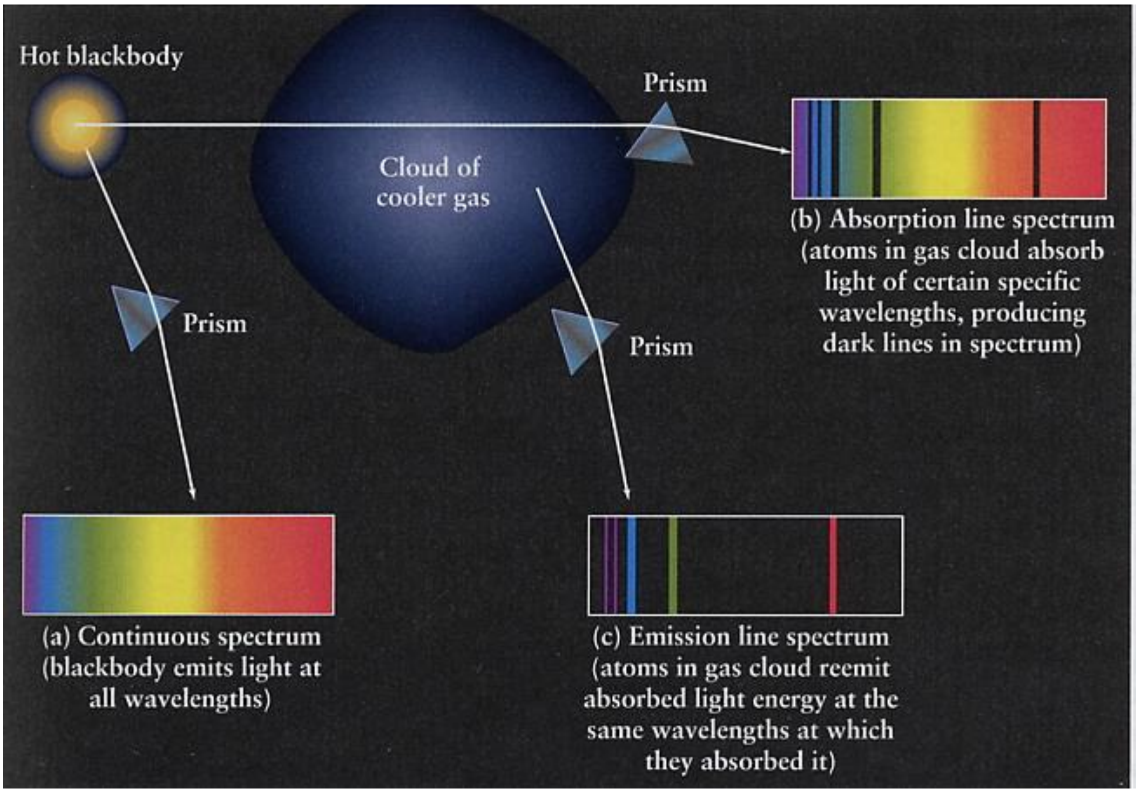
emission line spectrum

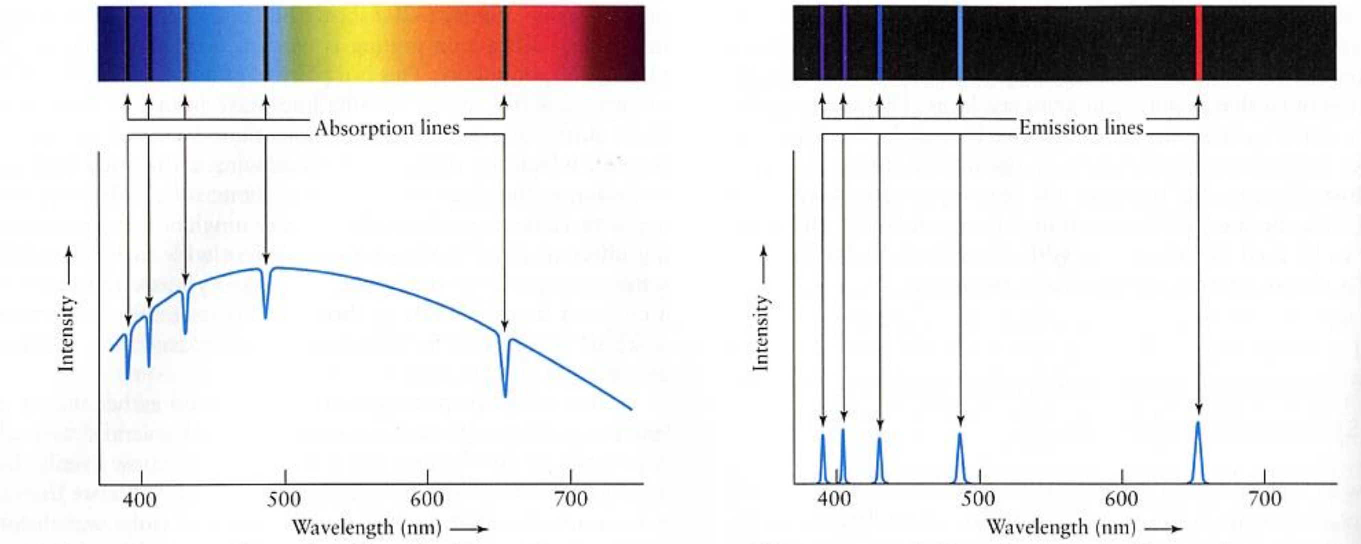
electrons in excited atoms drop to lower energy levels, emitting photons

