Cosmology

Q1.

(a) Describe the links between galaxies, black holes and quasars.

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____

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(2)

(b) At a distance of 5.81×10^8 light year, Markarian-231 is the closest known quasar to the Earth. The red shift z of Markarian-231 is 0.0415

Use these data to estimate an age, in seconds, of the Universe.

age = ____________________ s

(4)

(c) A typical quasar is believed to be approximately the size of the solar system, with a power output similar to that of a thousand galaxies.

Estimate, with reference to the inverse-square law, how much further the most distant visible quasar is likely to be compared to the most distant visible galaxy.

(3)
(Total 9 marks)

Q2.

Evidence to support the Big Bang theory comes from cosmological microwave background radiation and the relative abundance of hydrogen and helium in the Universe.

(a) Explain what is meant by cosmological microwave background radiation and how its existence supports the Big Bang theory.

(3)

(b) Explain how the relative abundance of hydrogen and helium supports the Big Bang theory.

(3)
(Total 6 marks)

Q3.

According to NASA nearly 2000 exoplanets had been discovered by 2016, and the search continues. One aim of this search is to find an Earth-like planet orbiting a Sun-like star.

Discuss the difficulties associated with the detection of an Earth-like planet orbiting a Sun-like star.

In your answer you should compare the methods that are used in the search and suggest which may be the most successful.

(Total 6 marks)

Q4.

Two methods involved in the detection of exoplanets are the radial velocity method and the transit method.

(a) Explain what is meant by the transit method of detection.

(3)

(b) Explain why it is important that there is more than one method of detection.

(2)
(Total 5 marks)

Q7.

(a) State which property of the first identified quasar led to its discovery.

(1)

(b) 3C48 is a quasar in the constellation Triangulum. It is believed to have a power output 4×10^{11} times greater than that of the Sun. At the Earth, the Sun's intensity is 1.4×10^{17} times greater than that of the quasar.

(i) Calculate, using the inverse square law, the distance from Earth to this quasar in AU.

distance = ____________________ AU

(3)

(ii) Measurements of the red shift of the quasar suggest the expansion of the Universe has accelerated since the detected light left the quasar.
State the cause of this acceleration.

____

(1)

(Total 5 marks)

Q8.

NGC 3842 is a galaxy which contains one of the biggest black holes ever discovered.

(a) State what is meant by a black hole.

____

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____

(1)

(b) The mass of the black hole in NGC 3842 is believed to be 1.0×10^{10} times greater than that of the Sun.

Calculate the radius of its event horizon.

radius = ____________________ m

(2)

(c) NGC 3842 is 3.3×10^{8} light years from the Earth, and is receding at a velocity of 6.3×10^{6} m s^{-1}.

Estimate, using these data, an age in seconds for the Universe.

age of Universe = ____________________ s

(3)

(Total 6 marks)

Q9.

(a) State what is meant by the Hubble constant.

____

____

(1)

(b) The recessional velocity of a galaxy 8.0×10^8 ly from Earth is measured to be 1.8×10^4 km s^{-1}.

Show that this suggests a value for the Hubble constant of 73 km s^{-1} Mpc^{-1}.

(2)

(c) (i) Using the value for the Hubble constant given in part (b), estimate the age of the Universe.
Give your answer in years.

age of the Universe ______________________ years

(3)

(ii) State **one** assumption that must be made to justify the estimate made in part (i).

____

____

(1)

(Total 7 marks)

Q1.

