Cambridge AS & A Level · Physics 9702 · Notes

Astronomy and cosmology A2

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Read first: **Waves**, **Quantum physics**, **Nuclear physics**

What you need to know

By the end of this topic you should be able to:

1. **Understand luminosity** L: the total power of radiation a star emits.
2. **Recall and use the inverse square law** for radiant flux intensity, $F = \dfrac{L}{4\pi d^2}$.
3. **Understand that an object of known luminosity is a standard candle.**
4. **Understand how standard candles are used to find the distances to galaxies.**
5. **Recall and use Wien's displacement law**, $\lambda_{\max} \propto \dfrac{1}{T}$, to estimate the surface temperature of a star.
6. **Use the Stefan–Boltzmann law**, $L = 4\pi\sigma r^2 T^4$.
7. **Use Wien's law and the Stefan–Boltzmann law together** to estimate the radius of a star.
8. **Understand that spectral lines from distant objects are shifted** to longer wavelengths than their known values.
9. **Use** $\dfrac{\Delta\lambda}{\lambda} \approx \dfrac{\Delta f}{f} \approx \dfrac{v}{c}$ for the redshift of radiation from a source moving relative to an observer.
10. **Explain why redshift leads to the idea that the Universe is expanding.**
11. **Recall and use Hubble's law** $v \approx H_0 d$, and **explain how it leads to the Big Bang theory**. Only SI units are used (so H_0 is in s^{-1}).

The Doppler effect for sound comes from Waves; photon energy $E = hf$ and spectral lines from Quantum physics; $E = mc^2$ from Nuclear physics.

Understand it

Luminosity and radiant flux intensity

A star's **luminosity** L is the **total power** of electromagnetic radiation it emits, at all wavelengths and in all directions. Its unit is the watt. The Sun's luminosity is about 3.85×10^{26} W.

Far from the star, that power has spread out evenly over a sphere of radius d, with area $4\pi d^2$. The power arriving per unit area at right angles to the radiation is the **radiant flux intensity** F (unit W m^{-2}):

$$F = \frac{L}{4\pi d^2}$$

This is an **inverse square law**: twice as far away, a quarter of the flux intensity. At the Earth, 1.50×10^{11} m from the Sun, $F = \dfrac{3.85 \times 10^{26}}{4\pi \times (1.50 \times 10^{11})^2} = 1.36 \times 10^3$ W m^{-2}.

How **bright** a star looks depends on F, so a star can look brighter for two reasons: it has a **greater luminosity**, or it is **closer**. A dim-looking star may be powerful but far away.

The luminosity also tells you how fast the star loses mass: its energy comes from nuclear fusion, and by $E = mc^2$ the mass converted into energy each second is $\dfrac{L}{c^2}$. For the Sun that is about 4.3×10^9 kg every second.

Standard candles

If you measure F and already **know** L, the inverse square law gives the distance:

$$d = \sqrt{\frac{L}{4\pi F}}$$

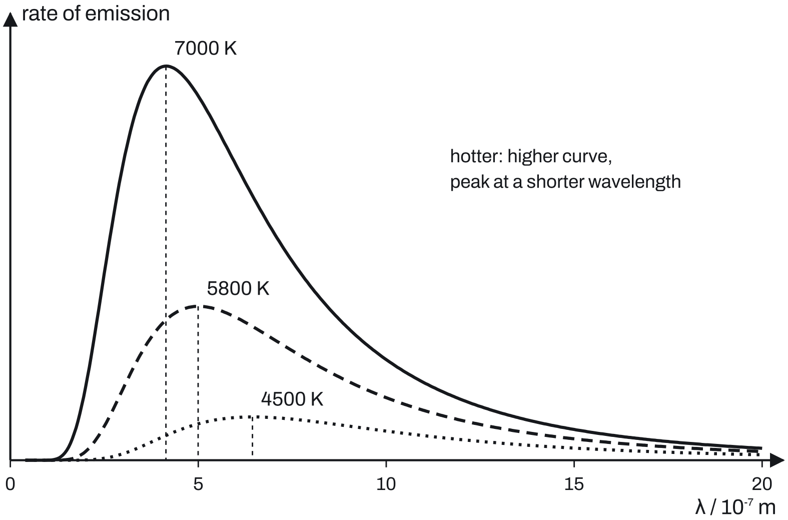
A **standard candle** is an astronomical object whose **luminosity is known** (for example, a certain type of star or supernova whose luminosity can be worked out from other observations). To find the distance to a galaxy:

