D_4D_5 *[107 marks]*

1a. Describe the formation of a type Ia supernova. *[2 marks]*

Markscheme

a white dwarf accretes mass «from a binary partner»

when the mass becomes more than the Chandrasekhar limit (1.4M_s) «then asupernova explosion takes place»

[2 marks]

Type Ia supernovae typically have a peak luminosity of around 5×10^5 L_S, where L_S is the luminosity of the Sun (3.8×10^{26} W). A type Ia supernova is observed with an apparent peak brightness of 1.6×10^{-6} W m^{-2}.

1b. Show that the distance to the supernova is approximately 3.1×10^{18} m. *[2 marks]*

Markscheme

d = $\sqrt{\frac{L}{4\pi b}} = \sqrt{\frac{5\times10^{5}\times3.8\times10^{26}}{4\pi\times1.6\times10^{-6}}}$

d = 3.07×10^{18} «m»

At least 3 sig fig required for MP2.

[2 marks]

1c. State **one** assumption made in your calculation. *[1 mark]*

Markscheme

type Ia supernova can be used as standard candles

there is no dust absorbing light between Earth and supernova

their supernova is a typical type Ia

[1 mark]

2a. Outline, with reference to the Jeans criterion, why a cold dense gas cloud is more likely to form new stars than a hot diffuse gas cloud. *[2 marks]*

Markscheme

«For a star to form»: magnitude of PE of gas cloud > KE of gas cloud

OR

Mass of cloud > Jean's mass

OR

Jean's criterion is the critical mass

hence a hot diffuse cloud could have KE which is too large/PE too small

OR

hence a cold dense cloud will have low KE/high PE

OR

a cold dense cloud is more likely to exceed Jeans mass

OR

a hot diffuse cloud is less likely to exceed the Jeans mass

Accept $E_p + E_k < 0$

[2 marks]

2b. Explain how neutron capture can produce elements with an atomic number greater than iron. *[2 marks]*

Markscheme

Neutron capture creates heavier isotopes / heavier nuclei / more unstable nucleus

β^- decay of heavy elements/iron increases atomic number «by 1»

OWTTE

[2 marks]

3a. The Sun is a second generation star. Outline, with reference to the Jeans criterion (M_J), how the Sun is likely to have been formed. *[4 marks]*

Markscheme

interstellar gas/dust «from earlier supernova»

gravitational attraction between particles

if the mass is greater than the Jean's mass/M_j the interstellar gas coalesces

as gas collapses temperature increases leading to nuclear fusion

MP3 can be expressed in terms of potential and kinetic energy

---

3b. Suggest how fluctuations in the cosmic microwave background (CMB) radiation are linked to the observation that galaxies collide. *[3 marks]*

Markscheme

fluctuations in CMB due to differences in temperature/mass/density

during the inflationary period/epoch/early universe

leading to the formation of galaxies/stars/structures

gravitational interaction between galaxies can lead to collision

[Max 3 Marks]

3c. Show that the critical density of the universe is *[3 marks]*

$$\frac{3H^2}{8\pi G}$$

where H is the Hubble parameter and G is the gravitational constant.

Markscheme

ALTERNATIVE 1

kinetic energy of galaxy $\frac{1}{2}mv^2 = \frac{1}{2}mH^2r^2$ «uses Hubble's law»

potential energy = $\frac{GMm}{r} = G\frac{4}{3}\pi r^3\rho\frac{m}{r}$ «introduces density»

KE=PE to get expression for critical ρ

ALTERNATIVE 2

escape velocity of distant galaxy $v = \sqrt{\frac{2GM}{r}}$

where $H_0r = \sqrt{\frac{2GM}{r}}$

substitutes $M = \frac{4}{3}\pi r^3\rho$ to get result

4a. Outline, with reference to star formation, what is meant by the Jeans criterion. *[2 marks]*

Markscheme

a star will form out of a cloud of gas

when the gravitational potential energy of the cloud exceeds the total random kinetic energy of the particles of the cloud
OR
the mass exceeds a critical mass for a particular **radius and temperature**

[2 marks]

4b. In the proton–proton cycle, four hydrogen nuclei fuse to produce one nucleus of helium releasing a total of 4.3×10^{-12} J of energy. The Sun will spend 10^{10} years on the main sequence. It may be assumed that during this time the Sun maintains a constant luminosity of 3.8×10^{26} W. *[2 marks]*

Show that the total mass of hydrogen that is converted into helium while the Sun is on the main sequence is 2×10^{29} kg.

Markscheme

number of reactions is $\frac{10^{10} \times 365 \times 24 \times 3600 \times 3.8 \times 10^{26}}{4.3 \times 10^{-12}} = 2.79 \times 10^{55}$

H mass used is $2.79 \times 10^{55} \times 4 \times 1.67 \times 10^{-27} = 1.86 \times 10^{29}$ «kg»

[2 marks]

4c. Massive stars that have left the main sequence have a layered structure with different chemical elements in different layers. Discuss this structure by reference to the nuclear reactions taking place in such stars. *[2 marks]*

Markscheme

nuclear fusion reactions produce ever heavier elements depending on the mass of the star / temperature of the core

the elements / nuclear reactions arrange themselves in layers, heaviest at the core lightest in the envelope

[2 marks]

5a. Describe how some white dwarf stars become type Ia supernovae. *[3 marks]*

Markscheme

white dwarf must have companion «in binary system»

white dwarf gains material «from companion»

when dwarf reaches and exceeds the Chandrasekhar limit/1.4 M_{SUN} supernova can occur

5b. Hence, explain why a type Ia supernova is used as a standard candle. *[2 marks]*

Markscheme

a standard candle represents a «stellar object» with a known luminosity

this supernova occurs at an certain/known/exact mass so luminosity/energy released is also known

OWTTE

MP1 for indication of known luminosity, MP2 for any relevant supportive argument.