(a) Quasars are produced by (supermassive) black holes. ✓

These black holes are at the centre of (active) galaxies (active galactic nuclei.) ✓

2

(b) Using v = cz gives

$v = 3 \times 10^8 \times 0.0415$ ✓ $= 1.25 \times 10^7 = 1.25 \times 10^4$ kms^{-1}

Using 1pc = 3.26 lyr

$d = 5.81 \times 10^8$ lyr $= 5.81 \times 10^8/3.26$ ✓ $= 1.78 \times 10^8$ pc

$= 1.78 \times 10^2$ Mpc ($= 5.5 \times 10^{24}$ m)

Using v = Hd

($H = v/d = 1.25 \times 10^4/1.78 \times 10^2 = 70$ kms^{-1} Mpc^{-1})

Age of Universe = 1/H = d/v ✓

$= 5.81 \times 10^8 \times 9.47 \times 10^{15}/1.25 \times 10^7 = 4.42 \times 10^{17}$ s ✓

The first mark is for use of zc.

The second mark is for a calculation of d.

The third mark is for using the idea that the age of the Universe is 1/H.

The fourth mark is for the answer.

Allow own H for 3rd and 4th marks.

4

(c) Both quasar and galaxy should have same brightness (and therefore similar received power) ✓

Use of Inverse square law eg

Power of quasar/(distance to quasar)^2 = power of galaxy / (distance to galaxy)^2 ✓

Or $1000/d^2 = 1/1$

So distance to quasar = $(1000)^{½}$ = about 30 times greater than distance to galaxy ✓

The first mark is for relating the similar "brightness". Accept intensity. Accept in form of equation linking quasar and galaxy.

The second mark is for applying the inverse square law. Simply quoting it does not get this mark.

The final mark is for coming to a valid conclusion related to the distance to the quasar compared to the distance to the galaxy.

Do not accept answers involving square roots.

These are standalone marks.

1
2

[9]

Q2.

(a) It is the radiation coming from all parts of the Universe ✓

When the Universe cooled sufficiently for matter and radiation to 'decouple', with the combination of protons and electrons to form neutral atoms ✓

This radiation has been red-shifted into the microwave region as the Universe has expanded ✓

OR

This is (em) radiation from all parts of the Universe, ✓

the spectrum has a peak in the microwave region / corresponds to a temperature of 2.7 K ✓

It can be interpreted as the radiation left over from the Big Bang / the photons having been stretched to longer wavelengths and lower energies ✓

One mark is for stating that CMBR comes from all parts of Universe.

Accept Isotropic.

Condone homogeneous.

Condone same at all points in universe.

Another is for referencing the idea that the radiation has a peak in the microwave region.

The third is for linking it to the Big Bang theory.

Condone "left over heat from Big Bang".

3

(b) (The Big Bang theory suggests that a very brief period of) fusion occurred (when the Universe was very young), resulting in the production of helium from fusing hydrogen. ✓

Fusion stopped as the Universe then expanded and cooled ✓

Resulting in a relative abundance of hydrogen and helium in the ratio of 3:1/ cooled too rapidly for the creation of larger nuclei,

Or suitable relevant observation ✓

One mark is for linking helium production to fusion in the early Universe. This mark can also be awarded for description of proton and neutron creation/ 7:1 ratio

3

[6]

Q3.

The mark scheme gives some guidance as to what statements are expected to be seen in 1 or 2 mark (L1), or 3 or 4 mark (L2) and 5 or 6 mark (L3) answer. Guidance provided in section 3.10 of the 'Mark Scheme Instructions' document should be used to assist in marking this question.

<table>
<tr><th>Mark</th><th>Criteria</th><th>QoWC</th></tr>
<tr><td>6</td><td>All three methods described.

All three methods applied to Earth-like planets.

