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

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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.

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 Ω 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.

Question 8 (10 marks)

What is meant by the Hubble period in cosmology? Calculate the Hubble period for the 'most likely' Hubble constant $H_0 = 75$ km s^{-1} Mpc^{-1}.
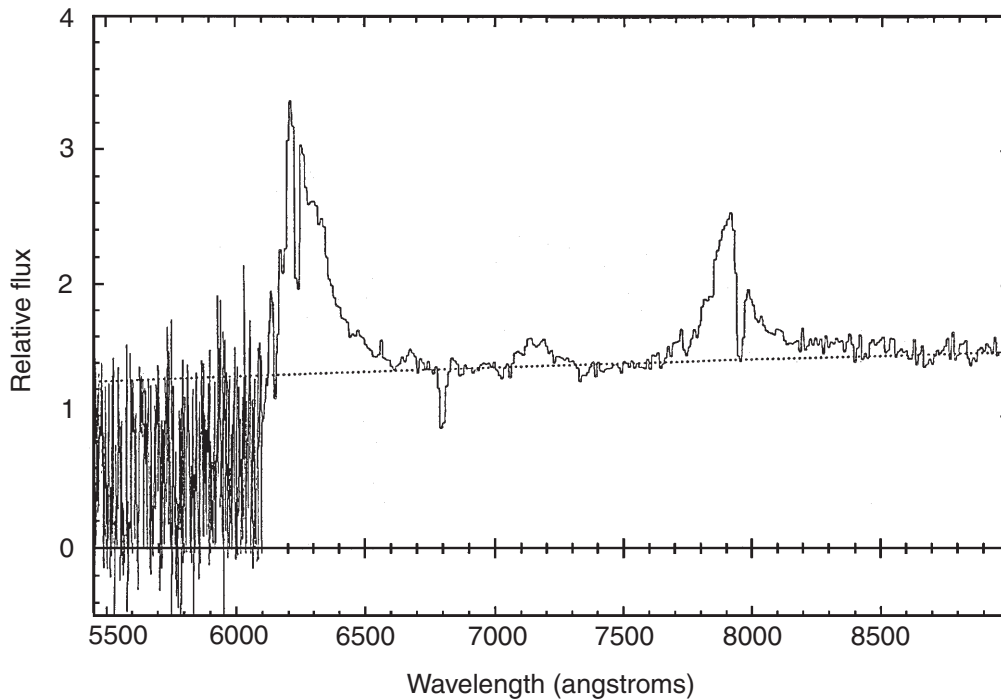
Question 9 (10 marks)

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 $700 \, \mathrm{km \, s^{-1}}$ (the velocity dispersion of the cluster).

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

(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.

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Cosmology

Data Sheet

Physical Constants and Conversion Factors

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	$2.997\,924\,58 \times 10^{8}$ m s^{-1} (exact)
permeability of a vacuum	μ_0	$4\pi \times 10^{-7}$ H m^{-1}
permittivity of a vacuum, $[\mu_0 c^2]^{-1}$	ϵ_0	$8.854\,187\,817\ldots \times 10^{-12}$ F m^{-1}
elementary charge (of proton)	e	$1.602\,177\,33(49) \times 10^{-19}$ C
gravitational constant	G	$6.672\,59(85) \times 10^{-11}$ N m^2 kg^{-2}
Planck constant	h	$6.626\,0755(40) \times 10^{-34}$ J s
Avogadro constant	N_A	$6.022\,1367(36) \times 10^{23}$ mol^{-1}
molar gas constant	R	$8.314\,510(70)$ J K^{-1} mol^{-1}
Boltzmann constant	k	$1.380\,658(12) \times 10^{-23}$ J K^{-1}
unified atomic mass constant	m_u	$1.660\,5402(10) \times 10^{-27}$ kg
rest mass of electron	m_e	$9.109\,3897(54) \times 10^{-31}$ kg

SI secondary units

astronomical unit	AU	$1.495\,978 \times 10^{11}$ m
parsec	pc	3.0856×10^{16} m = 3.262 ly
Gregorian calendar year	y	365.2425 days = 31 556 952 s
jansky	Jy	10^{-26} W m^{-2} Hz^{-1}

Indicative values

earth mass	5.977×10^{24} kg
solar mass, $M_\odot$	1.989×10^{30} kg
galaxy mass	$10^{11}\,M_\odot$
Hubble constant, H_0	$100\,h$ km s^{-1} Mpc^{-1} (typically h ranges from 1 to 0.5)

Conversion factors

distance (light-year)	ly	9.460×10^{15} m = 63 240 AU
energy (erg)	erg	10^{-7} J
magnetic field (gauss)	G	10^{-4} T
wavelength (angstrom)	Å	10^{-10} m

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