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 30 Minutes for upload of work

Tuesday 12 January 2021
09:30 AM – 12:00 NOON

Examiners: Prof S Matthews, Dr 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	$\mu_0 = 4\pi \times 10\text{-}7\ \mathrm{Hm^{-1}}$
	$\approx 1.26 \times 10^{-6}\ \mathrm{Hm^{-1}}$
Permittivity of a vacuum	$\varepsilon_0 = 8.85 \times 10\text{-}12\ \mathrm{Fm^{-1}}$
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	$R_\infty = 1.097 \times 10^{7}\ \mathrm{m^{-1}}$
Unified atomic mass unit (kg)	$1u = 1.66 \times 10^{-27}$ kg
Unified atomic mass unit (MeV)	$1u = 931$ MeV
1 electron volt (eV)	$1\ \mathrm{eV} = 1.60 \times 10^{-19}$ 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	$R = 8.31\ \mathrm{JK^{-1}mol^{-1}}$
Boltzmann constant	$k = 1.38 \times 10^{-23}\ \mathrm{JK^{-1}}$
Stefan-Boltzmann constant	$\sigma = 5.67 \times 10^{-8}\ \mathrm{Wm^{-2}K^{-4}}$
Avogadro constant	$N_A = 6.02 \times 10^{23}\ \mathrm{mol^{-1}}$
Gravitational constant	$G = 6.67 \times 10^{-11}\ \mathrm{m^3kg^{-1}s^{-2}}$
Acceleration of free fall on the Earth's surface	$g = 9.8\ \mathrm{ms^{-2}}$

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. HAT-P-2 b is a transiting gas giant exoplanet that orbits an F-type star. The planet has a mass that is 8.7 times that of Jupiter. The planet's host star has a radius of 1.41 times that of the Sun. It takes 5.6 days for HAT-P-2 b to complete one orbit around its parent star.

(a) If HAT-P-2 b was twice as massive, what would its orbital period be? Include relevant equations in your estimate. **[2]**

(b) Can HAT-P-2 b be detected via the radial velocity technique? Include any relevant relations or equations in your explanation. **[3]**

(c) An astronomer measuring HAT-P-2 b's host star finds that the star dims by 0.64% when the planet transits. Calculate the bulk density of HAT-P-2 b. **[3]**

(d) How often does HAT-P-2 b transit its host star? **[2]**

2. Delta is a star with an apparent V-band magnitude of +12.3 and an absolute V-band magnitude of 5.3. Gamma is a star with an apparent V-band magnitude of -1.2 and an absolute V-band magnitude of -12.0.

(a) Which of the stars gives off more light in the V-band? Explain your reasoning including any relevant relations or equations. **[3]**

(b) Which star has a larger V-band flux measured by the QUB Teaching Observatory, a 0.35-m diameter mirror telescope? Explain your reasoning including any relevant relations or equations. **[3]**

(c) Which star is closer to the Earth? Explain your reasoning including any relevant relations or equations. **[4]**

SECTION A

3. **(a)** Assuming that a molecular cloud consists predominantly of H_2 $\left(m_{H_2} = 3.35 \times 10^{-27}\text{kg}\right)$, calculate the density of a molecular cloud in particles per m^3 if the free-fall timescale is 110,000 years. **[4]**

(b) Describe the evolution of a 1.5-solar mass star. Include an H-R diagram to show the path the star takes. **[6]**

4. **(a)** Describe how the presence of interstellar dust grains affects the magnitudes and colours of distant stars. **[3]**

(b) Initial main-sequence fitting of the galactic cluster M7, ignoring the effects of the interstellar medium, results in an apparent distance to the cluster of 285 pc. Subsequent spectroscopy shows that G2V stars in this cluster have a colour of $(B - V) = 0.77$. If the Sun has a colour $(B - V) = 0.67$, calculate the true distance of the cluster, and the mean extinction per kpc in this direction at visual wavelengths. **[5]**

(c) Briefly explain a method for observing stars found behind dust clouds that are within the line of sight of the observer. **[2]**

END OF SECTION A

SECTION B

Answer <u>ONE</u> question from this section, each question is worth 30 marks.

