Queen Mary
University of London

BSc/MSci Examination

PHY101 Our Universe

Time allowed: 2 hours 15 minutes

Date: 25 MAY 2005

Time: 10:00

Answer any 4 questions from Section A, each carrying 10 marks, and any 2 questions from Section B, each carrying 30 marks. Maximum total marks 100. An indicative marking scheme is shown in square brackets [ ].
Answers should be clear and coherent; contain concrete, relevant detail rather than generalities, and be supplemented with clearly annotated diagrams.

Calculators may be used

Any of the following information may be used:

1 AU = 1.50×10^{11} m,
1 yr = 3.16×10^{7} s
1" = 4.85×10^{-6} radians
1 radian = 206,265"
$c = 3.00\times10^{8}$ m s^{-1}
$G = 6.67\times10^{-11}$ N m^2 kg^{-2}

Sun: $M_{sun} = 1.99\times10^{30}$ kg, $R_{sun} = 6.96\times10^{8}$ m, $L_{sun} = 3.90\times10^{26}$ W

The mass efficiency of the most efficient chemical reactions is $\sim10^{-9}$;
of Hydrogen fusion ~0.007.

Black Body radiation: $F = \sigma T^4$, where $\sigma = 5.67\times10^{-8}$ W m^{-2} K^{-4}

Ideal gas law: $P = \Re\, \rho\, T$ where $\Re = 8.31\times10^{3}$ J K^{-1} kg^{-1}

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SECTION A: [Answer any 4 questions. Each question carries 10 marks]

A.1 The stars appear to move across the sky at night. Explain why this happens. Why do the positions of the constellations in the night sky change with the seasons? Explain how the seasons on the Earth arise, also making clear physically why winter is colder than summer. Explain what is meant by the "precession of the equinoxes". Illustrate *all* your explanations with appropriate sketches.

A.2 Sketch the positions of the Earth, the Sun, and the Moon in: (i) a solar eclipse; (ii) a lunar eclipse. Explain why solar and lunar eclipses don't occur every lunar orbit (27.3 days). With the aid of a sketch explain why the Moon is red at the time of its complete eclipse. State explicitly any physical laws used in your explanations.

A.3 What is the major factor limiting the resolution of an optical telescope on the earth? Explain, with the aid of a sketch, how adaptive optics overcome this limitation. For observations made at an 8 m telescope the "seeing" is stated as 0.7"; explain what this means. What is the diffraction-limited resolution of this telescope at a wavelength of 1 μm?

A.4 Kepler's third law for a planet is, in the usual notation, $P^2 = \left[\frac{4\pi^2}{G(M_p + M_{sun})}\right] a^3$

Explain the meaning of each symbol and use the equation to estimate the orbital period of Saturn, given that Saturn has a semimajor axis of 9.54 AU. You may assume that Saturn's mass is negliable compared to that of the Sun. Saturn's moon Titan orbits with a semimajor axis of 1.22×10^7 km and has a period of 15.9 days. What is Saturn's mass, assuming Titan's mass is much smaller?

A.5 Using a sketch, explain what is meant by *parallax angle*; hence define the parsec and calculate the value of 1 pc in metres. The distance to the star Tau Ceti is quoted as 11.9 light years. What is its distance in pc and its parallax? The Ring Nebula, known to be at a distance of 1.5 kpc, has a measured angular size of approximately 27.5". Calculate its linear size in pc. The apparent magnitude of Tau Ceti is +3.49; hence use your knowledge of its distance to calculate its absolute magnitude.

Section A is continued on the next page.

A.6 The majority of stars lie on the main sequence. What can we conclude from this observation? What is the currently estimated age of the solar system? Give at least two examples of where these estimates come from. Hence, using the given data on the Sun, show that its energy source cannot be chemical but must be hydrogen fusion. Empirically the main sequence mass-luminosity law can be represented by a power law: $L \propto M^{3.5}$. Given that the Sun has an expected main sequence lifetime of 1×10^{10} yrs estimate the time spent by a $15M_{sun}$ star on the main sequence.

A.7 Explain the different physical mechanisms responsible for the stability of the Sun, a white dwarf star and a pulsar. Procyon B has a luminosity, L=0.0006L_{sun} and a temperature of 6,500K: estimate its radius in terms of R_{sun}. Explain what is meant by the Chandrasekhar mass and state its value. Explain the physical significance of the Schwartzschild radius and state what properties it depends on (or give a formula for it).

