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GUIDED EXPLANATION

AQA A-Level Physics (A2)

Astrophysics - Classification of stars

Specification Reference: 3.10.1.2

Learning Objectives

1. Understand and describe the classification of stars based on their spectral class, temperature, and colour.
2. Explain the relationship between a star's surface temperature and its peak emission wavelength using Wien's Displacement Law.
3. Describe the main features of the Hertzsprung-Russell (HR) diagram and locate different types of stars on it.
4. Explain the luminosity of a star in terms of its radius and surface temperature using Stefan's Law.
5. Analyse and interpret stellar data to classify stars and determine their properties.

Astrophysics - Classification of stars

1. Introduction to Stellar Classification

Stars, despite appearing as mere points of light in the night sky, exhibit a vast range of properties. To make sense of this diversity, astronomers classify stars based on observable characteristics. The primary characteristics used for classification are a star's surface temperature, colour, and the features present in its spectrum. These properties are intrinsically linked and provide crucial insights into a star's physical state and evolutionary stage. Understanding stellar classification is fundamental to astrophysics, allowing us to map the life cycles of stars and comprehend the structure of galaxies.

Stellar Classification

The systematic categorisation of stars based on their observable physical properties, primarily surface temperature, colour, and spectral characteristics.

2. Stellar Temperature, Colour, and Wien's Displacement Law

Temperature and Colour

The colour of a star is a direct indicator of its surface temperature. This is because stars behave approximately as black bodies, emitting radiation across a continuous spectrum. Hotter stars emit more of their radiation at shorter (bluer) wavelengths, while cooler stars emit more at longer (redder) wavelengths. This phenomenon is described by Wien's Displacement Law, which quantifies the relationship between a black body's temperature and the wavelength at which it emits the most radiation. Therefore, observing a star's colour provides an immediate, albeit qualitative, estimate of its surface temperature.

Black Body Radiation

Electromagnetic radiation emitted by an idealised object that absorbs all incident electromagnetic radiation. The spectrum of radiation emitted depends only on the object's temperature.

$$\lambda_{max} T = 2.898 \times 10^{-3} \text{ m K}$$

Where: λ_{max} = wavelength of peak emission (m)
T = absolute surface temperature (K)
2.898×10^{-3} = Wien's displacement constant (m K)

- Wien's Displacement Law states that the peak wavelength of emitted radiation (λ_{max}) is inversely proportional to the absolute temperature (T) of the black body.
- This means that as temperature increases, the peak wavelength shifts towards shorter (bluer) wavelengths.
- Conversely, as temperature decreases, the peak wavelength shifts towards longer (redder) wavelengths.

3. Spectral Classes of Stars

The OBAFGKM Classification System

Stars are formally classified into spectral classes based on the characteristics of their absorption spectra. These absorption lines are produced when specific wavelengths of light are absorbed by elements in the star's outer atmosphere. The strength and presence of these lines are highly dependent on the star's surface temperature, as temperature dictates the ionisation state of atoms and the excitation levels of electrons. The standard classification system uses the letters O, B, A, F, G, K, M, ordered from hottest to coolest. Each class is further subdivided into 10 subclasses (e.g., G0, G1, ..., G9).

- **O-type stars:** Hottest (30,000 - 50,000 K), blue, strong ionised helium lines, weak hydrogen lines.
- **B-type stars:** Hot (10,000 - 30,000 K), blue-white, neutral helium lines, moderate hydrogen lines.
- **A-type stars:** Medium-hot (7,500 - 10,000 K), white, very strong hydrogen lines (Balmer series), ionised metal lines.
- **F-type stars:** Warm (6,000 - 7,500 K), yellow-white, weaker hydrogen lines, strong ionised calcium lines.
- **G-type stars:** Moderate (5,200 - 6,000 K), yellow (like our Sun), strong ionised calcium lines, many metal lines, weak hydrogen lines.
- **K-type stars:** Cool (3,700 - 5,200 K), orange, strong neutral metal lines, molecular bands beginning to appear.
- **M-type stars:** Coolest (2,400 - 3,700 K), red, strong molecular bands (e.g., titanium oxide), neutral metal lines.

