Any calculator, except one with pre-programmable memory, may be used in this examination.

LEVEL 2
Examination contributing to the Degrees of Bachelor of Science (BSc) and Master in Science (MSci)

PHY2003
Astrophysics I

Duration: 2 hours plus additional 1 hour for upload of work

Monday 16th of August 2021
09:30 AM – 12:30 PM

Examiners: Prof S Matthews, Prof F. Peters
and the internal examiners
Dr S Sim (s.sim@qub.ac.uk)

Answer ALL questions in Section A for 10 marks each.
Answer ONE question from Section B for 30 marks.
Answer ONE question from Section C for 30 marks.

If you have any problems or queries, contact the School Office at mpts@qub.ac.uk or 028 9097 1907, and the module coordinator m.schwamb@qub.ac.uk

THE QUEEN'S UNIVERSITY OF BELFAST

DEPARTMENT OF PHYSICS AND ASTRONOMY

Physical Constants

Speed of light in a vacuum	$c = 3.00 \times 10^{8}$ m/s
Permeability of a vacuum	$\mu_0 = 4\pi$x10-7 Hm^{-1}
	$\approx 1.26 \times 10^{-6}$ Hm^{-1}
Permittivity of a vacuum	ε_0=8.85x10-12 Fm^{-1}
Elementary charge	$e = 1.60 \times 10^{-19}$ C
Electron charge	$= -1.60 \times 10^{-19}$ C
Planck Constant	$h = 6.63 \times 10^{-34}$ Js
Reduced Planck Constant	$\hbar = 1.05 \times 10^{-34}$ Js
Rydberg Constant for hydrogen	$R_\infty = 1.097 \times 10^{7}$ m^{-1}
Unified atomic mass unit (kg)	$1u = 1.66 \times 10^{-27}$ kg
Unified atomic mass unit (MeV)	$1u$= 931 MeV
1 electron volt (eV)	1 eV = 1.60×10^{-19} J
Mass of electron	$m_e = 9.11 \times 10^{-31}$ kg
Mass of proton	$m_P = 1.67 \times 10^{-27}$ kg
Mass of neutron	$m_N = 1.67 \times 10^{-27}$ kg
Molar gas constant	R = 8.31 $JK^{-1}mol^{-1}$
Boltzmann constant	$k = 1.38 \times 10^{-23}$ JK^{-1}
Stefan-Boltzmann constant	$\sigma = 5.67 \times 10^{-8}$ $Wm^{-2}K^{-4}$
Avogadro constant	$N_A = 6.02 \times 10^{23}$ mol^{-1}
Gravitational constant	$G = 6.67 \times 10^{-11}$ $m^3kg^{-1}s^{-2}$
Acceleration of free fall on the Earth's surface	g= 9.8 ms^{-2}

Astronomical Constants

Mass of Sun	$M_\odot = 1.99 \times 10^{30}$ kg
Radius of Sun	$R_\odot = 6.96 \times 10^{8}$ m
Luminosity of Sun	$L_\odot = 3.90 \times 10^{26}$ W
Effective temperature of Sun	$T_\odot = 5700$ K
Mass of Earth	$M_\oplus = 5.98 \times 10^{24}$ kg
Radius of Earth	$R_\oplus = 6.38 \times 10^{6}$ m
Astronomical Unit	1 au = 1.498×10^{11} m
Parsec	1 pc = 3.08×10^{16} m
Megaparsec	1 Mpc = 10^6 pc
Hubble Constant	H_0 = 71 km/sec/Mpc

Solar System Data

Planet	a (au)	e	i (°)	($M/M_\oplus$)	$R/R_\oplus$	Albedo
Mercury	0.387	0.206	7.00	0.056	0.38	0.06
Venus	0.723	0.007	3.39	0.815	0.95	0.76
Earth	1.000	0.017	0.00	1.000	1.00	0.40
Mars	1.524	0.093	1.85	0.107	0.53	0.16
Jupiter	5.203	0.048	1.31	318	11.19	0.51
Saturn	9.540	0.056	2.49	95	9.41	0.50
Uranus	19.18	0.047	0.77	14.5	4.01	0.66
Neptune	30.06	0.009	1.77	17.2	3.89	0.62

Dwarf Planet	a (au)	e	i (°)	($M/M_\oplus$)	$R/R_\oplus$	Albedo
Ceres	2.77	0.080	10.59	1.6×10^{-4}	0.15	0.37
Pluto	39.44	0.249	17.15	2.0×10^{-3}	0.18	0.50
Eris	67.67	0.442	44.19	2.8×10^{-3}	0.18	0.96

Satellite	a (km)	e	i (°)	($M/M_\oplus$)	$R/R_\oplus$	Albedo
Moon	384,400	0.055	5.15	0.012	0.27	0.08