Judgement reached.</td><td rowspan="2">The student presents relevant information coherently, employing structure, style and spg to render meaning clear. The text is legible.</td></tr>
<tr><td>5</td><td>Only two methods described and all three applied,

Or

All three described and only two applied.</td></tr>
<tr><td>4</td><td>Two methods described and applied,

Or three described and only one applied.</td><td rowspan="2">The student presents relevant information and in a way which assists the communication of meaning. The text is legible. SPG are sufficiently accurate not to obscure meaning.</td></tr>
<tr><td>3</td><td>Three methods described,

Or

Two methods described and one applied.</td></tr>
<tr><td>2</td><td>Only one method described and applied

Or two methods described with application.</td><td rowspan="2">The student presents some relevant information in a simple form. The text is usually legible. SPG allows meaning to be derived although errors are sometimes obstructive.</td></tr>
<tr><td>1</td><td>Only one method described.</td></tr>
<tr><td>0</td><td>No relevant information.</td><td>The student's presentation, SPG seriously obstruct understanding.</td></tr>
</table>

Higher Level (5 or 6 marks)

All three methods of measurement are described (transit, radial and direct observation)

Problems associated with each one are discussed, with particular reference to detecting an object an Earth-like planet.

Intermediate Level (3 or 4 marks)

Only two of the three methods are described and little effort is made to link the methods to the detection of an Earth-like planet.

Low level (1 or 2 marks)

Only one method is described, or two methods poorly.

Little or no reference is made to the detection of an Earth-like planet.

(a more detailed mark scheme will be produced with levelled statements)

Transit *– dips in brightness as planet crosses in front of star from our point of view.*

Alignment must be correct for planets to eclipse, so many possible candidates not observed. Earth-like planet could be observed provided not too far away.

Radial velocity *(Doppler) – periodic shift in spectra of star due to star's movement around common centre of mass with planet.*

Earth-like planet mass much less than mass of Sun-like star so effect slight. Earth-like planet could be detected with highly sensitive spectrometers.

Direct observation *– very unlikely as Earth-like planet to small and too near star and too cool to be detected against the brightness of the Sun-like star. Unlikely to be detected.*

[6]

Q4.

(a) Apparent magnitude of star is measured over a long period of time ✓

When planet passes in front of star (as seen from Earth), some of the light from star is absorbed and therefore the amount of light reaching Earth reduced ✓

This produces a light curve showing constant value with a dip periodically as the planet passes in front of the star ✓

3

(b) Dip in light curve can be caused by other effects ✓

Except for planets very close to star, periods likely to be very long and may take many years of observation using transit method alone ✓

2

[5]

Q7.

(a) The quasar is a <u>bright</u> radio source. ✓

Allow strong / intense / powerful for bright.

Ignore reference to pulses

Other incorrect properties, eg red shift, loses the mark.

1

(b) (i) Using $I = I_0/d^2$ with some evidence of substitution ✓

$P_q = 4 \times 10^{11} P_s$

$I_s = 1.4 \times 10^{17} I_q$ at Earth

$P_s/1^2 = 1.4 \times 10^{17} (4 \times 10^{11} P_s/d^2)$ ✓

$d^2 = 4 \times 10^{11} \times 1.4 \times 10^{17}$

$=5.6 \times 10^{28}$

$d = 2.4 \times 10^{14}$ AU ✓

The first mark is for some evidence of using the inverse square law. Do not condone equation the wrong way up.

The second is for an attempt to compare the two stars using the inverse square law.

The third is for the final answer.

3

(ii) Dark energy

Evidence of hedging bets eg dark energy / dark matter etc. loses the mark

1

[5]

Q8.

(a) an object with an escape velocity greater than the speed of light ✓

Ignore references to singularity and density etc.

Allow gravity so strong light cannot escape.

1

(b) mass of black hole = $1 \times 10^{10} \times 1.99 \times 10^{30} = 2 \times 10^{40}$ kg ✓

M correct for the first mark

Use of

$R = 2GM / c^2$

$= 2 \times 6.67 \times 10^{-11} \times 2 \times 10^{40} / (3.00 \times 10^8)^2$

$= 3 \times 10^{13}$ m ✓ allow 2.9 or 2.95 etc.

Final answer correct for the second mark.

Allow ce for the mass.

No sf penalty.

2

(c) V= Hd

v (in kms^{-1}) = 6300

D (in MPc) = $3.3 \times 10^8 / 3.26 \times 10^6$

= 101 ✓

H = v / d = 6300 / 101 = 62 kms^{-1} Mpc^{-1} ✓

Alternatively.