1. find a standard candle in the galaxy, so its luminosity L is known;
2. measure the radiant flux intensity F of its radiation at the Earth;
3. calculate d from $F = \dfrac{L}{4\pi d^2}$.

The standard candle and its galaxy are at (very nearly) the same distance, so this is the distance to the galaxy. Two standard candles that look equally bright have $\dfrac{L}{d^2}$ the same: one with 16 times the luminosity must be 4 times as far away.

The spectrum of a star: Wien's displacement law

A star emits a continuous spectrum with a characteristic shape: the rate of emission rises from zero at short wavelengths, reaches a **peak** at a wavelength λ_{max}, then falls away more slowly at long wavelengths.



Wien's displacement law: the wavelength at which the rate of emission is **maximum** is **inversely proportional** to the **thermodynamic temperature of the star's surface**:

$$\lambda_{\max} \propto \frac{1}{T} \qquad \text{so} \qquad \lambda_{\max} T = \text{constant}$$

A hotter star peaks at a shorter wavelength (it looks bluer); a cooler star peaks at a longer wavelength (it looks redder). To estimate a star's temperature, measure its spectrum, find $\lambda_{\max}$, and compare with an object of **known** temperature and peak wavelength (usually the Sun: about 502 nm at 5780 K):

$$T_{\text{star}} = T_{\text{Sun}} \times \frac{\lambda_{\text{max,Sun}}}{\lambda_{\text{max,star}}}$$

A star peaking at 723 nm has $T = 5780 \times \dfrac{502}{723} = 4010$ K.

On a graph of emission against wavelength for two stars of the **same size**, the cooler one has its peak **further right** and **lower**: a cooler surface emits less power from every square metre.

The Stefan–Boltzmann law and the radius of a star

The luminosity of a star depends on its surface area $4\pi r^2$ and, very strongly, on its surface temperature:

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

$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is the Stefan–Boltzmann constant (on the data sheet). Doubling the temperature of a star of the same radius multiplies its luminosity by $2^4 = 16$. For the Sun, $L = 3.85 \times 10^{26}$ W and $r = 6.96 \times 10^8$ m give $T = 5780$ K.

Estimating a star's radius puts the whole topic together:

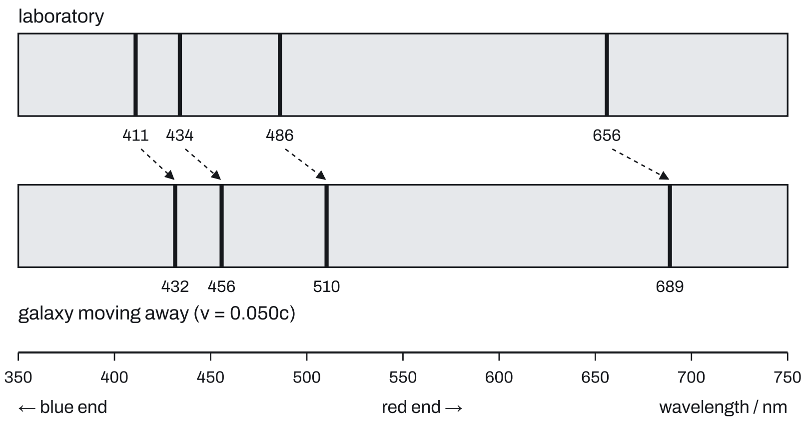
1. **temperature** T from the peak wavelength (Wien's law);
2. **luminosity** L from a measured F and a known distance d ($L = 4\pi d^2 F$);
3. **radius** from $r = \sqrt{\dfrac{L}{4\pi\sigma T^4}}$.