5c. Explain how the observation of type Ia supernovae led to the hypothesis that dark energy exists. *[3 marks]*

Markscheme

distant supernovae were dimmer/further away than expected

hence universe is accelerating

dark energy «is a hypothesis to» explain this

6a. State the Jeans criterion for star formation. *[2 marks]*

Markscheme

a gas cloud will collapse to form a star
if «the magnitude of» the gravitational potential energy of the particles is greater than the kinetic energy of the particles ***OR*** mass of the cloud is greater than the Jeans mass

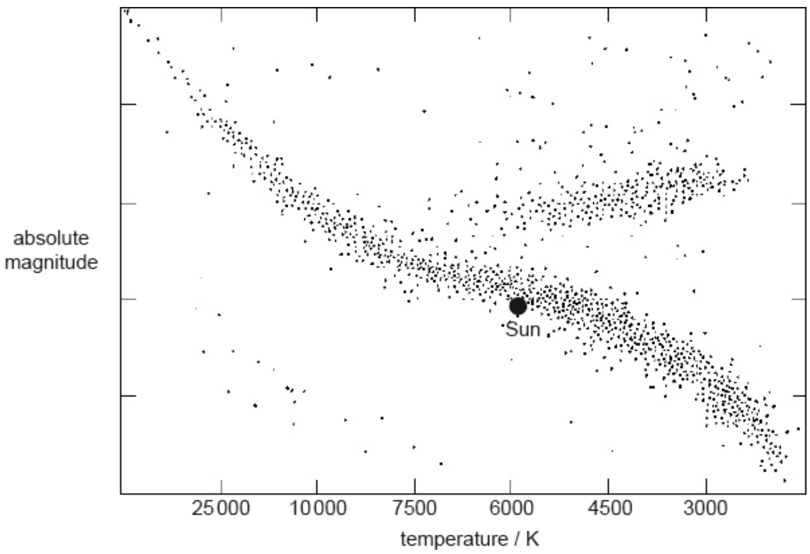
6b. Describe **three** differences between type Ia and type II supernovae. *[3 marks]*

Markscheme

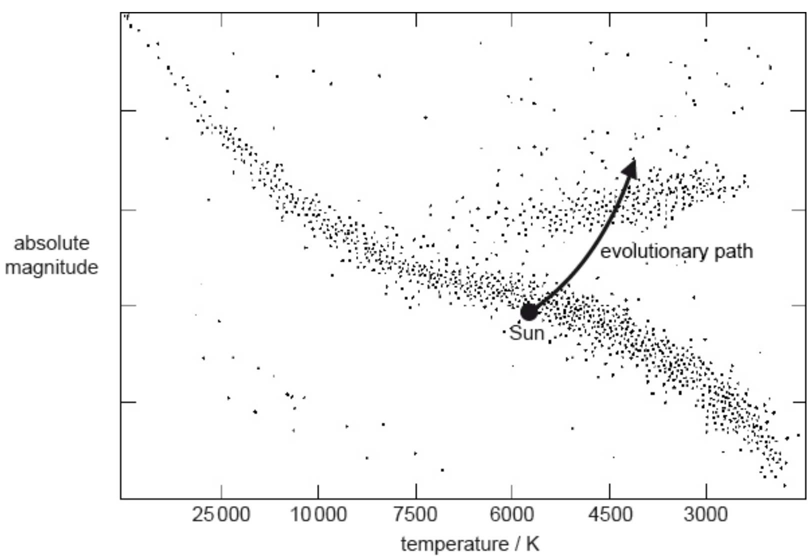
Ia have consistent maxima in their light curves but II vary
Ia has a strong ionized SiII line but II has hydrogen lines in their spectra
Ia was a white dwarf but II are massive stars
Ia form from binary systems but II are the result of core collapse of a star
Ia can be used as standard candles but II are not

This question is about the Hertzsprung–Russell (HR) diagram and the Sun.

A Hertzsprung–Russell (HR) diagram is shown.



The Sun will remain on the main sequence of the HR diagram for about another five billion years. After this time it will become a red giant, following the evolutionary path shown in the diagram.