Age of universe = 1 / H

= D / v

= $3.3 \times 10^8 \times 9.47 \times 10^{15}$✓/ 6.3×10^6 ✓

= 5.0×10^{17} s ✓

age of Universe = 1 / H

= 1 / 62

= 1.6×10^{-2} Mpc s km^{-1}

= $1.6 \times 10^{-2} \times 3.1 \times 10^{16} \times 10^6 / 10^3$

= 5.0×10^{17} s ✓

The first mark is for calculating D, the second for substituting correctly to find H

The third is for determining 1 / H in seconds.

If other value of H used, 1 mark max.

3

[6]

Q9.

(a) Gives the ratio of the (recessional) velocity (of galaxies) to distance from Earth

Accept equation with terms defined

not

v depends on d,

the relationship between them, shows the relationship between them

B1

1

(b) *d* changed to Mpc (2.45×10^2)

or 1.8×10^4 / their attempt to convert distance

Or d change to m and v to m s^{-1}

B1

(*H*=) 73.35 or 73.47 seen to at least 3 sf

B1

2

(c) (i) *T* = 1 / *H* or *H* = 2.4×10^{-18} s seen

e.g. 3.08×10^{-19} / 73

C1

Value in s calculated (4.2×10^{17})

A1

Correct conversion to years 1.3×10^{10}

Allow their value in s

B1
3

(ii) Universe is expanding at constant / steady <u>rate</u>

B1
1

[7]

Q1.

This question tested the students' knowledge of Hubble's Law and the inverse-square law in the context of quasars and galaxies.

(a) Many answers to this question focused on simple properties of the three objects rather than the relationship between them. Some students, who did see what was required, suggested incorrectly that quasars are black holes, or that galaxies orbit a black hole in a similar way to planets orbiting stars, perhaps. Only 18.2% of students gained both marks here.

(b) This calculation was carried out correctly by the majority of students (54.8%). Those who failed to achieve full marks often tried to work backwards from a 'known' age of the universe, or used the Hubble constant available in the data booklet. Most correctly calculated a value for the speed and distance and either directly determined a time or calculated a value for H and determined 1/H in seconds.

(c) The use of the inverse-square law proved to be significantly more demanding. There was evidence of students obtaining the square root of 1000 as an answer and then missing a mark by leaving it in this form. Answers of 10, 100 or even 1 000 000 were also relatively common. It was clear that many students knew the inverse-square law but were not sure how to apply it. The important point is that the intensity received at the Earth is the same for the two objects, but that was rarely stated. Only 12.1% of students gained all three marks; the proportion that failed to gain even a single mark was 48.5%.

Q2.

This question addressed the general practicalities of making measurements (which was conspicuously poorly-answered in 2017) and use of log graphs to discover power laws.

(a) Two approaches were seen for obtaining the vertical distance y. The indirect approach involved measuring the height of the tape (from the floor) at the free end and subtracting this from the height of the bench. The two measurements involved required the use of a vertical ruler and how this was to be achieved was widely ignored. Examiners were looking for the use of a set-square in contact with the ruler and the floor to make the ruler vertical, a detail that could easily be provided if the students added detail to Figure 7 as was suggested. That so few chose to follow this advice explains why barely 10% were able to score both marks. Another suggested method employed a horizontal reference, established by laying a straight edge along the bench to overhang the free end of the tape. A ruler (made vertical with a set-square) could then measure y directly. Those students taking this route were more prepared to add detail to the diagram, but often showed the straight edge failing to reach the bench or omitted detail involving the set-square. Other approaches, where safe and relevant, could earn credit, such as the use of a plumb line or spirit level. Those who suggested using bits of string, lasers or trigonometry did not gain credit. Disappointingly, nearly half of the students failed to gain any credit for their answer.

