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Wednesday 21 June 2017 – Morning

A2 GCE PHYSICS B (ADVANCING PHYSICS)

G495/01 Field and Particle Pictures

INSERT

Duration: 2 hours

INSTRUCTIONS TO CANDIDATES

- This Insert contains the article required to answer the questions in Section C.

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- This document consists of **8** pages. Any blank pages are indicated.

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Heat, Light and Stars

Heated objects emit electromagnetic radiation. Filament light bulbs and electric heaters are familiar modern applications of this, but the effect has actually been known about since antiquity. Hot metallic objects in furnaces and forges provide particularly vivid examples.

The electromagnetic radiation emitted from a hot object covers a broad range of wavelengths. The 'Planck curves' in Fig. 1 show how the intensity of radiation emitted by a hot object (arbitrary units) varies with wavelength at three different temperatures.

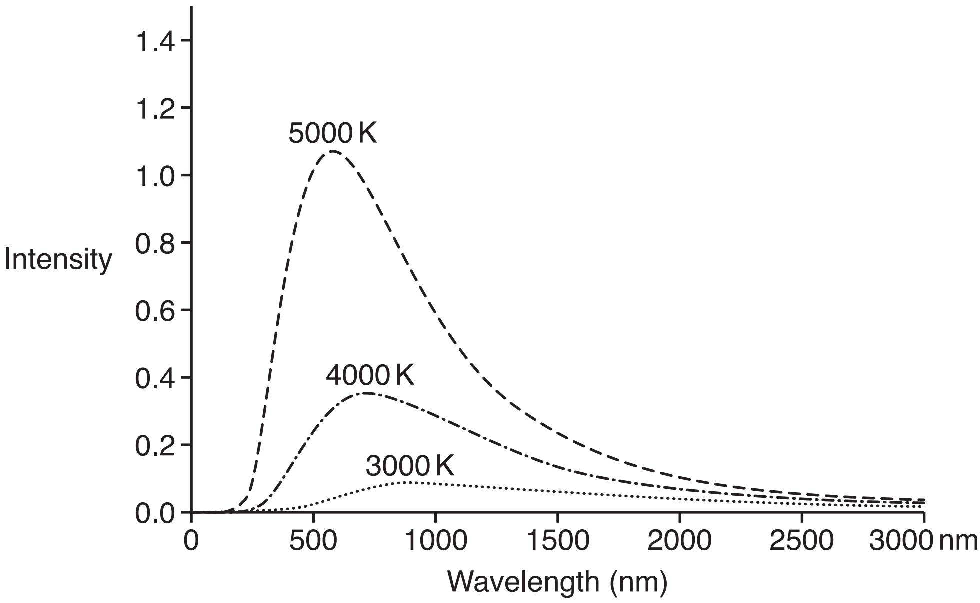

Fig. 1: The variation of intensity of emitted radiation with wavelength

It can be seen that the intensity (a measure of the number of photons per unit area per second) is not uniform across the range, but peaks at a specific wavelength value (λ_{max}) which depends on the temperature of the object. Towards the end of the nineteenth-century graphs such as these could be obtained experimentally, but explaining their shape provided the greatest scientific challenge of the day and new conceptual models were developed to meet the challenge. Max Planck, Wilhelm Wien, James Jeans, Lord Rayleigh and others formulated ideas and laws that eventually led to the emergence of Quantum Theory in the early part of the twentieth century. (The models developed were based on idealised electromagnetic emitters – 'blackbodies' – which were hot objects that could emit and absorb radiation at the same rate to maintain a constant temperature. This aspect of the model lies beyond the scope of this article and no examination questions will be asked about it.)

It was found that as the temperature of the emitter increased, so did the total amount of radiation emitted, but at the same time the value of λ_{max} decreased. Graphs such as those shown in Fig. 1 are known as Planck curves and show both the rise in intensity and the decrease in λ_{max} with increasing temperature, although the basic shape of the curve remains the same. A law formulated by Wilhelm Wien neatly describes how the value of λ_{max} changes with temperature (equation 1):

$$\lambda_{max} = 0.003 / T \qquad \textbf{Equation 1}$$

in which λ_{max} is measured in metres and T is the temperature in kelvin.

Radiation emitted by stars

Electromagnetic radiation can be emitted by a hot gas both at discrete wavelengths and over a continuous range. Discrete sets of wavelengths require energy transitions of electrons in bound states but a continuous range of emitted or absorbed wavelengths requires the electrons to be unbound or “free”. The temperatures in the cores of stars, where nuclear fusion occurs, are of the order of millions of kelvin, but the light-emitting surface of a star (the photosphere) is much cooler. The photosphere of the Sun, for example, has a temperature of around 5800 K. Even at this lower temperature, there are enough free electrons to produce a continuous range of wavelengths, but as we have seen in Fig. 1, the emission is not uniform across the range. For the Sun, the wavelength at which the greatest intensity of radiation is produced is around 500 nm. Equation 1 allows the surface temperature of a star to be determined from the wavelength of the predominant colour of radiation being emitted. Fig. 2 shows some of these colour-relationships.