7a. Outline why the Sun will leave the main sequence, and describe the nuclear processes that occur as it becomes a red giant. *[4 marks]*

Markscheme

insufficient hydrogen (to continue fusion);

star collapses (under gravity);

temperature increases;

initiated fusion of helium, (energy released causes) rapid expansion of star;

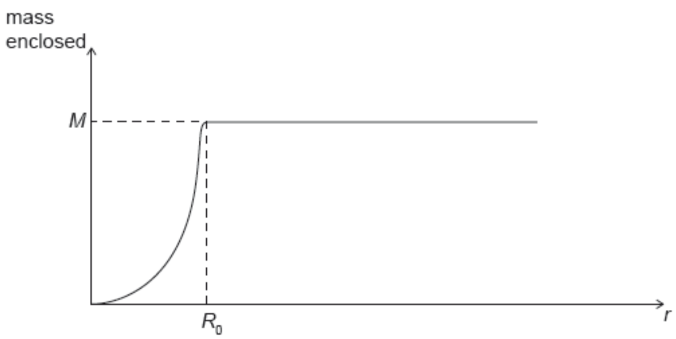
7b. Describe **two** physical changes that the Sun will undergo as it enters the red giant stage. *[2 marks]*

Markscheme

rapid expansion / increase of size;

decrease in temperature / cooler stars appear red in colour / increase of luminosity;

A galaxy can be modelled as a sphere of radius R_0. The distance of a star from the centre of the galaxy is *r*.



For this model the graph is a simplified representation of the variation with *r* of the mass of **visible matter** enclosed inside *r*.

8a. The mass of visible matter in the galaxy is *M*. *[1 mark]*

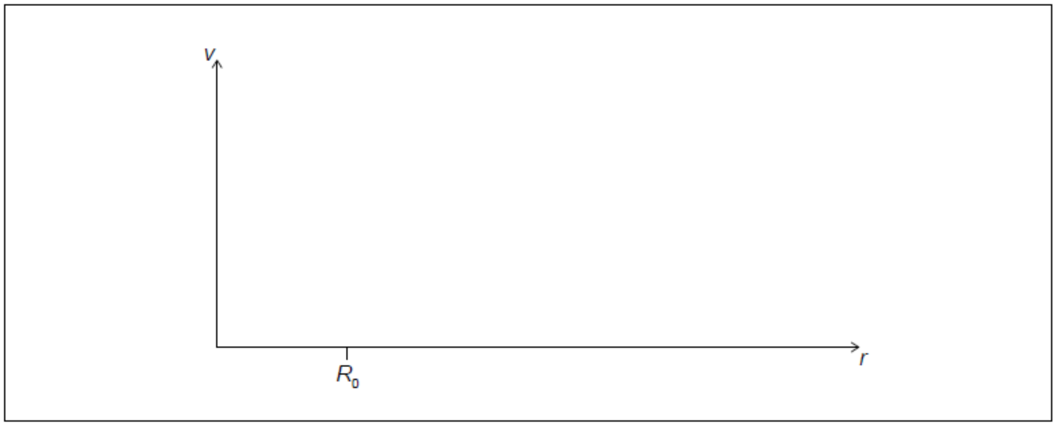
Show that for stars where $r > R_0$ the velocity of orbit is $v = \sqrt{\frac{GM}{r}}$.

Markscheme

$\frac{mv^2}{r} = \frac{GMm}{r^2}$ and correct rearranging

[1 mark]

8b. Draw on the axes the observed variation with *r* of the orbital speed *v* of stars in a galaxy. *[2 marks]*



Markscheme

linear / rising until R_0

then «almost» constant

[2 marks]

8c. Explain, using the equation in (a) and the graphs, why the presence of visible matter alone cannot account for the velocity of stars when $r > R_0$. *[2 marks]*

Markscheme

for *v* to stay constant for *r* greater than R_0, *M* has to be proportional to *r*

but this contradicts the information from the *M*-*r* graph

OR

if *M* is constant for *r* greater than R_0, then we would expect $v \propto r^{\frac{-1}{2}}$

but this contradicts the information from the *v*-*r* graph

[2 marks]

9a. Explain the evidence that indicates the location of dark matter in galaxies. *[3 marks]*

Markscheme

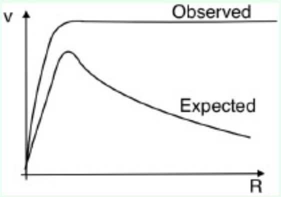
«rotational» velocity of stars are expected to decrease as distance from centre of galaxy increases

the observed velocity of outer stars is constant/greater than predicted

implying large mass on the edge «which is dark matter»

OWTTE

1st and 2nd marking points can be awarded from an annotated sketch with similar shape as the one below



[3 marks]

9b. Outline why a hypothesis of dark energy has been developed. *[3 marks]*

Markscheme

data from type 1a supernovae shows universe expanding at an accelerated rate

gravity was expected to slow down the expansion of the universe

OR

this did not fit the hypotheses at that time

dark energy counteracts/opposes gravity

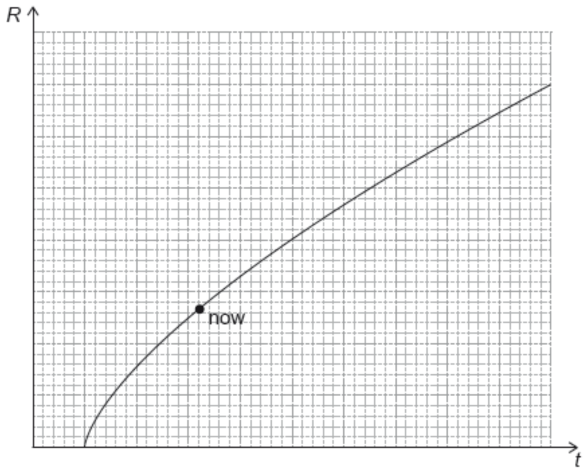
OR

dark energy causes the acceleration

OWTTE

[3 marks]