(b) Many students identified that y would become very small if x was less than 70 cm but barely 10% correctly stated that this made the percentage uncertainty in y unacceptably high.

(c) All of the marking points discriminated well but not always in combination, so only

10.2% of students scored all three marks. The line quality was usually good, but examiners expected the line to pass above the first and below the sixth points: a surprising number of students drew their line passing through or below the first point. The result of the gradient calculation usually fell within the expected range, but those who truncated it (usually to 4) were penalised. In addition, those who copied their gradient result onto the answer line for n failed to recognise that an integer was expected, so they too failed to score.

(d) About half of the students correctly stated that log A was the (log) y-intercept and many then correctly explained how, having obtained the intercept, they could calculate A. A few spoiled their answer by using base 10 for the first point and base e for the latter, and others, anticipating 02.5, stated that they would use data from Table 2. With a three-mark tariff, it was surprising how few students provided detail of how the intercept could be calculated indirectly, a comparatively easy process to describe if done carefully. Over a third of students scored two marks, but very few (4.3%) scored all three.

(e) The work seen here was sometimes very good and two-thirds of students could at least produce a suitable value for A. The problem for many was identifying the order of magnitude (most simply copied their result for A onto the answer line). To a lesser extent, many struggled to identify the unit, particularly when a non-integer was given for n. For a typical value of A, using the top row in Table 2, a result of 1.99×10^{-7} was routinely obtained. Examiners accepted -7 or 10^{-7} for the order of magnitude and cm^{-3} for the unit. A non-integer n such as 3.3 would produce $A = 6.09 \times 10^{-6}$ so the order of magnitude is -5 and the unit $cm^{-2.3}$. As with question 02.4, all the marking points were accessible, but it was unusual to see all scored together; just less than 10% gained full credit.

Q3.

This question was related to another aspect of current astronomical research: the search for planets orbiting other stars. Most students were able to recall the transit and radial velocity methods of detection, without making much more progress. More success was made by those that mentioned problems of direct observation. Very few students related any of these methods to the particular situation of an Earth-like planet orbiting a Sun-like star or made any attempt to discuss which method would be most successful in this situation. The most successful students were able to point out that most of the planets discovered so far have been so-called ‘hot Jupiters’ and that the Earth, being relatively small and far from the Sun, would make little impact on the apparent magnitude of the Sun, or affect its motion significantly.

Q7.

(a) There were several recall questions on this paper. Despite this being explicit on the specification relatively few students knew the property that led to the discovery of the first quasar.

(b) The inverse square law is a useful idea in many different branches of physics. It was clear, however, that few students had had little practice in its use with questions of this kind. The best answers often started from first principles, using the equation for the surface of a sphere, which was given full credit. Far too often answers were seen that made very little or no progress.

(c) It was expected that many students would be able to give the correct answer for this but some lost the mark by stating two answers, or demonstrated some confusion by simply writing “the big bang”.

Q8.

On this specification, the defining property of a black hole is that it has an escape velocity greater than the speed of light. References to singularities were ignored.

The calculation of the radius of the event horizon was the most accessible question on the paper, with 84% of students getting both marks.

The calculation of the age of the Universe caused more problems for some students. Many gained full marks by simply converting the distance into metres and dividing it by the speed, removing the need to calculate Hubble's constant and convert the units into seconds.

Q9.

(a) Only small minority were able to express what is meant by the Hubble constant clearly. Most gave vague answers such as that it gives the relationship between velocity and distance of galaxies.

(b) Here the first requirement was to show the change the distance from ly to Mpc. Those who could do this usually managed the next step without difficulty.

(c) (i) There were many who were unable to make any progress with this calculation. Some clearly had a number for the age of the Universe ($\approx 10^{10}$y) in mind and made an incomprehensible series of calculations to arrive at that number. Converting between units was a problem for many.

(ii) Relatively few candidates gave an acceptable response to this part.