A hot star with a small luminosity must be small; a cool star with a large luminosity must be huge.

Redshift

Each element emits and absorbs light only at particular wavelengths, giving **spectral lines** (see Quantum physics). The pattern is known from laboratory measurements: hydrogen, for instance, has visible lines at about 411, 434, 486 and 656 nm.

In light from distant galaxies, the **same pattern** of lines appears, but every line is at a **longer wavelength** (lower frequency) than its known value: it is moved towards the red end of the spectrum. This is **redshift**. It is the Doppler effect for light: the source is **moving away** from the observer.



For a source moving at speed v (much less than c) along the line of sight:

$$\frac{\Delta\lambda}{\lambda} \approx \frac{\Delta f}{f} \approx \frac{v}{c}$$

λ is the **emitted** (known, laboratory) wavelength and $\Delta\lambda$ the change, observed minus emitted. So $\Delta\lambda$ is proportional to λ: in the diagram, $v = 0.050c$ moves 411 nm by 21 nm but 656 nm by 33 nm.

- A source **moving away**: observed wavelength **longer** (redshift).
- A source **moving towards** you: observed wavelength **shorter** (blueshift).
- Motion **across** the line of sight gives no shift.

A rotating star. One edge of a spinning star moves away from us and the other towards us, while the middle of the disc moves across our line of sight. So a line from the receding edge is shifted to a longer wavelength, from the approaching edge to a shorter one, and from the middle it is unshifted. The shift at an edge gives the rotation speed v at the equator, and with the period T, the radius: $v = \dfrac{2\pi R}{T}$. If a line at 656.2800 nm from the centre is at 656.2860 nm from the receding edge, $v = 3.00 \times 10^8 \times \dfrac{0.0060}{656.2800} = 2.7 \times 10^3$ m s^{-1}; with a period of 2.2×10^6 s, $R = \dfrac{vT}{2\pi} = 9.6 \times 10^8$ m.

The expanding Universe

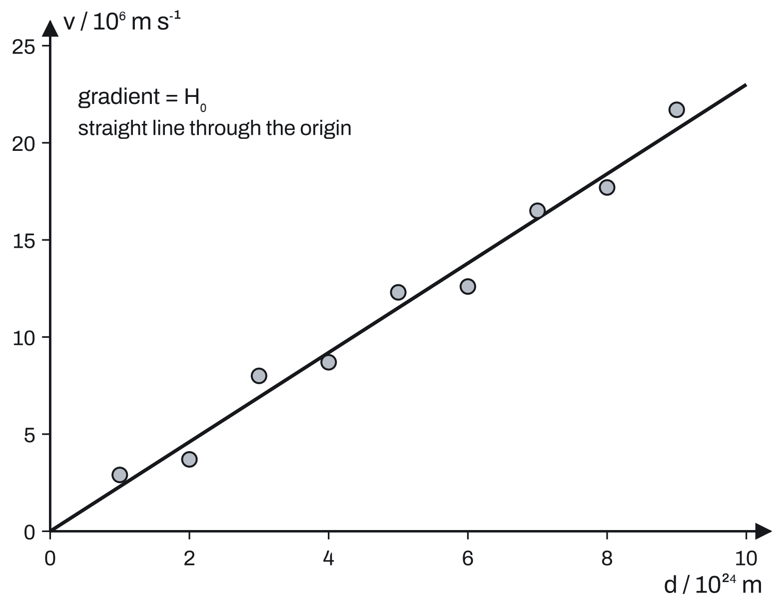
Light from almost all distant galaxies is redshifted, so they are **all moving away from us**, and more distant galaxies show bigger redshifts. We are not at a special place, so the same would be seen from any galaxy: the galaxies are all moving **apart from each other**. That means the **Universe is expanding**.