The strength of hydrogen lines, for example, is not simply strongest in the hottest stars. Hydrogen lines are strongest in A-type stars because their temperatures are ideal for hydrogen atoms to have electrons in the second energy level, from which they can absorb photons to higher levels (Balmer series). In O-type stars, hydrogen is mostly ionised, so there are fewer neutral hydrogen atoms to produce absorption lines. In cooler stars (K and M), electrons are mostly in the ground state, requiring higher energy photons to excite them, which are less abundant at these temperatures.

4. Stellar Luminosity and Stefan's Law

Luminosity and Absolute Magnitude

The luminosity of a star is the total power it radiates into space. It is an intrinsic property of the star, independent of its distance from Earth. Luminosity is often expressed in Watts (W) or in terms of solar luminosities ($L_{\odot}$). Absolute magnitude is another measure of a star's intrinsic brightness, defined as the apparent magnitude a star would have if it were located at a standard distance of 10 parsecs from Earth. A lower (more negative) absolute magnitude indicates a higher luminosity.

Luminosity (L)

The total energy radiated per second by a star, measured in Watts (W).

$$L = 4\pi R^2 \sigma T^4$$

> **Where:** **L** = luminosity (W)
> **R** = radius of the star (m)
> **σ** = Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
> **T** = absolute surface temperature (K)

- Stefan's Law (also known as the Stefan-Boltzmann Law) states that the total energy radiated per unit surface area of a black body per unit time is directly proportional to the fourth power of its absolute temperature.
- Multiplying this by the total surface area of a spherical star ($4\pi R^2$) gives the total luminosity.
- This law highlights that a small change in temperature can lead to a significant change in luminosity, especially for stars with large radii.

5. The Hertzsprung-Russell (HR) Diagram

Construction and Interpretation

The Hertzsprung-Russell (HR) diagram is one of the most important tools in astrophysics. It is a scatter plot of stars showing the relationship between their luminosity (or absolute magnitude) and their surface temperature (or spectral class/colour). By plotting these properties for many stars, distinct patterns emerge, revealing different stages of stellar evolution. The vertical axis typically represents luminosity (increasing upwards) or absolute magnitude (decreasing upwards), while the horizontal axis represents surface temperature (decreasing from left to right) or spectral class (OBAFGKM from left to right). This inverse temperature scale on the x-axis is crucial for understanding the diagram.

- **Main Sequence:** This diagonal band running from the top-left (hot, luminous) to the bottom-right (cool, dim) contains about 90% of all stars. Stars on the main sequence are fusing hydrogen into helium in their cores. Our Sun is a G2V main sequence star.
- **Red Giants:** Located in the upper-right region of the diagram (cool, luminous). These are stars that have exhausted hydrogen in their core and have expanded significantly, becoming cooler but much larger and thus more luminous.
- **Red Supergiants:** Found in the very top-right corner (coolest, most luminous). These are even larger and more luminous than red giants, representing the late evolutionary stage of very massive stars.
- **White Dwarfs:** Situated in the bottom-left region (hot, dim). These are the remnants of low-to-medium mass stars after they have shed their outer layers. They are very dense, small, and hot, but due to their small surface area, they have low luminosity.
- **Blue Giants/Supergiants:** Located in the upper-left region (hottest, most luminous). These are very massive, young stars that burn through their fuel extremely quickly.

The HR diagram is not a plot of stars' positions in space, nor is it a snapshot of a single star's life cycle. Instead, it represents a statistical distribution of stars at various stages of their lives. A star's position on the HR diagram changes over billions of years as it evolves, moving from one region to another. For example, a star like our Sun will move from the main sequence to the red giant region, then shed its outer layers to become a white dwarf.