SECTION A

Answer all questions in this section

1. (a) Calculate in arcseconds the angular size of the Sun viewed during a clear day by Belfast citizens when the Earth is at aphelion. **[5]**

(b) If the Earth was twice as massive, how would this change your answer to part a? Briefly explain your reasoning. **[2]**

(c) If the Earth was three times further away and the Sun was three times as big, how would this change your answer to part a. Explain your reasoning including any relevant relations or equations. **[3]**

2. (a) A Bond movie villain claims to have a laser beam device that can stop fusion in the Sun's core. James Bond has access to a flare detector, that measures the frequency and strength of stellar flares emerging from the photosphere, and a neutrino detector, that measures the neutrino flux at Earth. Which instrument should Agent Bond use to check whether the villain's device had been used on the Sun? Explain your reasoning in 2-4 sentences. **[5]**

(b) At different times during its trip, a space probe orbited two moons (X and Y) that are identical in size. Though the probe orbited both moons in circular orbits at the same distance from the centre of mass, ground control finds that the probe had a faster orbital period at moon X than moon Y. Compare the compositions of moon X and moon Y. Explain your reasoning in 2-4 sentences with relevant expressions. **[5]**

3. (a) Draw a diagram of a pulsar and use this to explain why not every neutron star is observed as a pulsar. Explain your reasoning in 2-4 sentences**.** **[4]**

(b) A pulsar is observed to have a frequency of 850 Hz:

(i) Explain whether this pulsar is likely a single star or part of a binary. Explain your reasoning in 2-4 sentences. **[2]**

(ii) Estimate its density, state any assumptions you make. **[4]**

SECTION A

4. **(a)** Discuss with relevant examples three different methodologies for determining the distances to different objects in the Universe. Your answer should include a discussion of how accurate each respective method is. **[6]**

(b) Initial main-sequence fitting of the globular cluster M62, ignoring the effects of the interstellar medium, results in an apparent distance to the cluster of 7.1 kpc. Subsequent spectroscopy shows that K4 stars in this cluster have a colour of (B-V) = 1.08. If K4 stars normally have a colour of (B–V) = 1.05 in the absence of dust, calculate the true distance of the cluster. **[4]**

SECTION B

Answer ONE question from this section, each question is worth 30 marks.

5. (a) Star Zeta has a planet that orbits every 10 years with a semimajor axis equal to 7 au. A comet orbiting Star Zeta has a perihelion of 1.5 au and an aphelion of 4 au. How long does it take for the comet to complete one orbit around Star Zeta? **[6]**

(b) Altair is a star with an 0.77 V-band apparent magnitude measured at Earth. Altair is located 1.583x10^{14} m from Earth. You view Altair through an interstellar dust cloud that is located halfway between the Earth and the star. The dust cloud allows through only 70% of optical light. At visual wavelengths one photon has an energy of 3.6×10^{-19}J and the apparent V-band magnitude of an object is given by $V = -2.5\log(f) - 18.74$.

(i) On Earth, Stella views Altair with sunglasses on that block 20% of the optical light. What are the number of photons from Altair that pass through to Stella's eye (5 mm diameter opening) in 3s? **[8]**

(ii) On Earth, Mindy uses a telescope to measure Altair's brightness. She does not know that the dust cloud is along her line of sight to Altair. What is the V-band absolute magnitude Mindy would estimate for Altair? **[4]**

(iii) Mork, an alien astronomer, views Altair from 5.13 parsecs along a different direction free of the dust cloud. What is the absolute V magnitude that Mork measures for Altair? **[6]**

(c) The 2.4-m Hubble Space Telescope (HST) can resolve details as small as 46 milliarcseconds. At the Moon's closest approach to Earth (perigee), how large a crater could HST resolve on the lunar surface, in meters. [You should assume the distance between HST and the Moon is the same as the distance between the Earth and the Moon.] **[4]**

(d) Guru is a star with an apparent r-band magnitude of 22.3 and an absolute r-band magnitude of 7.1. Mando is a star with an r-band apparent magnitude of 25.2 and an r-band absolute magnitude of 5.1. Which star gives off the largest total amount of energy? Briefly explain your reasoning. **[2]**

SECTION B

6. **(a)** In order to keep the Athena mission in orbit around an asteroid with a diameter of 200 m, the spacecraft is placed in an initial orbit that is 4.5 hours long with a radius of 15 km. Later the spacecraft touches down on the asteroid's surface to sample rocks. How fast does the spacecraft need to fire its engines in order to escape the asteroid's surface? **[5]**

(b) A comet is located 100,000 au from the Sun and 1.5 pc from Alpha Centauri. Alpha Centauri has a mass of $1.3M_{\odot}$. Calculate the comet's acceleration due to the gravitational pull of both stars. You can assume the comet, Sun, and Alpha Centauri are on the same line with the comet between the two stars. **[4]**