Hubble's law

Plotting the recession speed v of galaxies (from their redshifts) against their distance d (from standard candles) gives a straight line through the origin:

$$v \approx H_0 d$$

Hubble's law: the speed at which a galaxy is moving away from an observer is (approximately) **proportional to its distance** from the observer. The constant H_0 is the **Hubble constant**, the gradient of the graph. In SI units it is about 2.3×10^{-18} s^{-1} (speed in m s^{-1} divided by distance in m). A galaxy 1.0×10^{25} m away recedes at about $2.3 \times 10^{-18} \times 1.0 \times 10^{25} = 2.3 \times 10^{7}$ m s^{-1}.



Hubble's law compares **different galaxies at different distances at the same time**; it does not say that a galaxy speeds up as it moves away.

The Big Bang theory

Run the expansion backwards in time. The galaxies are moving apart, and the more distant ones are moving apart faster, so in the past all the matter in the Universe was **closer together**. Far enough back, all of it was **in one very small, very dense and very hot region**, from which it started moving apart very fast. That beginning is the **Big Bang**: the Universe started from a single point and has been expanding ever since. Light from very distant galaxies left them long ago, so looking further away is also looking further back in time.

Key facts and formulas

"Given" means it is on the data sheet printed in Paper 4. "Learn it" means you must remember it.

Formula	Status
Radiant flux intensity $F = \frac{L}{4\pi d^2}$ (inverse square law)	Learn it
Distance from a standard candle $d = \sqrt{\frac{L}{4\pi F}}$	Learn it
Wien's displacement law $\lambda_{\max} \propto \frac{1}{T}$, so $\lambda_1 T_1 = \lambda_2 T_2$	Learn it
Stefan–Boltzmann law $L = 4\pi\sigma r^2 T^4$	Given
Doppler redshift $\frac{\Delta\lambda}{\lambda} \approx \frac{\Delta f}{f} \approx \frac{v}{c}$	Given
Hubble's law $v \approx H_0 d$ (H_0 in s^{-1})	Learn it
Speed at a star's equator $v = \frac{2\pi R}{T}$	Learn it
Mass converted per second $\frac{\Delta m}{\Delta t} = \frac{L}{c^2}$ (from $E = mc^2$)	Learn it
$c = \lambda f$; photon energy $E = hf = \frac{hc}{\lambda}$	Learn it
$\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}, $c = 3.00 \times 10^{8}$ m s^{-1}, $h = 6.63 \times 10^{-34}$ J s	Given

How to do it

In the Paper 4 questions we have tagged for this topic (16 different questions, 2022–2025; 7 more appear on two papers), the types came up this often. Every one of the 16 questions mixes two or more types, so the counts add up to more than 16.

Question type	Questions
Redshift, the expanding Universe and the Big Bang (explanations)	11
Luminosity, radiant flux intensity and standard candles	10
Wien and Stefan–Boltzmann: temperature, luminosity and radius	8
Redshift calculations	8
Hubble's law and the Hubble constant	8
Uncorrected redshift: effect on estimates	4
Mass converted into energy each second	1

1. Redshift, the expanding Universe and the Big Bang (11 questions)

These are short explanations marked point by point. Learn each chain, in meaning:

- **What redshift is**: the **observed** wavelength of a spectral line is **longer** (its observed frequency lower) than the **known, emitted** value, because the source is **moving away** from the observer.
- **How we know light is redshifted**: measure the spectral lines in the star's light and **compare** them with the **known spectrum** of the same element measured in a laboratory: same pattern, longer wavelengths.
- **Why redshift means the Universe is expanding**: (1) light from distant galaxies is redshifted; (2) so they are moving away from us; (3) so galaxies are moving **apart from each other**; (4) so the Universe is expanding.
- **How Hubble's law leads to the Big Bang**: (1) recession speed is proportional to distance, so more distant galaxies move away faster; (2) so in the past all the matter was **closer together**; (3) at the start it was all in a very small, dense region, moving apart very fast. Write about the past in the past tense.