absorption line spectrum

when light from an object passes through cooler gas along the line-of-sight, photons with exactly the correct amount of energy are absorbed in exciting atoms to higher energy levels.







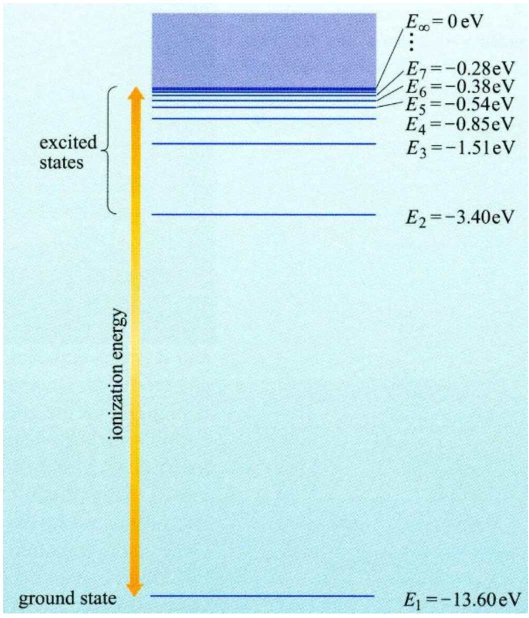
(a) Two representations of an absorption line spectrum

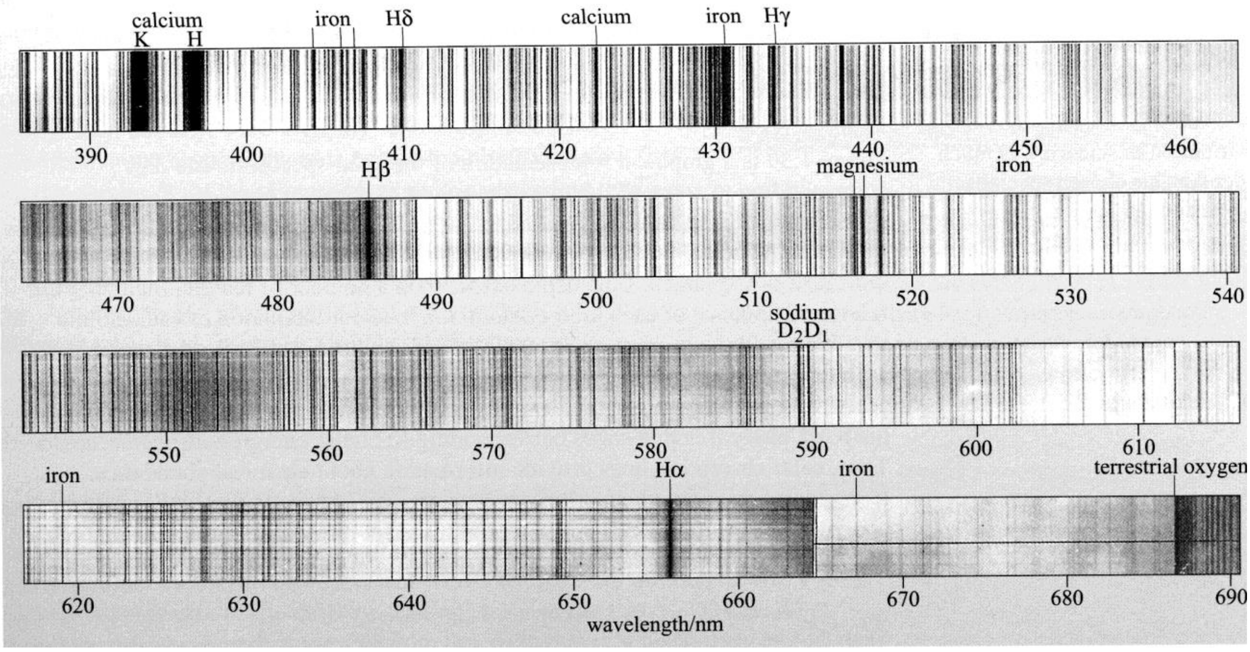
(b) Two representations of an emission line spectrum

The image to the right shows the energy levels of the hydrogen atom. Prominent spectral lines in the visible part of the spectrum are those of the Balmer series, involving transitions from/into the E_2 energy level.