(c) Large Kuiper belt object Orcus has a perihelion of 30.281 au and an orbital period of 245.19 years. What is the eccentricity of Orcus' orbit? What is the velocity of Orcus when its distance from the Sun equals the semimajor axis of Neptune orbit? **[6]**

(d) Guru is a star with an apparent r-band magnitude of 22.3 and an absolute r-band magnitude of 7.1. Guru has a (V-r) colour of 0.5. Stella tries to observe the faint star with the 10 m Keck telescope with the V filter. In a 40 s exposure, Guru is measured to have a signal-to-noise ratio of 5. Estimate the photons/s sky background contribution from the Moon. At visual wavelengths one photon has an energy of 3.6×10^{-19}J and the apparent V-band magnitude of an object is given by $V = -2.5log(f) - 18.74$ **[10]**

(e) The TRAPPIST-1 star has a mass of 1.8 $M_{\odot}$. The planetary system contains a transiting planet with a mass of 1.308 times that of Earth. Assuming the planet is on a circular orbit with a semimajor axis of 0.0158 au, what is the radial velocity signal Sandeep measures for TRAPPIST-1 due to the orbiting exoplanet? **[5]**

SECTION C
Answer ONE question from this section, each question is worth 30 marks.

7. (a) Astronomers have been observing a star at a distance of 72 pc and have determined its luminosity to be 0.041 $L_\odot$, its mass to be 0.50 $M_\odot$ and its radius to be 0.50 $R_\odot$. The bolometric correction is -1.42. A student is making further observations of the star, and they think that this star is about to leave the main sequence.

(i) State what the likely end-product of stellar evolution is for this star. **[2]**

(ii) Calculate the age of the star based on its mass and luminosity and discuss whether the student's assessment that the star is about to leave the main sequence is correct. State any assumptions you make. [You should assume that the main-sequence lifetime of the Sun is 9.3 Gyr]. **[6]**

(iii) Calculate the star's effective temperature and its bolometric, absolute, and apparent magnitude. **[7]**

(b) (i) From the Andromeda galaxy, Hα emission (rest wavelength 656.28 nm) is observed with a wavelength of 655.624nm. What velocity is Andromeda travelling towards the Milky Way? If Andromeda is 780 kpc away and is travelling at a constant rate, estimate how many years it will take Andromeda to reach the Milky Way. **[4]**

(ii) The average separation between stars is 1 pc and the average radius of a star in the galaxy is $1R_\odot$, estimate the volume in parsecs swept out by a star from Andromeda passing through the Milky Way with the same velocity estimated in (i), over a 1000 year period. **[4]**

(iii) Using your answer from (ii), estimate the mean time between the physical collision of a star from Andromeda with a star in the Milky Way during the merger of the two galaxies. Comment on the significance of your answer. **[4]**

(iv) Discuss the likely outcome of the merger of two spiral galaxies such as Andromeda and the Milky Way. Your answer should discuss the effect of the merger on the interstellar medium. **[3]**

SECTION C

8. (a) Astronomers observe an eclipsing binary and determine the absolute magnitudes to be $M_{V,A} = 1.50$ and $M_{V,B} = 4.35$ for star A and B, respectively. With a smaller telescope they are unable to resolve the binary, but they find that the apparent magnitude for both stars combined is $m_{V,combined} = 12.24$

(i) Calculate the distance and parallax for this binary. **[3]**

Follow-up measurements reveal that the stars have radii of $\mathrm{R_A} = 14.6\ \mathrm{R_\odot}$ and $\mathrm{R_B} = 1.15\ \mathrm{R_\odot}$, respectively, while their masses are $\mathrm{M_A} = 0.95\ \mathrm{M_\odot}$ and $\mathrm{M_B} = 1.1\ \mathrm{M_\odot}$. The bolometric corrections are -1.0 and -0.08 for star A and B, respectively.

(ii) Draw a theoretical H-R diagram and indicate the main components. Include the Sun in your diagram. **[4]**

(iii) Calculate the luminosity and effective temperature for both stars and place them on the H-R diagram. Which of these stars is more evolved? Explain your reasoning and indicate if this would be expected based on their masses. **[8]**

(b) (i) If decoupling between radiation and matter occurs at 3000K, calculate the redshift of the Universe when it first became transparent. Estimate the change in size of the Universe between that time and now and calculate the expected observed wavelength of a Hα photon (rest wavelength 656.28nm) emitted at decoupling assuming it has travelled unimpeded since it was emitted. **[4]**

(ii) QSO 3C279 is a quasar with a measured redshift of $z = 0.538$ and an apparent magnitude of $m_V = 17.75$. Calculate the distance to QSO 3C279 and make an estimate for the absolute magnitude of the quasar. **[5]**

(iii) Describe three pieces of evidence that suggest the existence of dark matter. Briefly discuss the role that dark matter and dark energy play in determining the fate of the Universe. **[6]**

END OF EXAMINATION