5. **(a)** The diameter of Betelgeuse is estimated to be 1000 Sun diameters in size. It takes 650 years for light from Betelgeuse to travel to Earth. Star spots were observed on Betelgeuse in 2020. What is the diameter of the star spot on Betelgeuse in metres that the future 39-m Extremely Large Telescope (ELT) could resolve using its adaptive optics (AO) system? Assume the AO system operates at a near-infrared wavelength of λ = 1600nm. **[4]**

(b) Comet Halley has an orbital period of 27484.5 days and has a perihelion of 0.586 au.

(i) Calculate the comet's aphelion distance. **[3]**

(ii) Draw Comet Halley's orbit. At perihelion and aphelion, draw the directions that the comet's ion and dust tails will be pointing. **[3]**

(iii) What is Comet Halley's orbital velocity when the comet is located at a distance that equals the semimajor axis of Uranus' orbit? **[3]**

(c) Enceladus is an icy moon of Saturn which has active vents that are expelling liquid water. Explain how the heat required to melt the interior of Enceladus is generated. **[3]**

(d) Holga and Hilda are two asteroids. They have the same size and shape and are the same distance from the Sun. Holga is icy with an albedo of 0.9. Hilda is rocky with an albedo of 0.1. Which asteroid is brighter in visible light? Which asteroid has a higher surface temperature? Explain your answer including relevant expressions. **[5]**

Question 5 continued on next page

SECTION B

(e) Astronomers are planning to send the Poseidon space mission to Neptune, when the planet is at perihelion. At what distance from the Sun would the planned spacecraft feel the same gravitational force from Neptune as the Sun? Assume the Sun, the spacecraft, and Neptune all lie on the same line. **[4]**

(f) The Poseidon spacecraft is equipped with two solar panels. Each solar panel is 2.7m wide by 8.9m long. On Earth, 7.85×10^{13} neutrinos pass through the 10-m Keck telescope's mirror every 10 seconds. At 30 au, estimate the number of neutrinos that will pass through both of Poseidon's solar panels after one minute. **[5]**

SECTION B

6. (a) The Parker Solar Probe has an orbit with a perihelion of 7.2 million km and an aphelion at the same distance as Venus' semimajor axis. What is the semimajor axis, eccentricity, and orbital period of the probe's orbit? **[6]**

(b) Draw the expected tidal bulge(s) produced on the Earth when the Sun, Earth, and Moon are in the following configuration. Distances and sizes of the astronomical bodies in the figure below are not to scale. **[4]**

(c) The Subaru Telescope is a ground-based telescope designed for optical and near-infrared observations. The Hubble Space Telescope (HST), orbiting in space, is equipped with instruments also capable of taking optical images. What is the main benefit of having a space-based optical telescope over a ground-based optical telescope? **[3]**

(d) Stella is observing a small rotating asteroid with the QUB Teaching Observatory, a 0.35-m mirror telescope. The asteroid is a contact binary (two spherical planetesimals stuck together). The larger sphere has a diameter of 20 km and an albedo of 0.3. The smaller sphere has a diameter of 7 km and an albedo of 0.1. Stella observes the asteroid at two separate times, when the asteroid has different surfaces visible to Earth as shown below:

How many times fainter is the asteroid's flux observed by Stella at Time 2 than at Time 1? What is the magnitude difference observed by Stella? **[6]**

Question 6 continued on next page

SECTION B

(e) The absolute R-band magnitude of a star in the Andromeda galaxy (distance 690 kiloparsecs) is M=6. It explodes as a supernova, becoming one billion (10^9) times brighter. The (V-R) colour of the supernova is 0.3 magnitudes. The 2.56-m Nordic Optical Telescope (NOT) observes the supernovae through clouds that are blocking out 10% of the optical light. What is the number of V-band photons collected by the NOT after a 5s exposure? 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 $V = -2.5log(f) - 18.74$ **[11]**

END OF SECTION B

SECTION C

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

7. (a) In stars more massive than the Sun, the PP cycle is no longer the dominant energy production method. Instead, the star's energy will come from the CNO cycle which can be summarized as:

$$4\,{}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2\nu_{\mathrm{e}} + 2\mathrm{e}^{+} + 3\gamma$$

During this process, 4.3×10^{-12} J is released in each net reaction. Astronomers observe a star with a $B - V = 0.170$, they determine its luminosity to be 8.29 $L_{\odot}$. Its apparent V-magnitude is 9.88. This star uses the CNO cycle for nuclear fusion.