Variations you will meet:

- **Sketch the observed spectrum** for a receding galaxy: the **same number** of lines in the **same pattern**, each moved to a **longer** wavelength (to the right on a wavelength scale, to the left on a frequency scale), all by a similar amount on a short visible range. No calculation is wanted.
- **The two edges of a rotating star**: the edge moving towards the Earth gives a **shorter** observed wavelength than emitted, even though the star as a whole may be receding.
- **"Name the phenomenon"** and **"what does it show about the galaxy"**: redshift; the galaxy is moving away from us (not "the galaxy is expanding").

2. Luminosity, radiant flux intensity and standard candles (10 questions)

- **Luminosity**: the **total power of radiation emitted** by the star. Every word earns its place: total, power (not energy or intensity), radiation (all wavelengths, not just light), emitted.
- **Standard candle**: an **astronomical object of known luminosity**. It is an object, not a luminosity or a measuring device.
- **Finding a galaxy's distance**: the three steps in "Standard candles" above: known L; measure F; use $F = \dfrac{L}{4\pi d^2}$ for d.

1. **Calculate** F from L and d: square the distance. Unit W m^{-2}.
2. **Calculate** d from L and F: $d = \sqrt{\dfrac{L}{4\pi F}}$.
3. **Calculate** L from F and d: $L = 4\pi d^2 F$.

Variations you will meet:

- **Two reasons one star looks brighter than another**: it is **closer**, or it has a **greater** luminosity (say which way, not just "different").

- **A graph of F against $\frac{1}{d^2}$**: a straight line through the origin with gradient $\frac{L}{4\pi}$, so $L = 4\pi \times$ gradient. Read the powers of ten in the axis labels carefully.

3. Wien and Stefan–Boltzmann: temperature, luminosity and radius (8 questions)

1. **State Wien's law**: the wavelength of **maximum** (peak) emission is **inversely proportional** to the **thermodynamic temperature** of the star's **surface**.
2. **Temperature from a peak**: $T_2 = T_1 \times \frac{\lambda_1}{\lambda_2}$, using a reference star. Read λ_{max} at the top of each curve, carefully against the axis scale.
3. **Luminosity, radius or temperature**: $L = 4\pi\sigma r^2 T^4$; rearrange first, raise T to the power **4**, and take the fourth root for T.
4. **Radius of a star**: T from Wien, L from F and d, then $r = \sqrt{\frac{L}{4\pi\sigma T^4}}$.

Variations you will meet:

- **Explain how the surface temperature is found**: measure the spectrum and find the wavelength of **peak** intensity; do the same for an object of **known** temperature; use $\lambda_{\text{max}} \propto \frac{1}{T}$.
- **Sketch the curve for a cooler star of the same radius**: the same shape, with the peak at a **longer** wavelength and **lower** (first diagram).
- **Conclusions from graphs** of two stars' spectra (and an F–$\frac{1}{d^2}$ graph): the peak further left means **hotter** (give T); a higher curve or larger gradient means a **greater luminosity** (give L); with L and T you can give r. Quantitative conclusions are safest.
- **"How else does star B look?"**: a longer peak wavelength means it looks **redder**.

4. Redshift calculations (8 questions)

1. $\Delta\lambda =$ observed $-$ emitted.
2. $\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$ with λ the **emitted** (laboratory) value, so $v = c \times \frac{\Delta\lambda}{\lambda}$.
3. Or, given v, find the observed wavelength: $\lambda_{\text{obs}} = \lambda + \lambda\frac{v}{c}$.

The nanometres cancel in $\frac{\Delta\lambda}{\lambda}$, so no conversion is needed; but put c in m s^{-1} to get v in m s^{-1}. Keep all the digits of close wavelengths: $\Delta\lambda$ comes from a small difference.

Variations you will meet:

- **"Show that $v = \ldots$"**: write the formula, substitute the difference of wavelengths, the emitted wavelength **and** $c = 3.00 \times 10^8$, then give one more significant figure than printed.
- **The rotating Sun or star**: v from the shift between an edge and the centre of the disc, then $R = \frac{vT}{2\pi}$, then perhaps T_{surface} from $L = 4\pi\sigma R^2 T^4$.

