Cosmology
Distinction Course
Modules 4, 5, 6 and 7 (including Residential 2)

General Instructions
• Reading time – 5 minutes
• Working time – 2 hours
• Write using black or blue pen
• Board-approved calculators may be used
• A data sheet is provided at the back of this paper

Total marks – 120

Section I Page 3
20 marks
• Attempt FIVE questions from Questions 1–7
• Allow about 20 minutes for this section

Section II Pages 4–5
40 marks
• Attempt FOUR questions from Questions 8–13
• Allow about 40 minutes for this section

Section III Page 6
60 marks
• Attempt Questions 14–15
• Allow about 60 minutes for this section
Section I

20 marks
Attempt FIVE questions from Questions 1–7
Allow about 20 minutes for this section

Answer each question in the writing booklet provided. Extra writing booklets are available.

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Question 1 (4 marks)
Define and explain the Principle of Equivalence used in General Relativity.

Question 2 (4 marks)
Explain how a universe can be finite but unbounded.

Question 3 (4 marks)
Give a brief explanation of how gravity affects clocks and time. Give one practical example of the effect.

Question 4 (4 marks)
Heinrich Olbers’ paradox says that any line of sight should end in a star. Why is the night sky dark?

Question 5 (4 marks)
Describe the essential difference between the futures of universes that have Euclidean space and universes that have spherical space.

Question 6 (4 marks)
Contrast the concepts of simultaneous events as understood by Newton and Einstein.

Question 7 (4 marks)
The density parameter $\Omega$ is now thought to be less than 1.0. Explain the significance of this experimental result.
Section II

40 marks
Attempt FOUR questions from Questions 8–13
Allow about 40 minutes for this section

Answer each question in the writing booklet provided. Extra writing booklets are available.

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**Question 8** (10 marks)

What is meant by the Hubble period in cosmology? Calculate the Hubble period for the ‘most likely’ Hubble constant $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

**Question 9** (10 marks)

Define *redshift* as used in astronomy. Show clearly, using a space/time diagram, what is meant by the lookback time to a quasar of redshift 5.0.

**Question 10** (10 marks)

Compare and contrast the cosmological models used to describe the nineteenth century Newtonian universe and the variety of universes outlined in 1922–1927 by Alexander Friedmann and Georges Lemaitre.
Question 11 (10 marks)

The graph shows the optical spectrum from a typical quasar with redshift 4.15.

(a) Describe the likely origin of the emission feature at wavelength 626 nm.

(b) What information about the Universe may be gained from the spectral features between 550 and 610 nm called the Lyman alpha forest?

Question 12 (10 marks)

The Hydra Cluster, at a distance of 1200 Mpc, consists of several hundred galaxies moving within the cluster at speeds that are typically 700 km s\(^{-1}\) (the velocity dispersion of the cluster).

(a) Calculate the redshift to the cluster, using a Hubble constant of 75 km s\(^{-1}\) Mpc\(^{-1}\).

(b) Calculate the additional red or blue shift caused by the Doppler effect.

Question 13 (10 marks)

Briefly describe one key experiment since COBE (a recent, current or planned mission) to study the cosmic microwave background (CMB). Explain what additional information about the CMB is expected from your chosen mission.

Please turn over
Section III

60 marks
Attempt Questions 14–15
Allow about 60 minutes for this section

Answer each question in the writing booklet provided. Extra writing booklets are available.

Question 14 (30 marks)

Douglas Adams wrote in The Hitch Hiker’s Guide to the Galaxy ‘Space is big. Really big’. Describe the experimental methods for measuring the Distance Scale of the Universe. Discuss our present knowledge of this scale for both the local and the distant Universe. Describe the limits to which we may observe.

Question 15 (30 marks)

Explain how the Theory of General Relativity predicts the effects of gravitational lensing. Describe some of these effects and discuss what information about the Universe is provided by our observations of lensing effects.

End of paper
Recommended values

Abstracted from the consistent set of constants in CODATA Bull. No. 63 (1986) by the Royal Society, the Institute of Physics, and the Royal Society of Chemistry.

The number in parenthesis after each value is the estimated uncertainty (standard deviation) of the last digit quoted.

speed of light in a vacuum \( c \)
\[
2.997\,924\,58 \times 10^8\ \text{m s}^{-1} \text{ (exact)}
\]

permeability of a vacuum \( \mu_0 \)
\[
4\pi \times 10^{-7}\ \text{H m}^{-1}
\]

permittivity of a vacuum, \( \left[ \mu_0 c^2 \right]^{-1} \) \( \varepsilon_0 \)
\[
8.854\,187\,817\ldots \times 10^{-12}\ \text{F m}^{-1}
\]

elementary charge (of proton) \( e \)
\[
1.602\,177\,33(49) \times 10^{-19}\ \text{C}
\]

gravitational constant \( G \)
\[
6.672\,59(85) \times 10^{-11}\ \text{N m}^{2}\ \text{kg}^{-2}
\]

Planck constant \( h \)
\[
6.626\,075\,5(40) \times 10^{-34}\ \text{J s}
\]

Avogadro constant \( N_A \)
\[
6.022\,136\,7(36) \times 10^{23}\ \text{mol}^{-1}
\]

molar gas constant \( R \)
\[
8.314\,510(70)\ \text{J K}^{-1}\ \text{mol}^{-1}
\]

Boltzmann constant \( k \)
\[
1.380\,658(12) \times 10^{-23}\ \text{J K}^{-1}
\]

unified atomic mass constant \( m_u \)
\[
1.660\,540\,2(10) \times 10^{-27}\ \text{kg}
\]

rest mass of electron \( m_e \)
\[
9.109\,389\,7(54) \times 10^{-31}\ \text{kg}
\]

SI secondary units

astronomical unit \( \text{AU} \)
\[
1.495\,978 \times 10^{11}\ \text{m}
\]

parsec \( \text{pc} \)
\[
3.086 \times 10^{16}\ \text{m} = 3.262\ \text{ly}
\]

Gregorian calendar year \( \text{y} \)
\[
365.2425\ \text{days} = 31\,556\,952\ \text{s}
\]

jansky \( \text{Jy} \)
\[
10^{-26}\ \text{W m}^{-2}\ \text{Hz}^{-1}
\]

Indicative values

earth mass
\[
5.977 \times 10^{24}\ \text{kg}
\]
solar mass, \( M_\odot \)
\[
1.989 \times 10^{30}\ \text{kg}
\]
galaxy mass
\[
10^{11} \ M_\odot
\]

Hubble constant, \( H_0 \)
\[
100\ h\ \text{km s}^{-1}\ \text{Mpc}^{-1} \text{ (typically \( h \) ranges from 1 to 0.5)}
\]

Conversion factors

distance (light-year) \( \text{ly} \)
\[
9.460 \times 10^{15}\ \text{m} = 63\,240\ \text{AU}
\]

energy (erg) \( \text{erg} \)
\[
10^{-7}\ \text{J}
\]

magnetic field (gauss) \( G \)
\[
10^{-4}\ \text{T}
\]

wavelength (angstrom) \( \text{Å} \)
\[
10^{-10}\ \text{m}
\]