(i) If the star's absolute magnitude in V-band is 1.89, determine its parallax. **[4]**

(ii) Based on the luminosity, estimate the star's mass. State any assumptions you make. **[4]**

(iii) Calculate the number of fusion reactions occurring per second in this star, and the resulting neutrino flux as measured on the Earth. **[7]**

(b) Describe briefly the differences between H I regions, H II regions, and molecular clouds in the interstellar medium. Your answer should include a discussion of the emission mechanisms in each region. **[5]**

(c) An O7 type star has a temperature of 43,000 K and a luminosity of $120{,}000 L_{\odot}$.

(i) Assuming the star acts as a blackbody, estimate the peak wavelength of emission from the star and state what part of the electromagnetic spectrum this corresponds to. **[3]**

(ii) Assuming that the star emits only ionising photons at the peak wavelength calculated in part (i), estimate the number of ionising photons emitted by the star per second. **[3]**

[Wien's displacement constant = 2.898×10^{-3} mK]

Question 7 continued on next page

SECTION C

(iii) If the density of hydrogen in the interstellar medium around the star is 1000 cm^{-3}, calculate the radius of the Stromgren sphere around the star in parsecs. Take a value of $\alpha = 3 \times 10^{-13}$ cm^3 s^{-1} for the interstellar medium. **[4]**

SECTION C

8.

Table 1: $V - R$ colors an absolute V-magnitude for a number of stars.

Name	$V - R$	M_V
The Sun	0.36	4.8
Sirius A	0.00	1.4
Sirius B	-0.12	11.2
Betelgeuse	1.6	-5.9
Proxima Centauri	1.7	15.6

Table 2: V-R colours, bolometric corrections, and effective temperatures for stars.

$V - R$	BC	T_{eff} (K)
-0.094	-2.06	20,700
-0.028	-0.42	10,700
0.190	-0.01	7,000
0.363	-0.11	5,800
0.537	-0.41	4,800
0.924	-1.38	3,800
1.241	-2.59	3,200

(a) When making H-R diagrams, it is sometimes better to use redder filters, such as the V & R band rather than B & V band to reduce the impact of dust on the measurements. Using the information in Table 1, sketch an approximate H-R diagram, identify these stars on the diagram and indicate the main components. **[5]**

(b) Astronomers have been studying a spectroscopic binary star. The binary has a parallax of 250 μas, and its stars are labelled A and B. Star A has a V-band magnitude of 13.710 and a R-band magnitude of 13.738. Star B has a V-band magnitude of 16.330. The R-band magnitude of star B was not measured directly, but the R-band magnitude for both stars combined is 13.586.

(i) Calculate the absolute magnitude in V-band for both stars, as well as their V-R colours, and in the H-R diagram from part (a), draw the approximate position of the two stars and state their evolutionary state and luminosity class. **[7]**

(ii) Using the information in Table 2, calculate the luminosity for each of the two stars. **[4]**

Question 8 continued on next page

SECTION C

(c) A supernova is observed at the outskirts of a large spiral galaxy. The supernova has an apparent magnitude of peak brightness of $m_V = +14.3$ while the galaxy has a redshift of $z = 0.017$.

(i) Briefly describe whether Type Ia or Type II supernovae are more accurate at determining extragalactic distances. Clearly explain your reasoning for your choice. **[4]**

(ii) The supernova has an absolute magnitude of $M_V = -19.6$ at peak brightness. Assuming no extinction along the line of sight, calculate the distance to this galaxy. **[4]**

(iii) From the information that you know about this event, and the host galaxy, calculate the age of the Universe in years assuming a constant expansion rate. Also, calculate the temperature of the Universe when this supernova occurred. **[6]**

END OF EXAMINATION