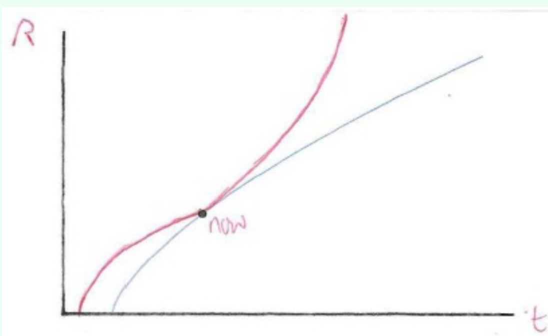
10a. The graph shows the variation with time t of the cosmic scale factor R in the flat model of the universe in which dark energy is ignored. *[1 mark]*



On the axes above draw a graph to show the variation of R with time, when dark energy is present.

Markscheme

curve starting earlier, touching at now and going off to infinity



[1 mark]

Recent evidence from the Planck observatory suggests that the matter density of the universe is $\rho_m = 0.32\ \rho_c$, where $\rho_c \approx 10^{-26}$ kg m^{-3} is the critical density.

10b. The density of the observable matter in the universe is only 0.05 ρ_c. Suggest how the remaining 0.27 ρ_c is accounted for. *[1 mark]*

Markscheme

there is dark matter that does not radiate / cannot be observed

Unexplained mention of "dark matter" is not sufficient for the mark.

[1 mark]

10c. The density of dark energy is $\rho_\Lambda c^2$ where $\rho_\Lambda = \rho_c - \rho_m$. Calculate the amount of dark energy in 1 m^3 of space. *[2 marks]*

Markscheme

$\rho_\Lambda = 0.68\rho_c = 0.68 \times 10^{-26}$ «kgm^{-3}»

energy in 1 m^3 is therefore $0.68 \times 10^{-26} \times 9 \times 10^{16} \approx 6 \times 10^{-10}$ «J»

[2 marks]

11a. Derive, using the concept of the cosmological origin of redshift, the relation *[2 marks]*

$T \propto \frac{1}{R}$

between the temperature T of the cosmic microwave background (CMB) radiation and the cosmic scale factor R.

Markscheme

the cosmological origin of redshift implies that the wavelength is proportional to the scale factor: $\lambda \propto R$

combining this with Wien's law $\lambda \propto \frac{1}{T}$

OR

use of $kT \propto \frac{hc}{\lambda}$

«gives the result»

Evidence of correct algebra is needed as relationship $T = \frac{k}{R}$ is given.

[2 marks]

11b. The present temperature of the CMB is 2.8 K. This radiation was emitted when the universe was smaller by a factor of 1100. Estimate the temperature of the CMB at the time of its emission. *[2 marks]*

Markscheme

use of $T \propto \frac{1}{R}$

= 2.8 x 1100 x 3080 ≈ 3100 «K»

[2 marks]

11c. State how the anisotropies in the CMB distribution are interpreted. *[1 mark]*

Markscheme

CMB anisotropies are related to fluctuations in density which are the cause for the formation of structures/nebulae/stars/galaxies

OWTTE

[1 mark]

12a. Describe what is meant by dark matter. *[2 marks]*

Markscheme

dark matter is invisible/cannot be seen directly
OR
does not interact with EM force/radiate light/reflect light

interacts with gravitational force
OR
accounts for galactic rotation curves
OR
accounts for some of the “missing” mass/energy of galaxies/the universe

OWTTE

[6 marks]

12b. The distribution of mass in a spherical system is such that the density ρ varies with distance r from the centre as *[1 mark]*

$\rho = \frac{k}{r^2}$

where k is a constant.

Show that the rotation curve of this system is described by

v = constant.

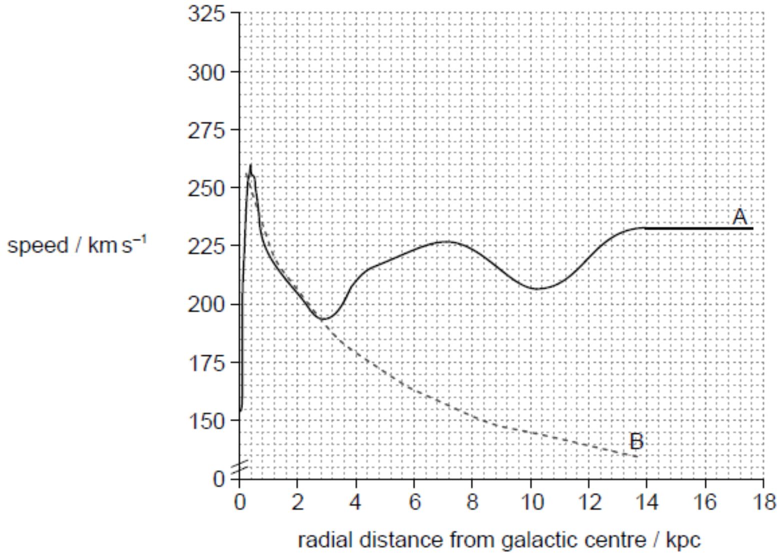
Markscheme

«from data booklet formula» $v = \sqrt{\frac{4\pi G\rho}{3}}r$ substitute to get $v = \sqrt{\frac{4\pi Gk}{3}}$

Substitution of ρ must be seen.