- **"Lowest energy" or "longest wavelength" visible line**: the longest one in the list (lowest photon energy, $E = \frac{hc}{\lambda}$). A line may first need its wavelength from an energy-level gap, $\lambda = \frac{hc}{\Delta E}$ (Quantum physics).

5. Hubble's law and the Hubble constant (8 questions)

1. **State Hubble's law**: the **speed of recession** of a galaxy is **proportional** to its **distance** from the observer. Say whose speed (a galaxy's, moving away) and distance from what (the observer).
2. **Distance**: $d = \frac{v}{H_0}$, with v from the redshift.
3. **Hubble constant**: $H_0 = \frac{v}{d}$, with d from a standard candle. Unit s^{-1}.

Variations you will meet:

- **Sketch v against d**: a **straight** line with positive gradient **through the origin**; the gradient is the **Hubble constant**.
- **Two-step questions**: redshift gives v, then $v = H_0 d$ gives d (or d is given and you find H_0). Use the **recession speed**, not c, in Hubble's law.

6. Uncorrected redshift: effect on estimates (4 questions)

If a student forgets to correct for redshift, every wavelength they measure is **too long**. Follow the effect through, one quantity at a time:

Quantity	Uncorrected value	Why
Peak wavelength	too **high**	redshift makes every wavelength longer
Surface temperature (Wien)	too **low**	$T \propto \frac{1}{\lambda_{\max}}$
Distance (standard candle)	the **same**	L and F don't use wavelengths
Luminosity (from F and d)	the **same**	$L = 4\pi d^2 F$
Radius (Stefan–Boltzmann)	too **high**	$r = \sqrt{\frac{L}{4\pi\sigma T^4}}$ and T is too low

On a spectrum graph measured on Earth for a receding star, the whole curve (and its peak) is shifted to **longer** wavelengths.

7. Mass converted into energy each second (1 question)

The star's output power is its luminosity, so by $E = mc^2$: mass converted per second $= \frac{L}{c^2}$. Use the luminosity, **not** the radiant flux intensity at the Earth.

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **M1** method mark: for a correct method, even if the numbers slip.
- **A1** accuracy mark: for a correct answer; it needs the M mark before it.
- **B1** mark for a correct result on its own, with no method needed.

Example 1

A particular type of star is used as a standard candle. One of these stars, in a distant galaxy, has luminosity 3.2×10^{30} W.

(a) State what is meant by the luminosity of a star. **[1]**

(b) Explain how this star can be used to find the distance of the galaxy from the Earth. **[3]**

(c) The radiant flux intensity at the Earth of the radiation from the star is 4.5×10^{-15} W m⁻². Calculate the distance of the galaxy from the Earth. **[2]**

(d) In another galaxy, a standard candle with 16 times the luminosity gives the same radiant flux intensity at the Earth. Determine the ratio of the distance of this galaxy to the distance in (c). **[1]**

Solution

(a) The total power of radiation emitted by the star. **B1**

(b) The star is a standard candle, so its luminosity is known. **B1** Its radiant flux intensity F is measured at the Earth. **B1** The distance is calculated from $F = \dfrac{L}{4\pi d^2}$. **B1**

(c) $d = \sqrt{\dfrac{L}{4\pi F}} = \sqrt{\dfrac{3.2 \times 10^{30}}{4\pi \times 4.5 \times 10^{-15}}}$ **C1** $= 7.52 \times 10^{21}$ m. **A1**

(d) Same F, so $\dfrac{L}{d^2}$ is the same: $d \propto \sqrt{L}$, and the ratio is $\sqrt{16} = 4$. **A1**

Example 2

The spectrum of the Sun has its peak intensity at a wavelength of 502 nm. The surface temperature of the Sun is 5780 K. The spectrum of a star S has its peak intensity at 380 nm, after correction for redshift.