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SECTION B: Answer any two questions

Each question carries 30 marks

B1. **(a)** Write an account of the nebular theory of the formation of the solar system, showing how the theory accounts for the properties of both the giant gaseous planets and the terrestrial planets, and for other important properties of the solar system. **[20 marks]**
(As a motivation for the nebular theory your account should start with a list of clues provided by current observations of the solar system. Discussion should then proceed to the significance of temperatures in the early solar nebula, and reference to the role played by condensation temperatures. In this context reference will be made to gases, solids, refractory elements, ices, dust as well as to which of these are made up of the more and less abundant elements - which elements remain gaseous and which solid and where? This should be followed by an account of how accretion into planets proceeds in the inner and outer solar nebula, pointing out the differences. This section should include mention of planetesimals, protoplanets and chemical differentiation.)

(b) An extra-solar planet has been discovered orbiting a Sun-like star in a nearly circular orbit with a semi-major axis of 0.045 AU. Estimate the average surface temperature of the planet assuming it has an albedo, A=0.5, similar to that of Jupiter. **[10 marks]**

B2. **(a)** List the nuclear reactions in the pp-I chain and the triple-alpha reaction and explain physically: (i) why high temperatures are required for these to occur, (ii) why the triple-alpha reaction requires a much higher temperature than the pp-I chain, and (iii) why the triple-alpha reaction requires three nuclei to combine rather than a chain of binary collisions. **[10 marks]**
Explain physically, by quoting the appropriate facts of nuclear physics, why there is an end-point to nuclear energy generation in all stars and indicate why lower mass stars ($M < 4 M_{sun}$) do not progress through as many stages of nucleosynthesis as those of higher mass. Discuss the abundance of elements in the universe, explaining in broad outline the origin of the elements beyond H, He, Li, Be and B. For the Sun give typical figures for the abundance by mass of Hydrogen, Helium and the metals. **[10 marks]**

(b) Explain what is meant by Population I and Population II stars. Explain how stellar clusters of these two classes of stars provide evidence for the theory of stellar evolution. Your account should include a clear explanation of how the ages of these clusters can be estimated from their HR diagrams. One of the very oldest globular clusters is M68. What is the cosmological significance of its age? **[10 marks]**

Section B is continued on the next page.

B.3 **(a)** Describe, with a sketch, the Hertzsprung-Russell (HR) diagram and indicate the positions of the main types of star. Indicate the positions on the Main Sequence of stars of masses $1M_{sun}$, $40\ M_{sun}$ and $0.5\ M_{sun}$. Name the various spectral classes and indicate where they occur on the HR diagram. What is the spectral class of the Sun? **[10 marks]**
Derive an expression to show that curves of constant stellar radius on the HR diagram are straight lines. **[4 marks]**

(b) Sketch on an HR diagram (or diagrams) an annotated evolutionary path of a one-solar-mass star from protostar to its final stages, indicating the names of important stages. Also very briefly comment on the nuclear processes responsible for energy generation and for rapid changes in the interior and envelope of the star as it evolves. Briefly compare this evolution with that of a star of $15M_{Sun}$, explaining how they differ.
[16 marks]

B.4 **(a)** Define the *red-shift*, *z*, and explain how the red-shift of galaxies is measured. State what is meant by Hubble's Law and explain in principle how the Hubble constant, H_o, can be determined from observations.
Give a simple argument, showing clearly all your reasoning, to approximately relate H_o to the age of the universe. Comment on any approximation made in your derivation. Given that the currently favoured value is H_o=70 km $s^{-1}Mpc^{-1}$, estimate the age of the Universe. **[14 marks]**

(b) Explain the significance of the scale factor $R(t)$ in describing the evolution of a homogeneous, isotropic universe and sketch its time dependence for three possible such universes. How is the density of the universe related to these three possibilities?
[8 marks]

(c) Give physical arguments to determine how the radiation and matter densities depend on $R(t)$. Hence explain why the early universe was a hot universe. What is the observational evidence now for this hot early universe? **[8 marks]**

End of Examination Paper **Dr A.J. Martin**