6. Applications and Further Concepts

Determining Stellar Radii

The HR diagram, combined with Stefan's Law, allows astronomers to estimate the radii of stars. If we know a star's luminosity (from its absolute magnitude) and its surface temperature (from its spectral class or colour), we can rearrange Stefan's Law to solve for the radius. This is particularly useful for distinguishing between stars of similar temperatures but vastly different luminosities, such as a red giant and a red dwarf, where the difference in luminosity is primarily due to a difference in radius.

$$R = \sqrt{[L / (4\pi\sigma T^4)]}$$

Where: **R** = radius of the star (m)
L = luminosity (W)
σ = Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
T = absolute surface temperature (K)

Stellar Evolution on the HR Diagram

The HR diagram is a powerful tool for visualising stellar evolution. Stars are born from nebulae and initially appear on the main sequence. Their position on the main sequence depends on their initial mass; more massive stars are hotter and more luminous, residing at the top-left. As stars age, they move off the main sequence. Low-mass stars become red giants, then white dwarfs. High-mass stars evolve into red supergiants before potentially ending their lives as supernovae, leaving behind neutron stars or black holes. The HR diagram provides a 'snapshot' of a stellar population, with different regions representing different evolutionary stages.

Worked Examples

Example 1: Using Wien's Displacement Law

Problem:
A star has a surface temperature of 9500 K. Calculate the wavelength at which it emits maximum radiation. State its likely colour and spectral class.

Solution:
Step 1: State Wien's Displacement Law: $\lambda_{max} T = 2.898 \times 10^{-3}$ m K
Step 2: Rearrange for λ_{max}: $\lambda_{max} = (2.898 \times 10^{-3}) / T$
Step 3: Substitute values: $\lambda_{max} = (2.898 \times 10^{-3}) / 9500$
Step 4: Calculate: $\lambda_{max} \approx 3.05 \times 10^{-7}$ m (or 305 nm)
Step 5: Interpret: This wavelength is in the ultraviolet part of the spectrum, but the peak emission being near the blue end of the visible spectrum means the star would appear white or blue-white. Its temperature of 9500 K places it in the A-type spectral class.

Example 2: Using Stefan's Law to find Luminosity

Problem:

A star has a radius of 5.0×10^9 m and a surface temperature of 3500 K. Calculate its luminosity. (Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4})

Solution:

Step 1: State Stefan's Law: $L = 4\pi R^2 \sigma T^4$

Step 2: Substitute values: $L = 4\pi (5.0 \times 10^9)^2 (5.67 \times 10^{-8}) (3500)^4$

Step 3: Calculate: $L = 4\pi (2.5 \times 10^{19}) (5.67 \times 10^{-8}) (1.500625 \times 10^{11})$

Step 4: Final answer: $L \approx 2.67 \times 10^{30}$ W

Example 3: Comparing Stellar Radii using Stefan's Law

Problem:

Star A has a luminosity of 100 $L_\odot$ and a surface temperature of 10,000 K. Star B has a luminosity of 1 $L_\odot$ and a surface temperature of 3000 K. Calculate the ratio of their radii, R_A / R_B. ($L_\odot = 3.828 \times 10^{26}$ W)

Solution:

Step 1: Rearrange Stefan's Law for R: $R = \sqrt{[L / (4\pi\sigma T^4)]}$

Step 2: Write the ratio of radii: $R_A / R_B = \sqrt{[L_A / (4\pi\sigma T_A^4)]} / \sqrt{[L_B / (4\pi\sigma T_B^4)]}$

Step 3: Simplify the ratio: $R_A / R_B = \sqrt{[(L_A / T_A^4) \times (T_B^4 / L_B)]} = \sqrt{[(L_A / L_B) \times (T_B / T_A)^4]}$

Step 4: Substitute values: $R_A / R_B = \sqrt{[(100\ L_\odot / 1\ L_\odot) \times (3000\ K / 10000\ K)^4]}$

Step 5: Calculate: $R_A / R_B = \sqrt{[100 \times (0.3)^4]} = \sqrt{[100 \times 0.0081]} = \sqrt{[0.81]}$

Step 6: Final answer: $R_A / R_B = 0.9$. Star A has a radius 0.9 times that of Star B, despite being much more luminous, due to its significantly higher temperature.