(a) State Wien's displacement law. **[2]**

(b) Determine the surface temperature of star S. **[2]**

(c) The luminosity of star S is 2.4×10^{28} W. Calculate its radius, and compare it with the Sun's radius of 6.96×10^{8} m. **[3]**

(d) Star S is in a galaxy that is moving away from the Earth. Its distance was found using a standard candle. State and explain how the values in (b) and (c) would compare with the true values if the redshift had not been corrected for. **[3]**

Solution

(a) The wavelength at which the emission is maximum is inversely proportional **M1** to the thermodynamic temperature of the star's surface. **A1**

(b) $\lambda_{\max}T$ is constant: $T = 5780 \times \dfrac{502}{380}$ **C1** $= 7640$ K. **A1**

(c) $L = 4\pi\sigma r^2T^4$, so $r = \sqrt{\dfrac{2.4 \times 10^{28}}{4\pi \times 5.67 \times 10^{-8} \times 7640^4}}$ **C1** $= 3.14 \times 10^{9}$ m **A1**, about 4.5 times the Sun's radius. **B1**

(d) The measured peak wavelength would be too high, so the temperature would be too **low**. **B1** The distance and luminosity don't depend on wavelength, so L would be unchanged **B1**; $r \propto \dfrac{1}{T^2}$ for fixed L, so the radius would be too **high**. **B1**

Example 3

A spectral line of hydrogen has a wavelength of 486.1 nm in the laboratory. In the light from a distant galaxy, the same line is observed at 503.6 nm.

(a) Explain why the observed wavelength is different from the laboratory value. **[2]**

(b) Calculate the speed of the galaxy relative to the Earth. **[2]**

(c) The Hubble constant is 2.3×10^{-18} s^{-1}. Determine the distance of the galaxy from the Earth. **[2]**

(d) A second galaxy is twice as far away. State its recession speed, and explain how observations like these lead to the Big Bang theory. **[4]**

Solution

(a) The galaxy is moving away from the Earth **B1**, so its light is redshifted (Doppler effect): the observed wavelength is longer than the emitted one. **B1**

(b) $\dfrac{\Delta\lambda}{\lambda} = \dfrac{v}{c}$: $v = 3.00 \times 10^{8} \times \dfrac{503.6 - 486.1}{486.1}$ **C1** $= 1.08 \times 10^{7}$ m s^{-1}. **A1**

(c) $v = H_0 d$, so $d = \dfrac{1.08 \times 10^{7}}{2.3 \times 10^{-18}}$ **C1** $= 4.7 \times 10^{24}$ m. **A1**

(d) By Hubble's law, $v \propto d$: 2.16×10^{7} m s^{-1}. **B1** Galaxies are all moving apart, and more distant ones move away faster. **B1** So in the past all the matter in the Universe was closer together **B1**, and at the start it was all in a very small, very dense region that began to expand. **B1**

Common mistakes

- **Incomplete definitions of luminosity.** March 2022, November 2022 and March 2025: "total" and "emitted" were often left out, power was confused with energy or intensity, and "light" was written instead of radiation.
- **A standard candle is an object.** March 2023: not "the luminosity of a known star", a unit or a measuring device. It is an astronomical object of **known luminosity**.
- **Forgetting to square** d, or using the luminosity formula instead of $F = \frac{L}{4\pi d^2}$ (June 2023, November 2022). In March 2022 some used the flux at the Earth instead of the luminosity when finding the mass lost per second.
- **Not raising** T **to the power 4** in $L = 4\pi\sigma r^2 T^4$ (November 2022). Give 3 significant figures when the data has 3 (March 2022).
- **Wien's law without "maximum".** June 2022: the law is about the wavelength of **peak** emission. Read the wavelength axis scale carefully (June 2022), and don't confuse the height of a peak with its position.
- **Temperature method without a reference.** November 2022: say that the peak wavelength is compared with that of an object of **known** temperature.
- **Redshift described vaguely.** June 2022: it is the **observed** wavelength that is longer than the **known** value; say how you know (compare with a known laboratory spectrum). June 2023: say it is caused by the galaxy moving away (the Doppler effect).
- **The wrong wavelength on the bottom of** $\frac{\Delta\lambda}{\lambda}$**.** June 2023 and March 2023: use the emitted (laboratory) wavelength, and in a "show that" include c. March 2025: the edge of a star moving **towards** us gives a **shorter** wavelength; not every shift is a redshift.
- **Hubble's law half-stated.** June 2022 and June 2023: say the speed is the **recession** speed of a **galaxy** and the distance is **from the observer**. Don't mix it up with Wien's law, and use v, not c, in $v = H_0 d$.
- **Galaxy or Universe?** June 2022 and November 2022: redshift shows the **galaxies** are moving away and apart; the **Universe** is expanding (not "the galaxy is expanding" or "the Universe is moving away from the Earth"). Hubble's law compares different galaxies now; galaxies don't speed up as they move away.

