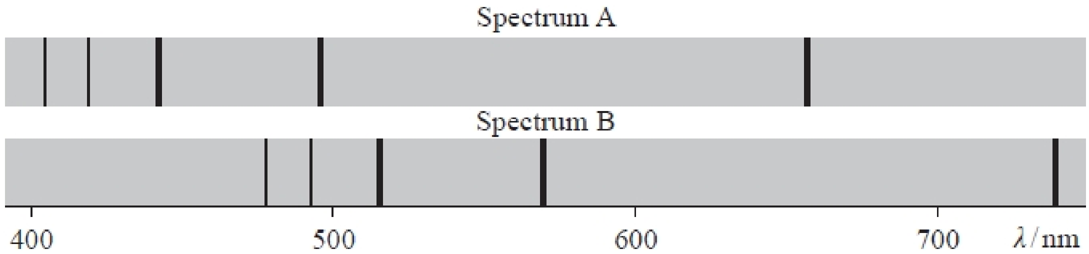
Doppler Effect, Redshift and Hubble's Law

Q1.

The diagram shows the spectra produced by two stars. Spectrum A is produced from the light from the Sun and spectrum B is produced from the light from a distant star.



The dark lines are produced when light from the core of the star is absorbed by hydrogen atoms in the outer regions of the star. Light is then re-radiated, but in all directions, giving rise to the dark lines in the spectrum.

Explain why the long wavelength lines are shifted by a greater amount than the short wavelength lines.

(2)

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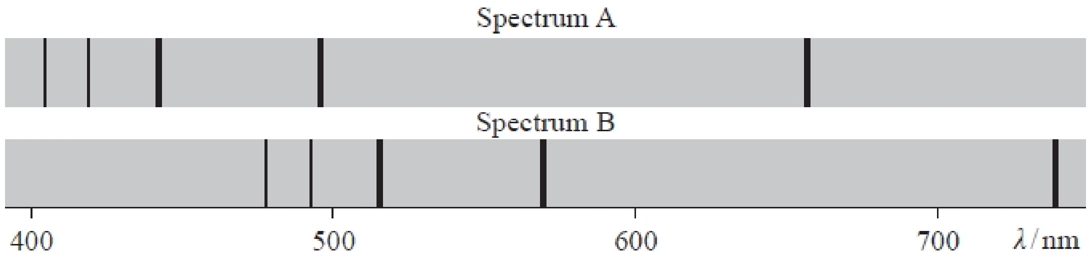
(Total for question = 2 marks)

Q2.

The diagram shows the spectra produced by two stars. Spectrum A is produced from the light from the Sun and spectrum B is produced from the light from a distant star.



The dark lines are produced when light from the core of the star is absorbed by hydrogen atoms in the outer regions of the star. Light is then re-radiated, but in all directions, giving rise to the dark lines in the spectrum.

One of the lines in the hydrogen spectrum occurs at a wavelength of 656 nm in the laboratory.

Explain what conclusion can be made from the shift in wavelength of this line in spectrum B. Your answer should include a calculation.

(4)

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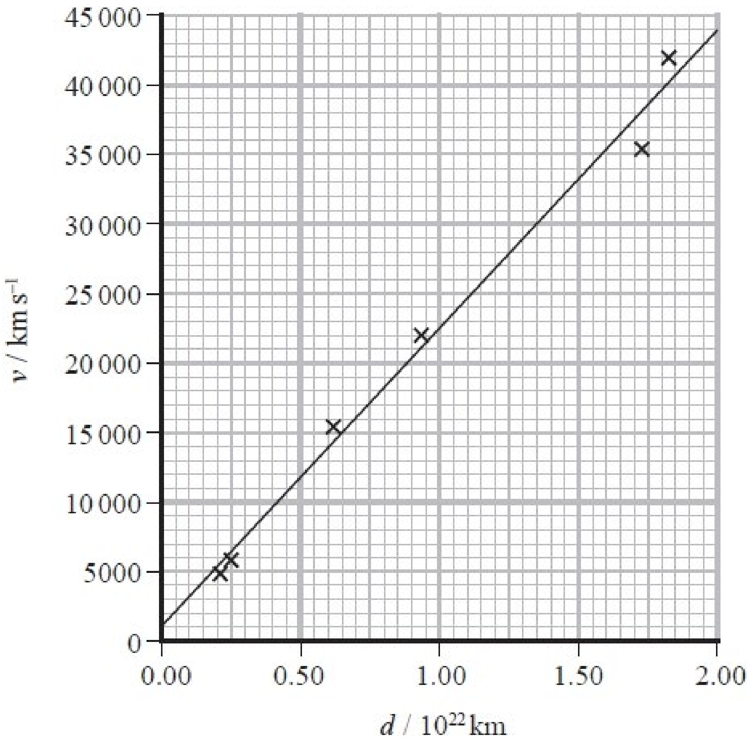
(Total for question = 4 marks)

Q3.