[1 mark]

12c. Curve A shows the actual rotation curve of a nearby galaxy. Curve B shows the predicted rotation curve based on the visible stars in the galaxy. *[2 marks]*



Explain how curve A provides evidence for dark matter.

Markscheme

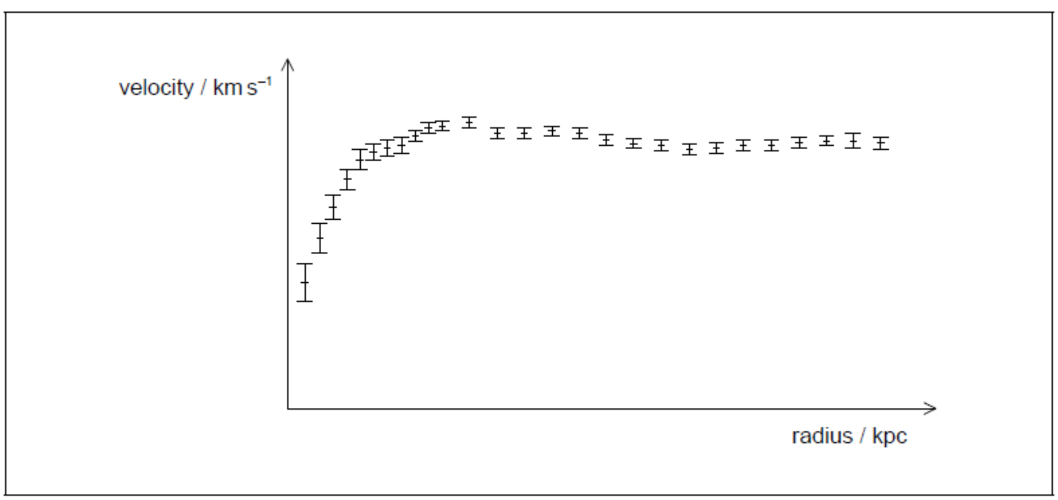
curve A shows that the outer regions of the galaxy are rotating faster than predicted

this suggests that there is more mass in the outer regions that is not visible
OR
more mass in the form of dark matter

OWTTE

[2 marks]

The graph shows the observed orbital velocities of stars in a galaxy against their distance from the centre of the galaxy. The core of the galaxy has a radius of 4.0 kpc.



13a. Calculate the rotation velocity of stars 4.0 kpc from the centre of the galaxy. The average density of the galaxy is 5.0×10^{-21} kg m^{-3}. *[2 marks]*

Markscheme

v = «$\sqrt{\frac{4\pi G\rho}{3}}r$» $= \sqrt{\frac{4}{3} \times \pi \times 6.67 \times 10^{-11} \times 5.0 \times 10^{-21}} \times \left(4000 \times 3.1 \times 10^{16}\right)$

v is about 146000 «m s^{-1}» ***or*** 146 «km s^{-1}»
Accept answer in the range of 140000 to 160000 «m s^{-1}».

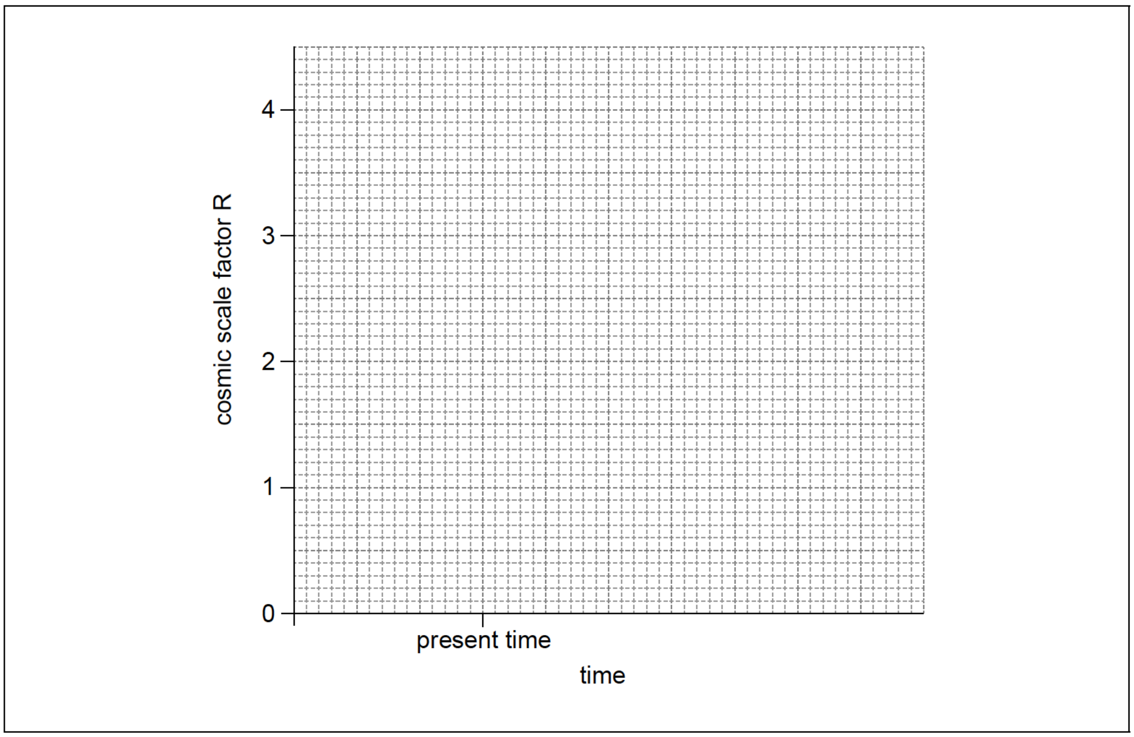
13b. Explain why the rotation curves are evidence for the existence of dark matter. *[2 marks]*

Markscheme

rotation curves/velocity of stars were expected to decrease outside core of galaxy

flat curve suggests existence of matter/mass that cannot be seen – now called dark matter

The Hot Big Bang model suggests several outcomes for the universe. There is now evidence that dark energy and dark matter exist.