Colour	Temperature/K
orange-red	4000
green-yellow	6000
blue	8000
violet	10 000
ultra-violet	20 000

Fig. 2: The relationship between colour and surface temperature

As already noted from the Planck curves, the total amount of radiation emitted increases with the temperature and it is useful to represent this behaviour of stars in the form of a diagram, as shown in Fig. 3, which shows how the total amount of radiation emitted (the luminosity) varies with temperature for stars of different radii.

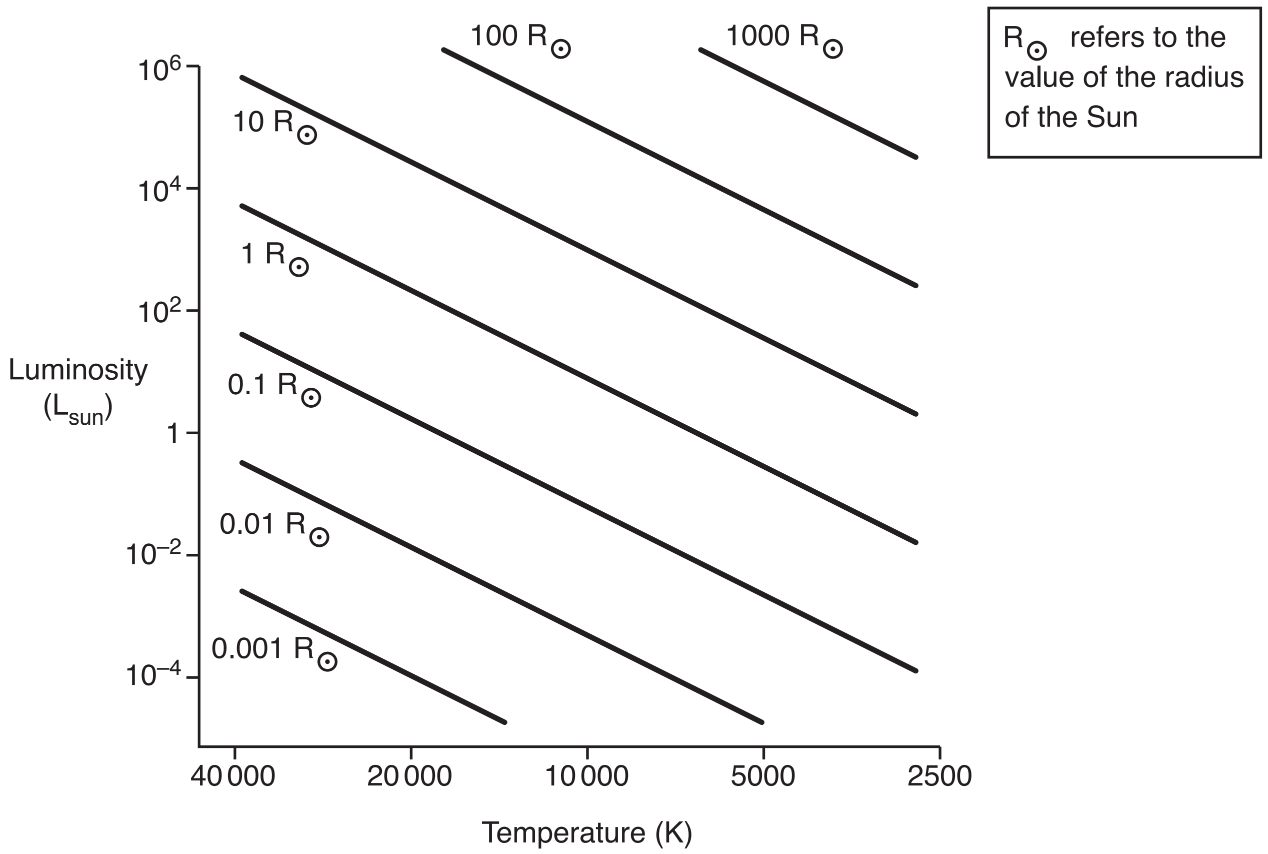

Fig. 3: The variation of luminosity with temperature for stars of different radii

There are several important things to note about this diagram:

1. The total amount of radiation emitted is called the luminosity and this will depend upon the size of the star as well as the temperature: stars with a larger radius have a greater surface area from which radiation can be emitted. This accounts for the set of lines, one for each radius of star. Astronomers refer to this luminosity as the absolute luminosity of the star.
2. The current power of the Sun is used here as the unit for luminosity (about 3.9×10^{23} W).
3. The surface temperatures increase from right to left. This is because when the chart was originally constructed, the *x*-axis displayed something called the Colour Index of the star (a label for the colour), which went in the order of decreasing temperature.
4. As well as going from right to left, the temperature scale is logarithmic.
5. The chart was generated using the known relationships between temperature, peak wavelength and luminosity.