An important astrophysical line is the H_α line, involving transitions between E_2 and E_3 corresponding to a wavelength of 656.3 nm.

Below you can see an old photographic plate image of the Sun's visible spectrum, showing a huge range of absorption lines (due to gas in the atmosphere of the Sun at slightly cooler temperature than the Sun's surface behind it). Note the prominent hydrogen lines (you measured these in Yr 1 Labs!).





Luminosities, Magnitudes and the HR Diagram

This is a brief summary of important background knowledge from Year 1 Lecture courses.

Suppose we know the ***absolute luminosity (L)*** of an object (i.e. total radiated power, in W).

At distance *D*,

$$\ell = \frac{L}{4\pi D^2} \Rightarrow D = \sqrt{\frac{L}{4\pi \ell}}$$

where ℓ = ***apparent luminosity*** (W.m^{-2}). ... a measured power flux

→ if we know or can estimate L and measure ℓ → can estimate D

Apparent luminosity is usually defined in terms of an ***apparent magnitude***, *m*

- logarithmic scale
- based upon ancient classification
  - → brightest naked–eye stars called ***first magnitude***
  - → faintest naked–eye stars called ***sixth magnitude***
- a brighter star has a smaller (more negative) magnitude

Definition

If the apparent luminosities of two objects differ by a factor of x 100, then the difference in apparent magnitude is 5. Expressing this statement mathematically:

$$\frac{\ell_1}{\ell_2} = 100^{\left[\frac{m_2 - m_1}{5}\right]} \rightarrow m_2 - m_1 = 2.5 \log \frac{\ell_1}{\ell_2}$$

We also define $m_{bol} = 0$ corresponds to $\ell = 2.54 \times 10^{-8}$ W.m^{-2}

Some apparent magnitudes:

The Sun	– 26.8
Sirius (brightest star)	– 1.4
Limit of human eye	+ 6
Limit of large telescopes	+ 25

The ***absolute magnitude, M*** of an object is the apparent magnitude it would have if seen from a distance of 10 pc (by definition). 1 parsec (pc) ≈ 3.26 light years ≈ 3 x 10^{16} m.

If *m* is the apparent magnitude of a star at a distance of *D* pc, and

M is the absolute magnitude of the same star at a distance of 10 pc

then,

$$\Rightarrow m - M = 5 \log D - 5 \equiv 5 \log\left(\frac{D}{10}\right)$$

(*m* – *M*) is called the ***distance modulus***

NOTE: This is a very simplistic version of the equation – you will meet more detailed versions during the course.

Colour Index and the Johnson UBV System

Apparent and absolute magnitudes measured over all wavelengths of the light emitted by a star are known as ***bolometric magnitudes***, denoted as m_{bol} and M_{bol} respectively. In practice, detectors tend to measure the radiant flux of a star over specific wavelength ranges,,set by the wavelength-dependent response of the particular detector. Consequently, measurements of stellar magnitudes are carried out in a series of well-defined narrow bands (using filters).

Stars are classified by their magnitudes in the so-called ***ultraviolet***, ***blue*** and ***visual*** bands.

Ultraviolet $U \equiv m_u \,, \quad \lambda_0 = 365\,\text{nm}$

Blue $B \equiv m_B \,, \quad \lambda_0 = 440\,\text{nm}$

Visual $V \equiv m_V \,, \quad \lambda_0 = 550\,\text{nm}$

$\Delta\lambda \simeq 100\,\text{nm}$

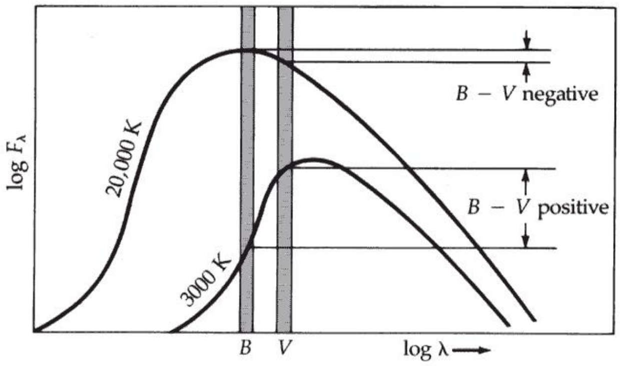
Other filters were later added, e.g. red R, etc.