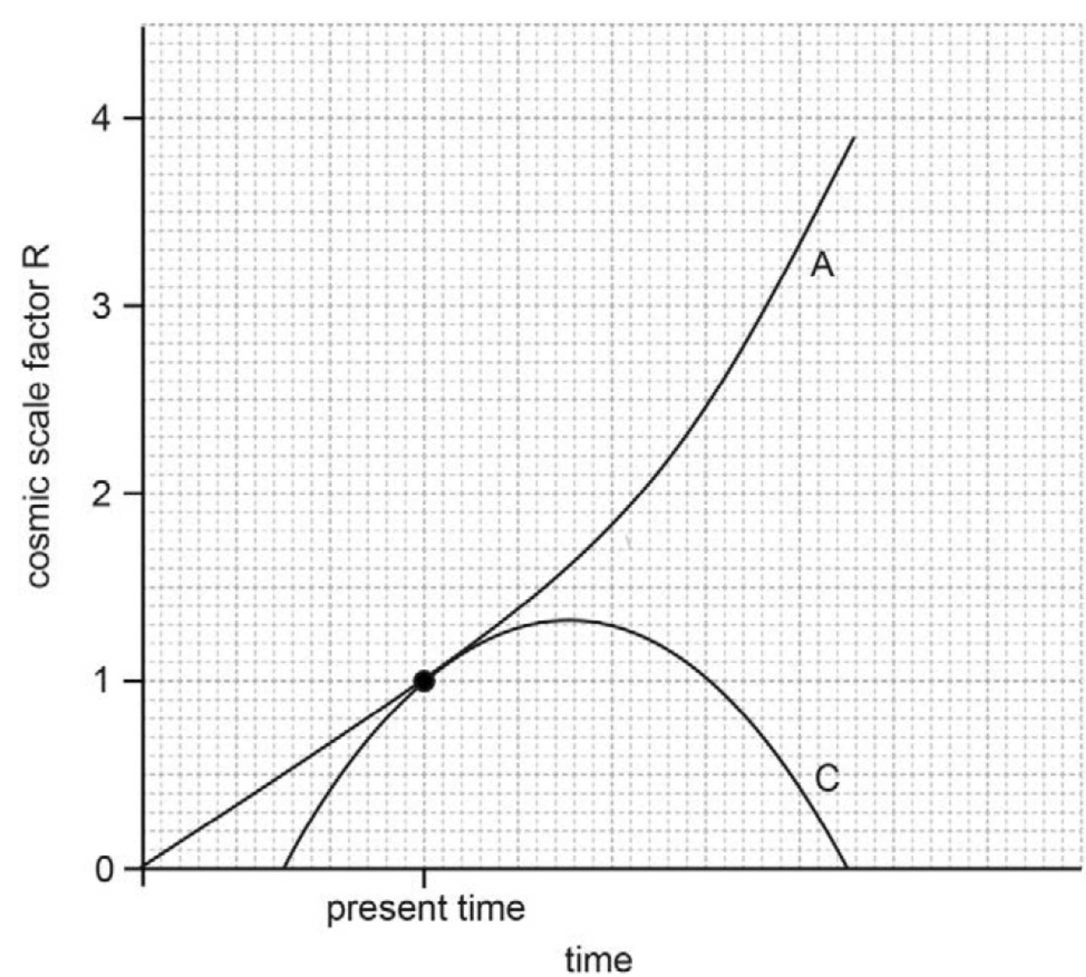
14a. On the axes, sketch a graph of the variation of cosmic scale factor with time for *[3 marks]*

(i) a closed universe without dark energy. Label this curve C.

(ii) an accelerating universe with dark energy. Label this curve A.

Markscheme

(i) curve beginning on R=0 before present time and ending after present time on R=0



(ii) curve starting earlier than C with general shape shown above
coincides with curve C at present time
Judge by eye.