Having constructed such a chart from theory, the question is: how do the colours and absolute luminosities of stars we observe in the night sky compare to it? Although the colours can be easily determined, measuring the luminosities requires knowledge of the distances of the stars from the Earth.

The intensity of light varies with 1/(distance from light source)^2. If it is possible to measure how bright a star *appears* to be and it is known how far away it is, then it is possible to determine how bright the star *actually* is (its absolute luminosity). Those stars that are most easily visible to observers on Earth are those that are closest to it, so their distances may be determined using the Stellar Parallax method.

Fig. 4 shows the positions of a selection of stars of known luminosity and temperature (colour), including some well-known ones such as Betelgeuse and Sirius. This chart is very important to astronomers and was developed, independently, by Ejnar Hertzsprung and Henry Russell around 1910. It is thus known today as the Hertzsprung-Russell (or H-R) diagram.

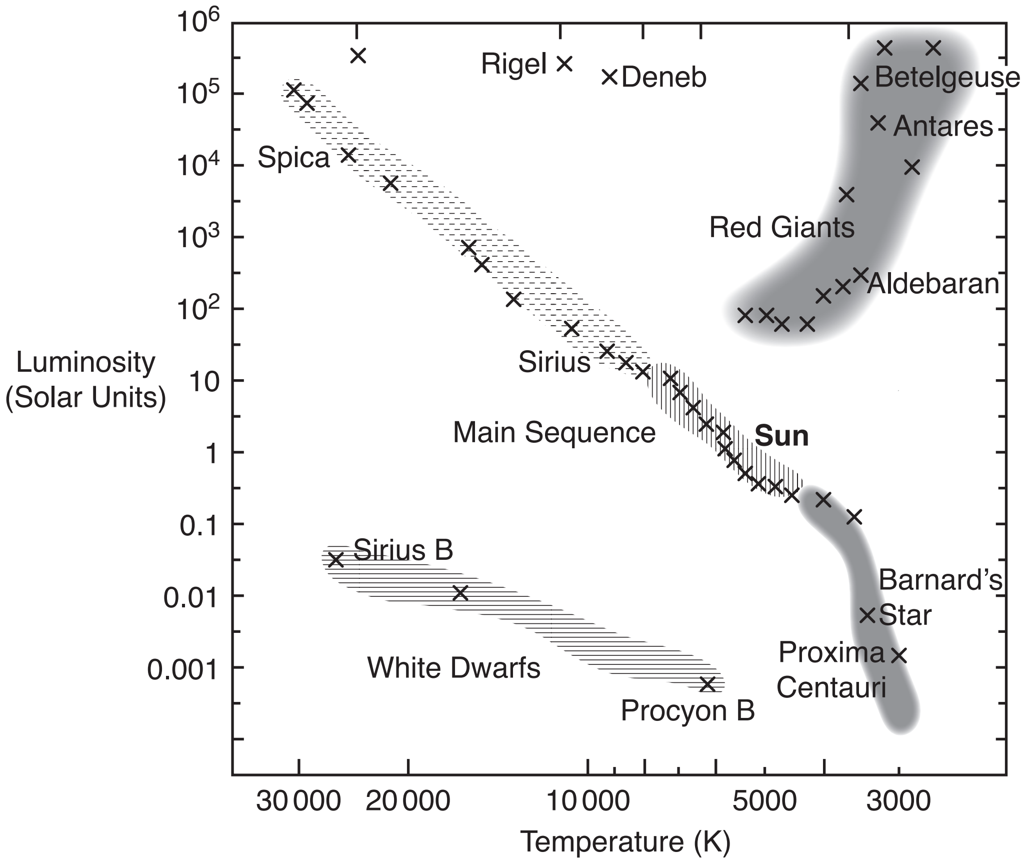

Fig. 4: The Hertzsprung-Russell diagram

There is a diagonal band stretching from top left to bottom right: this is not surprising since it is expected that hotter (bluer) stars are more luminous. However, there are exceptions, such as the Red Giants (for example, Betelgeuse) and White Dwarf stars. Giant stars have diameters many times that of the Sun.

The diagonal band is called the Main Sequence but must not be seen as an evolutionary path. In the course of a star's life it could go through different stages causing it to appear in various positions around the chart. Stars such as Sirius B and Procyon B (which feature in Fig. 4) are actually orbiting companions of larger stars and, since their orbital periods are often measurable, this allows the mass of the larger star they orbit to be determined. Such information added to that of the H-R diagram has enabled astronomers to study the stellar life cycle in detail and to develop models for stellar evolution. These include some of the more exotic objects to have been discovered in more recent times such as brown dwarfs, neutron stars, and black holes.

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