In 1990, the Hubble Space Telescope (HST) was launched into a low Earth orbit above the Earth's atmosphere.

High resolution images from HST allow astronomers to make detailed measurements of very distant galaxies. The graph shows how the recessional velocities of distant galaxies depend on their distance from Earth.



Determine an age for the universe.

(3)

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Age for the universe = ...

(Total for question = 3 marks)

Q4.

Barnard's star is a red dwarf star in the vicinity of the Sun. The wavelength of a line in the spectrum of light emitted from Barnard's star is measured to be 656.0 nm. The same light produced by a source in a laboratory has a wavelength of 656.2 nm.

Calculate the velocity of Barnard's star relative to the Earth.

(3)

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Velocity = ...

(Total for question = 3 marks)

Q5.

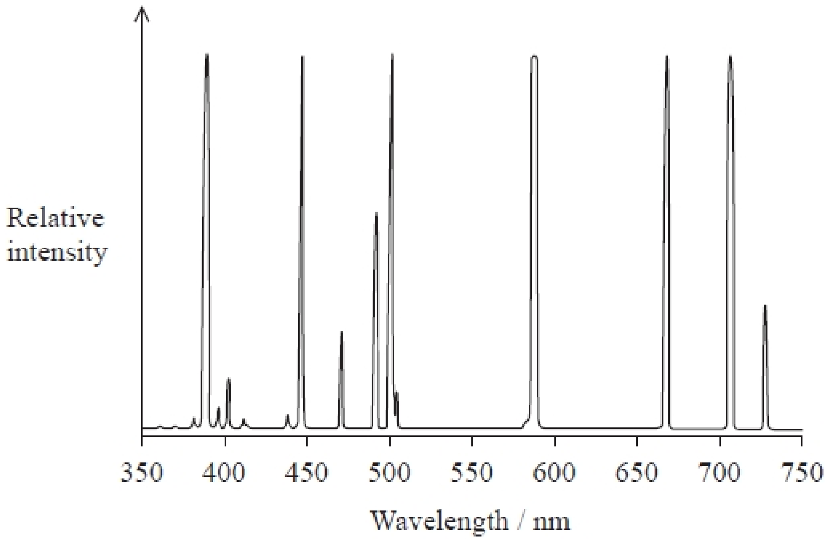
When a large potential difference is applied to a discharge tube, the gas in the discharge tube emits coloured light. When this light is passed through a diffraction grating, an emission spectrum which is made up of a series of lines of different wavelengths may be seen.

The photographs show the spectra produced from a tube containing hydrogen and a tube containing helium.

Hydrogen:

Helium:

The graph shows the relative intensities of different wavelengths of light in the spectrum of a sample of helium.



The graph shows that the lines are not at a single wavelength. This effect is known as thermal Doppler broadening and occurs because of the random motion of the helium atoms.

(i) Explain why the thermal motion of the helium atoms causes the broadening of the spectral lines.

(2)

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(ii) The width of a line may be used to determine the speed of the atoms in the gas and hence the temperature of the gas.

The spectral line with wavelength 587 nm for a particular tube containing helium has a width of 6×10^{-3} nm.

(1) Show that this corresponds to a speed, for a helium atom, of about 1500 m s^{-1}.

(2)

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(2) Assuming that this is the root mean square speed for the helium (He 4) atoms in the tube, calculate the temperature of the gas in the tube.

(3)

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Temperature = ...

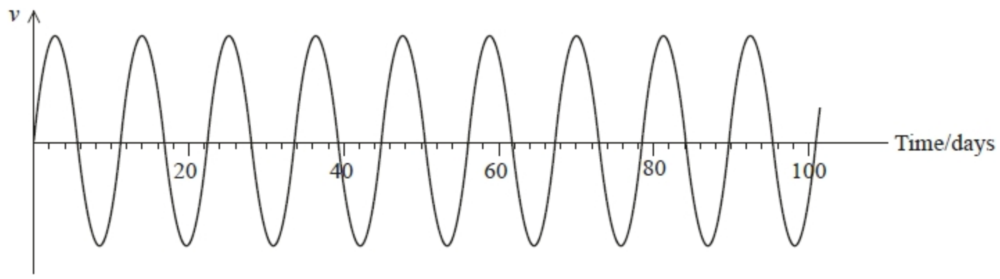
(Total for question = 7 marks)

Q6.

In 2016 astronomers announced the discovery of an Earth-like planet orbiting Proxima Centauri, the closest star to the Sun.

The planet was detected because of the small movement of the star as the planet orbited. The movement was detected using the Doppler shift in the frequency of light travelling to the Earth.

The graph shows how the component of the star's velocity *v* towards the Earth varied over time.