14b. Explain **one** experimental observation that supports the presence of dark **matter**. *[2 marks]*

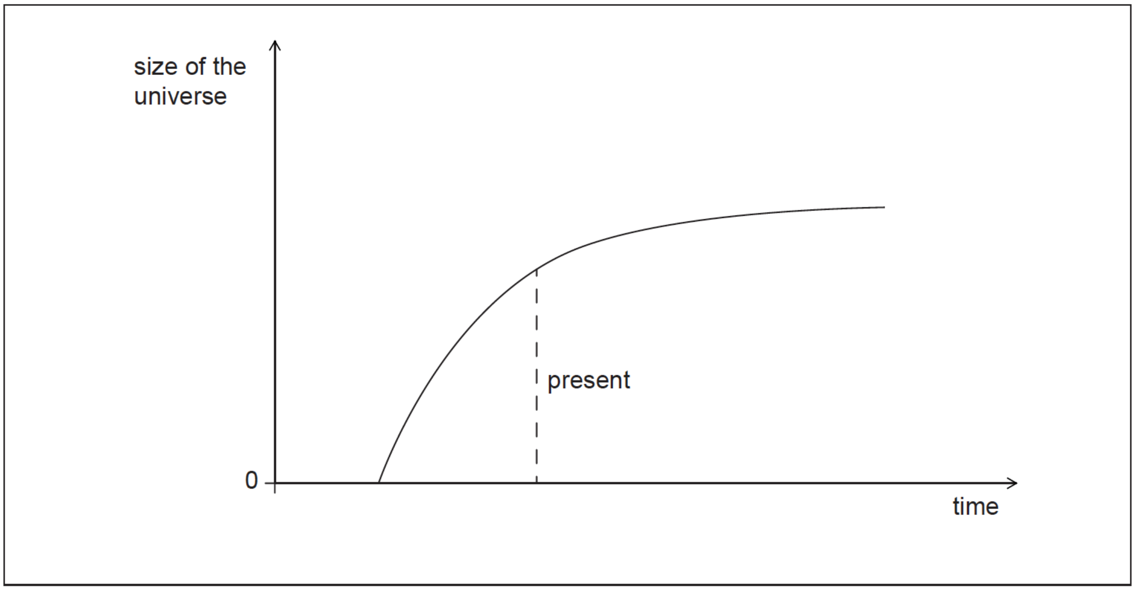
Markscheme

rotation speeds of galaxies is greater at the edges than expected
so the density at the edges must be greater than that supplied by luminous matter alone

Accept any other valid piece of evidence, eg gravitational lensing, which provides a good measure of galactic cluster masses.

This question is about the development of the universe.

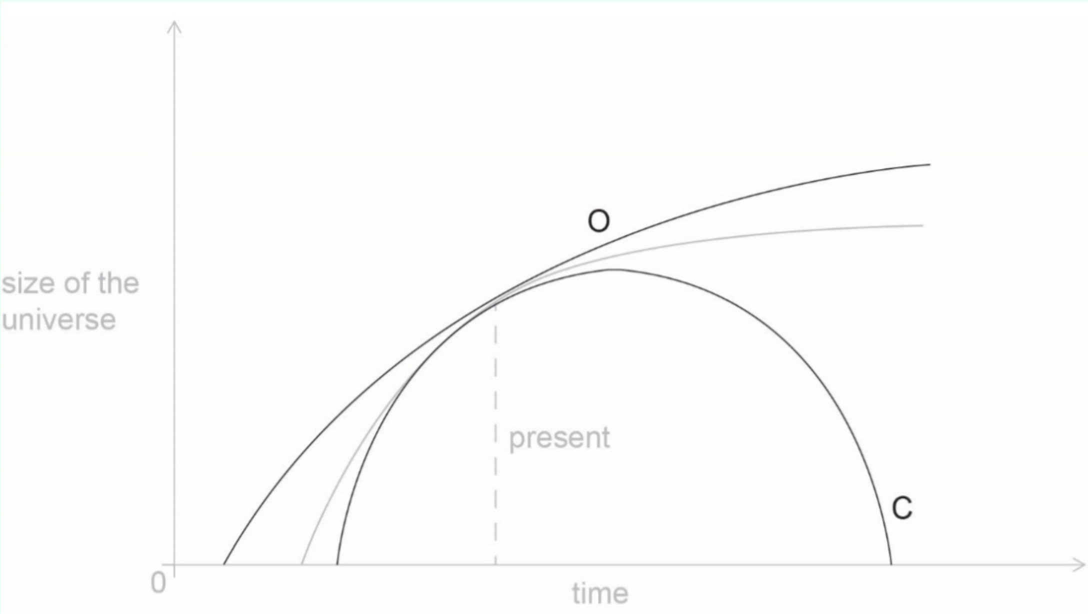
The graph shows one possible way in which the universe is thought to change with time. This type of universe is known as a fl at universe.



15a. On the graph, draw lines to show the variation with time of the size of the universe for both a closed universe and an open universe. Label your line for the closed universe C and your line for the open universe O. *[2 marks]*

Markscheme

after present, open universe curve drawn above flat curve **and** closed universe curve drawn under flat curve; *(both needed for mark)*
all meet at “present time”;*Ignore curves before present time.*



15b. Explain how the open and closed outcomes for the universe depend on the critical density of matter in the universe. *[3 marks]*

Markscheme

if density less than critical density/too low the universe will expand forever;
if greater than critical density the universe contracts;
after an initial expansion;*If critical density not mentioned award* ***[1 max]****.*

15c. State **one** reason why it is difficult to determine the density of the universe. *[1 mark]*

Markscheme

presence of dark matter / WIMPS / MACHOS *etc*;

This question is about cosmology.

16a. Theoretical studies indicate that the universe may be open, closed or flat. *[4 marks]*

(i) State, by reference to critical density, the condition that must be satisfied for the universe to be flat.

(ii) In a flat universe, the rate of expansion would be slowing down. Suggest a reason for this.

(iii) Outline why it has been difficult to determine whether the universe is open, closed or flat.