A measuring system must be calibrated (for power flux) by defining ***standard magnitudes*** for ***standard stars***.

We define (for a given star):

Colour Index

$$CI = B - V \equiv m_B - m_V$$
$$\equiv M_B - M_V$$



Since, $M_B = m_B + 5 - 5\log D$

and $M_V = m_V + 5 - 5\log D$

→ colour index is independent of the distance D to the star

→ can relate colour index to surface temperature

If the surface temperature is $T \approx 10{,}000$ K, then we get $B - V = 0$

→ this is the surface temperature of Vega … the primary standard star

NOTE: The discussion above ignores the effect of interstellar ***extinction***, which will not be discussed during this lecture course.

Interstellar extinction results from the presence of interstellar dust along the line of sight through the interstellar medium. This results in the propagating light being attenuated in intensity, so the observed object appears dimmer than it would without the extinction.
The distance modulus expression should read

$$m_\lambda - M_\lambda = 5\log[d] - 5 + A_\lambda$$

where A_λ is the (wavelength-dependent) extinction, in magnitudes.

On average, extinction seen through the interstellar medium is ~ 1-2 magnitudes per kpc.

Hertzsprung - Russell Diagram

- Stars are classified according to ***spectral type***, each type being identified by a letter.
- Spectral types O, B, A, F, G, K, M arranged in sequence of decreasing surface T
- Each spectral type is subdivided into 10 parts from 0 (hotter) to 9 (cooler).
- Sun has a surface temperature of ~ 5770 K and is of spectral type G2.

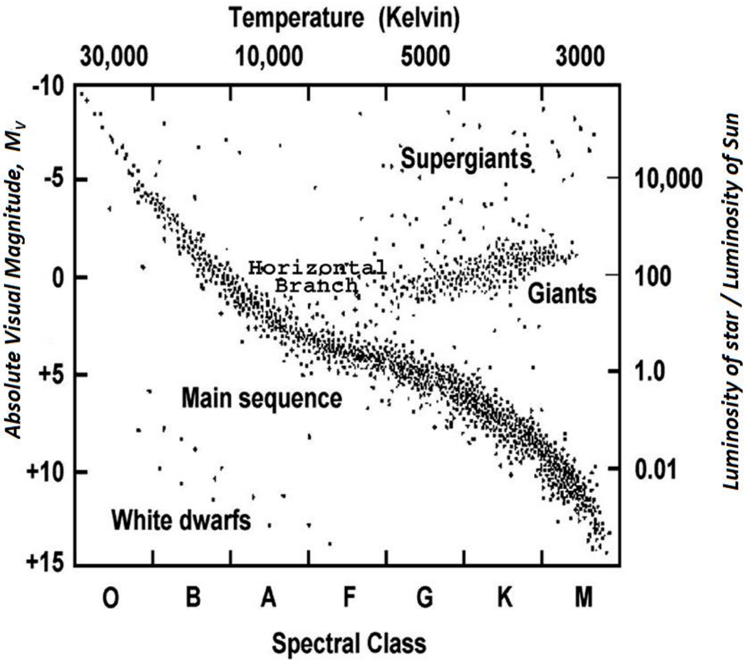
A plot of ***absolute magnitude*** (≡ luminosity) against ***spectral type*** (≡ surface temperature) for all varieties of stars is called a ***Hertzsprung-Russell diagram***. A star's evolution can be described by its change of position on the H-R diagram with time.

The sweeping band of stars, running from top left to bottom right of the plot is the ***Main Sequence***, where the majority of stars are found, including the Sun. This is the longest stage of a star's active life; it is when hydrogen is converted to helium via nuclear reactions.

Red Giants are large stars, with high luminosity and low surface temperature.

Supergiants are very massive stars of large size and very high luminosity

White Dwarfs are small, dense stars of low luminosity and high surface temp.



A commonly used (and rather outdated) mnemonic to remember the spectral sequence is Oh, Be A Fine Girl/Guy, Kiss Me, although I prefer Old, Belligerent Astrophysicists Fight Green, Killer Martians!

More detail on Blackbody Radiation and the Hertzsprung-Russell diagram was also given in Experiment T2 of the Year 1 Laboratory.