How to get the marks

- **Definitions and laws**: learn the ones in types 1, 2, 3 and 5 word for word in meaning; a law usually gets one mark for the proportionality and one for saying what each quantity is.
- **Calculations**: the **C1** is for the right equation with numbers in; the **A1** is the answer. Keep 3 significant figures when the data has them.
- **"Give a unit"**: W for luminosity, W m^{-2} for radiant flux intensity, K for temperature, m s^{-1} for speed, s^{-1} for H_0.
- **"Show that"**: substitute every value, constants included (σ, c), and give one more significant figure than printed.
- **"Explain" chains** (expanding Universe, Big Bang, standard candles, temperature from a spectrum): one mark per link, in order; don't skip the obvious first step.

- **"State and explain"** (too high, too low, shorter, longer): give the effect **and** the physics reason ("observed wavelength too high, so the temperature is too low because $T \propto \frac{1}{\lambda_{\text{max}}}$").
- **Sketches**: spectra keep the same pattern of lines, shifted the right way; emission curves keep the same shape; Hubble graphs are straight and through the origin.

Quick check

1. A star of luminosity 5.0×10^{27} W is 3.0×10^{17} m from the Earth. Calculate the radiant flux intensity at the Earth.
2. The Sun (surface 5780 K) has its peak emission at 502 nm. A star has its peak at 870 nm. Estimate its surface temperature.
3. The luminosity of the Sun is 3.85×10^{26} W. Calculate the mass converted into energy in the Sun each second.
4. A galaxy is moving away from the Earth at 1.5×10^{7} m s^{-1}. A line of wavelength 434.0 nm is emitted. Calculate the observed wavelength, and use $H_0 = 2.3 \times 10^{-18}$ s^{-1} to find the galaxy's distance.
5. Why does redshift in the light from distant galaxies suggest that the Universe is expanding?

Answers

1. $F = \dfrac{L}{4\pi d^2} = \dfrac{5.0 \times 10^{27}}{4\pi \times (3.0 \times 10^{17})^2} = 4.42 \times 10^{-9}$ W m⁻².
2. $T = 5780 \times \dfrac{502}{870} = 3340$ K.
3. $\dfrac{L}{c^2} = \dfrac{3.85 \times 10^{26}}{(3.00 \times 10^8)^2} = 4.28 \times 10^9$ kg.
4. $\Delta\lambda = 434.0 \times \dfrac{1.5 \times 10^7}{3.00 \times 10^8} = 21.7$ nm, so it is observed at 455.7 nm. $d = \dfrac{v}{H_0} = \dfrac{1.5 \times 10^7}{2.3 \times 10^{-18}} = 6.52 \times 10^{24}$ m.
5. The spectral lines are at longer wavelengths than their known values, so the galaxies are moving away from us; since this is seen in (almost) every direction, galaxies are moving apart from each other, so the Universe is expanding.

Past questions to try

- **9702/42/F/M/24 Q10**: the Sun's radius and flux at the Earth, a cooler star's spectrum, and a redshifted line.
- **9702/42/O/N/23 Q10**: Wien's law, standard candles, and which estimates are too high or too low without redshift correction.
- **9702/42/M/J/24 Q8**: redshifted hydrogen lines, a photon energy and energy level, then the galaxy's distance.
- **9702/42/F/M/22 Q12**: luminosity, flux at the Earth, mass lost per second, the Sun's temperature and Sirius's peak wavelength.