Markscheme

(i) a universe whose density is equal to the critical density;

(ii) the mutual gravitational attraction would slow the expansion down;

(iii) the density of the universe needs to be determined;
this involves many uncertainties related to measurement of distances/volume;
this involves many uncertainties related to presence of dark matter;

16b. Outline **one** piece of experimental evidence that supports the fact that the universe is expanding. *[2 marks]*

Markscheme

light from galaxies is observed to be red-shifted/to have a longer wavelength than that emitted;
indicating that the distance between galaxies is getting bigger/galaxies move away from each other/from us;
*Award **[1 max]** if galaxies are not mentioned.*

or

the presence of the cosmic microwave background radiation;
is evidence of cooling of the universe/increase in wavelength/red-shift due to expansion;

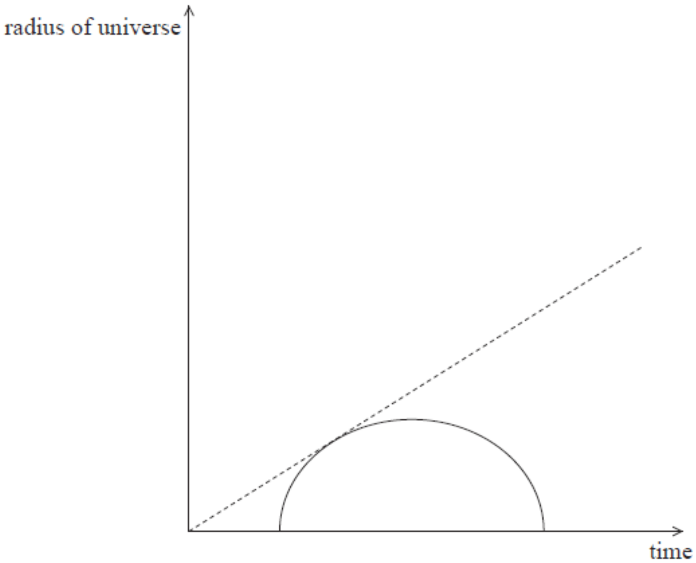
This question is about the development of the universe.

17a. Define, with reference to the flat model of the universe, *critical density*. *[2 marks]*

Markscheme

critical density is the density for which the universe stops expanding;
after an infinite amount of time;

17b. The diagram represents how the universe might develop if its density were greater than the critical density. *[3 marks]*



The dotted line represents the development of the universe if the density of the universe were zero.

On the diagram above,

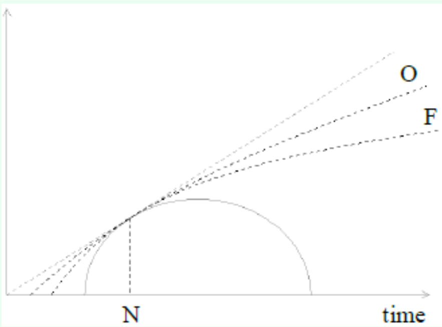
(i) label with the letter N the present time.

(ii) draw a line labelled F to represent the development of the universe corresponding to a flat universe.

(iii) draw a line labelled O to represent the development of the universe corresponding to the universe if its density were less than the critical density.

Markscheme

radius of the universe



(i) the time corresponding to where the two lines touch; { *(labelled N on the time axis or the graph)*

(ii) a slightly curved line between the dotted line and the closed universe line;
(*labelled F*)

(iii) a slightly curved line between the dotted line and the flat universe line;
(*labelled O*)

Allow an accelerating universe graph labelled either F or O.

This question is about the development of the universe.

18a. Light from distant galaxies, as seen by an observer on Earth, shows a red-shift. Outline why this observation suggests that the universe is expanding. *[2 marks]*

Markscheme

because of the Doppler effect;
light from sources moving away from an observer is observed to have a lower frequency than from the sources when stationary / redshift indicates motion away from observer/Earth;

18b. The future development of the universe is determined by the relationship between the apparent density of the universe and the critical density. *[5 marks]*

(i) Define the term *critical density*.

(ii) Discuss how the density of the universe determines its future development. Your discussion should include **one** problem associated with determining the density of the universe.

Markscheme

(i) this is the value of density for which the universe will begin to contract after an infinite amount of time;
Do not accept "density at which universe is flat".

(ii) if the density of the universe is less than the critical density it will continue expanding forever;
if the density is greater than the critical density then it will after a certain amount of time begin to contract;
the behaviour of galaxies suggests that there is more matter in the universe than is actually observed; { *(allow other relevant comment about dark matter)*
without knowing the mass of this matter the density cannot be determined;

This question is about the density of the universe.

19a. Explain, with reference to the possible fate of the universe, the significance of the critical density of matter in the universe. *[3 marks]*

Markscheme

if less than critical density, universe expands without limit;
if equal to critical density universe stops expanding after an infinite amount of time;
if greater than critical density, universe expands first then contracts;
*Award **[1 max]** if terms open, flat and closed are used and not defined.*

19b. Suggest **one** reason why it is difficult to estimate the density of matter in the universe. *[2 marks]*

Markscheme

there is matter that cannot be detected;
which is likely to consist of dark matter/neutrinos;

or

difficulty of measuring volume accurately;
because of difficulty of measuring distances accurately;

or

matter is not evenly distributed;
so density may vary from place to place;