Common Mistake

Confusing apparent magnitude with absolute magnitude or luminosity. Apparent magnitude depends on distance, while absolute magnitude and luminosity are intrinsic properties.

Common Mistake

Incorrectly interpreting the HR diagram's axes, especially the temperature scale.

Common Mistake

Forgetting to convert temperature to Kelvin when using Wien's or Stefan's Law.

Common Mistake

Assuming that a star's colour directly corresponds to the peak of its visible spectrum; the peak might be in the UV or IR, but the visible portion of the spectrum determines its perceived colour.

Common Mistake

Not explaining *why* certain spectral lines are stronger at specific temperatures (e.g., hydrogen lines in A-type stars).

Exam Tips

💡 **Exam Tip**

Always remember that the x-axis of an HR diagram has temperature decreasing from left to right. This is a common point of confusion.

💡 **Exam Tip**

When using Wien's Displacement Law or Stefan's Law, ensure temperature is in Kelvin (K).

💡 **Exam Tip**

Be able to describe the characteristics (temperature, colour, luminosity, size) and evolutionary stage of stars in different regions of the HR diagram.

💡 **Exam Tip**

Understand that the strength of absorption lines in a star's spectrum is not simply proportional to the abundance of an element, but also depends critically on the star's temperature and pressure.

💡 **Exam Tip**

Practice calculating stellar properties (L, R, T, λ_{max}) using the given equations and converting between units (e.g., $L_{\odot}$ to W).

Comparison of Main Stellar Types on HR Diagram

Property	Main Sequence (e.g., Sun)	Red Giant	White Dwarf	Red Supergiant
Spectral Class	O, B, A, F, G, K, M (depending on mass)	K, M	D (degenerate)	K, M
Temperature	2,400 - 50,000 K	2,500 - 5,000 K	5,000 - 25,000 K	2,500 - 4,000 K
Colour	Blue to Red	Red/Orange	White/Blue-white	Red
Luminosity	0.001 - 10^6 $L_\odot$	10 - 1000 $L_\odot$	0.0001 - 0.01 $L_\odot$	10^4 - 10^6 $L_\odot$
Radius	0.1 - 10 $R_\odot$	10 - 100 $R_\odot$	0.01 $R_\odot$ (Earth-sized)	100 - 1000 $R_\odot$
Evolutionary Stage	Hydrogen fusion in core	Helium fusion in core (post-main sequence)	Remnant of low-mass star	Late stage of massive star

Summary

Stellar classification is crucial for understanding the properties and evolution of stars. Stars are primarily classified by their surface temperature, which dictates their colour and spectral class. Wien's Displacement Law (λ_{max} T = constant) quantifies the inverse relationship between a star's peak emission wavelength and its absolute temperature, explaining why hotter stars appear bluer and cooler stars appear redder. The OBAFGKM spectral classification system categorises stars based on the absorption lines in their spectra, which are highly sensitive to temperature. Luminosity, the total power radiated by a star, is an intrinsic property related to its radius and temperature by Stefan's Law ($L = 4\pi R^2 \sigma T^4$). The Hertzsprung-Russell (HR) diagram plots luminosity against temperature (or spectral class), revealing distinct regions for main sequence stars (hydrogen fusion), red giants (expanded, cooler, luminous), red supergiants (very large, cool, highly luminous), and white dwarfs (hot, dense, dim remnants). This diagram is fundamental for tracing stellar evolutionary paths and comparing different types of stars.