Explain how the Doppler shift was used to obtain the data shown on the graph.

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(Total for question = 4 marks)

Q7.

About 100 years ago the first measurements of spectra from galaxies beyond the Milky Way were made. Wavelengths of spectral lines were observed to be shifted and Hubble discovered a rough correlation between the shift in the spectral line and the distance to the galaxy.

The graphs below show plots for data collected in 1929 (Figure 1) and 1931 (Figure 2).

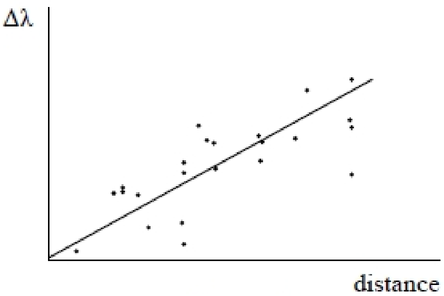

Figure 1

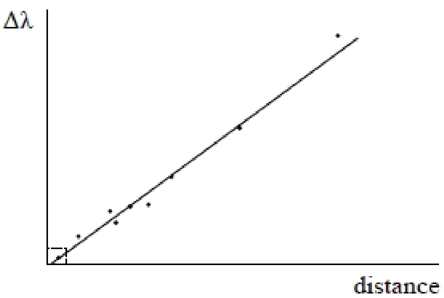

Figure 2

The data used by Hubble for his 1929 plot (Figure 1) is contained within the rectangle close to the origin of the 1931 plot (Figure 2).

Explain how Hubble's observations support the conclusion that the universe is expanding, and assess the reliability of this conclusion on the basis of Hubble's original data.

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(Total for question = 5 marks)

Q8.

A line in the hydrogen spectrum of a star in the Milky Way galaxy is observed to have a wavelength of 656.3 nm. In a laboratory on Earth this line has a wavelength of 654.9 nm.

Which of the following expressions gives the magnitude of the velocity of the star relative to Earth?

(1)

☐ **A** $\frac{656.3}{654.9} \times 3 \times 10^8 \, \text{m s}^{-1}$

☐ **B** $\frac{654.9}{(656.3 - 654.9)} \times 3 \times 10^8 \, \text{m s}^{-1}$

☐ **C** $\frac{654.9}{656.3} \times 3 \times 10^8 \, \text{m s}^{-1}$

☐ **D** $\frac{(656.3 - 654.9)}{654.9} \times 3 \times 10^8 \, \text{m s}^{-1}$

(Total for question = 1 mark)

Q9.

A source of sound of constant frequency is moving towards an observer. Compared to the frequency of the source, the frequency of sound heard by the observer is

☐ **A** higher, because the speed of sound increases.

☐ **B** lower, because the air is compressed.

☐ **C** higher, because the wavelength of the sound decreases.

☐ **D** lower, because the amplitude increases.

(Total for question = 1 mark)

Q10.

The wavelength of a line in the spectrum produced by a distant star is found to be shorter than the wavelength of the corresponding line in the spectrum produced by the Sun.

This is because the distant star is

☐ **A** cooler than the Sun.

☐ **B** hotter than the Sun.

☐ **C** moving away from the Earth.

☐ **D** moving towards the Earth.

(Total for question = 1 mark)

Mark Scheme – Doppler Effect, Redshift and Hubble's Law

Q1.

Question Number	Acceptable answers	Additional guidance	Mark
	An explanation that makes reference to the following points: • The fractional change in wavelength is proportional to the relative velocity of the source (1) • Hence the change in wavelength is proportional to the wavelength (1) **OR** • $\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$ and v and c are the same for all wavelengths **Or** $\frac{\Delta\lambda}{\lambda} = z$ and z is constant (1) • change in wavelength is proportional to the wavelength **Or** rearranges, e.g. $\Delta\lambda = x\lambda$ to demonstrate $\Delta\lambda$ is proportional to λ (1)		2

Q2.

Question Number	Acceptable answers	Additional guidance	Mark
	An explanation that makes reference to the following points: • Estimate λ_{star} (1) (above 7×10^{-7} m) • Use of $\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$ with (1) 656 nm as denominator • $v = 3.8 \times 10^7$ m s^{-1} (1) (range 3.4×10^7 m s^{-1} to 4.2×10^7 m s^{-1}) • (Star is) moving away from the Earth (1) **Or** (star is) receding	Example of calculation $\frac{(7.40 \times 10^{-7} - 6.56 \times 10^{-7})}{6.56 \times 10^{-7}\ m} = \frac{v}{3.00 \times 10^{8}\ m\ s^{-1}}$ $\therefore v = \frac{0.84 \times 10^{-7}\ \text{m}}{6.56 \times 10^{-7}\ \text{m}} \times 3.00 \times 10^{8}\ \text{m s}^{-1}$ $\therefore v = 3.84 \times 10^{7}\ \text{m s}^{-1}$	4

Q3.

Question Number	Acceptable Answer	Additional Guidance	Mark
	• Gradient of graph determined (1) • $v = Hd$, so $t = 1/H = 1/\text{gradient}$ (1) • $t = 4.7 \times 10^{17}$ s (1)	Example of calculation: Gradient= $\frac{(44000-1000)\ \text{km s}^{-1}}{(2.00-0.00)\times10^{22}\ \text{km}} = 2.15\times10^{-18}\text{s}^{-1}$ $t = \frac{1}{2.15\times10^{-18}\text{s}^{-1}} = 4.65\times10^{17}\text{s}$	3

Q4.

Question Number	Acceptable Answer	Additional Guidance	Mark
	• use of $\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$ with $\lambda = 656.2$ nm (1) • $v = 9 \times 10^4$ m s^{-1} (1) • the star is moving towards the Earth (1)	Example of calculation: $v = \left(\frac{(656.2 - 656.0)\times10^{-9}\,\text{m}}{656.2\times10^{-9}\,\text{m}}\right)\times 3.00\times10^{8}\,\text{m s}^{-1}$ $= 9.14\times10^{4}\,\text{m s}^{-1}$	3

Q5.

Question Number	Acceptable answers	Additional guidance	Mark
(i)	An answer that makes reference to the following: • because the helium atoms are moving, there is a change in frequency/ wavelength of the emitted light (1) • for particles moving away from the observer there will be an decrease in frequency and for particles moving towards the observer there will be an increase in frequency (1) OR for particles moving away from the observer there will be an increase in wavelength and for particles moving towards the observer there will be an decrease in wavelength (1)		**(2)**

Question Number	Acceptable answers	Additional guidance	Mark
(ii)(1)	• use of $v/c = \Delta\lambda/\lambda$ • $v = 1530\ \text{m s}^{-1}$	Example of calculation: $v / 3 \times 10^{8}\ \text{m s}^{-1} = 3 \times 10^{-3}\ \text{nm} / 587\ \text{nm}$ $v = 1530\ \text{m s}^{-1}$	**(2)**

Question Number	Acceptable answers	Additional guidance	Mark
(ii)(2)	• mass of helium atom = 4u • use of $\frac{1}{2} m \langle c^2 \rangle = 3/2\ kT$ • $T = 375$ K	Example of calculation: Mass of He atom = $4 \times 1.66 \times 10^{-27}$ kg = 6.64×10^{-27} kg $\frac{1}{2}\ 6.64 \times 10^{-27}\ \text{kg} \times (1530\ \text{m s}^{-1})^2 = 3/2 \times 1.38 \times 10^{-23}\ \text{J K}^{-1} \times T$ $T = 375$ K	**(3)**

Q6.

Question Number	Acceptable answers	Additional guidance	Mark
	• The frequency/wavelength (of a line in the spectrum) emitted by the star must be measured (1) • Determine the difference between this frequency/wavelength and that emitted in the lab (1) • (The Doppler equation is used to) determine the speed of the star (relative to the Earth) $v/c = \Delta f/f_0$ or $v/c = \Delta\lambda/\lambda_0$ (1) • Clear indication (stated in words or via a formula) that v is positive/approaching when the frequency has increased and negative/receding when it has decreased **Or** corresponding statement about wavelength (1)	MP2 – accept in terms of difference between measured frequency/wavelength with average frequency/wavelength	4

Q7.

Question Number	Acceptable answers	Additional guidance	Mark
	• The wavelength change is bigger the further away the galaxies are **(1)** • The further away galaxies are the faster they are moving, so all distant galaxies are moving away from each other (and the universe is expanding) **(1)** • There is a large amount of scatter in Hubble's original data set. **(1)** • The original data set covers a very small range of distances [only the closest galaxies considered] **(1)** • Hence, on the basis of the original data, the conclusion drawn by Hubble was quite speculative **(1)**		**5**

Q8.

Question Number	Answer	Mark
	D – $$\frac{(656.3 - 654.9)}{654.9} \times 3 \times 10^8 \text{ m s}^{-1}$$	**1**
	Incorrect Answers: correct method: $$\frac{change\ in\ wavelength}{wavelength\ in\ laboratory} \times speed\ of\ light$$ A – uses $$\frac{wavelength\ from\ star}{wavelength\ in\ laboratory} \times speed\ of\ light$$ B – uses $$\frac{wavelength\ in\ laboratory}{change\ in\ wavelength} \times speed\ of\ light$$ C – uses $$\frac{wavelength\ in\ laboratory}{wavelength\ from\ star} \times speed\ of\ light$$	

Q9.

Question Number	Answer	Mark
	C	1

Q10.

Question Number	Answer	Mark
	D	**1**