University of Durham

EXAMINATION PAPER

May/June 2011 Examination code: 042541/01

LEVEL 2 PHYSICS: STARS AND GALAXIES

SECTION A. OBSERVATIONAL TECHNIQUES
SECTION B. STARS
SECTION C. GALACTIC ASTRONOMY

Time allowed : 2 hours and 30 minutes

Examination material provided : None

Answer the compulsory question that heads each of sections A, B and C. These **three** questions have a total of 15 parts and carry 60% of the total marks for the paper. Answer **two** of the four optional questions, **not** both from the same section. If you attempt more than the required number of questions only those with the lowest question number compatible with the rubric will be marked: **clearly delete** those that are not to be marked. The marks shown in brackets for the main parts of each question are given as a guide to the weighting the markers expect to apply.

ANSWER EACH SECTION IN A SEPARATE ANSWER BOOK

Do **not** attach your answer booklets together with a treasury tag, unless you have used more than one booklet for a single section.

APPROVED TYPES OF CALCULATOR MAY BE USED.

Information

Elementary charge:	$e = 1.60 \times 10^{-19}$ C
Speed of light:	$c = 3.00 \times 10^{8}\,\mathrm{m\,s^{-1}}$
Boltzmann constant:	$k_{\mathrm{B}} = 1.38 \times 10^{-23}\ \mathrm{J\,K^{-1}}$
Electron mass:	$m_{\mathrm{e}} = 9.11 \times 10^{-31}$ kg
Gravitational constant:	$G = 6.67 \times 10^{-11}\ \mathrm{N\,m^2\,kg^{-2}}$
Proton mass:	$m_{\mathrm{p}} = 1.67 \times 10^{-27}$ kg
Planck constant:	$h = 6.63 \times 10^{-34}\ \mathrm{J\,s}$
Permittivity of free space:	$\epsilon_0 = 8.85 \times 10^{-12}\ \mathrm{F\,m^{-1}}$
Bohr magneton:	$\mu_{\mathrm{B}} = 9.27 \times 10^{-24}\ \mathrm{J\,T^{-1}}$
Magnetic constant:	$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H\,m^{-1}}$
Nuclear magneton:	$\mu_{\mathrm{N}} = 5.05 \times 10^{-27}\ \mathrm{J\,T^{-1}}$
Molar Gas constant:	$R = 8.31 \times 10^{3}\ \mathrm{J\,K^{-1}\,kmol^{-1}}$
Avogadro's constant:	$N_{\mathrm{A}} = 6.02 \times 10^{26}\ \mathrm{kmol^{-1}}$
Gravitational acceleration at Earth's surface:	$g = 9.81\ \mathrm{m\,s^{-2}}$
Stefan-Boltzmann constant:	$\sigma = 5.67 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$

SECTION A. OBSERVATIONAL TECHNIQUES

Question 1 is compulsory. Question 2 is optional.

1. (a) For a 10m telescope with a focal ratio of f/5.6, what is the effective focal length? [2 marks]

   What is the plate scale in arcseconds per mm for this telescope? [2 marks]

   (b) Name the two most commonly used telescope foci and state an advantage of each focus position. [1 mark for each focus and 1 mark for each reason]

2. (a) For a background limited observation of a star, state the equation relating signal to noise ratio to exposure time in terms of signal and background count rates. [3 marks]

   (b) If a fixed signal to noise ratio of 5 is required, determine the equation relating signal count rate to background count rate. [2 marks]

   (c) The PanSTARRS Medium Deep survey is being performed in a set of fields that are observed every night. Each night exposures of the same length are performed using five different filters.

   The sky background in each of the five filters increases with wavelength such that the background from the atmosphere is proportional to wavelength, λ, as $\lambda^{0.8}$. The filters, g, r, i, z and y, each transmit light over a 150 nm range and are matched to give full coverage of the optical band. The bluest filter, g, is sensitive to light from 350 to 500 nm and the reddest, y, from 950 to 1100 nm.

   If a star on a moonless night is detected with a signal to noise ratio of 5 with a magnitude of 25 in the g filter and the zero point magnitude for each filter is the same, what is the equivalent magnitude limit in the other four filters? You may assume the background in the filter is that of the wavelength in the centre of the filter response. [6 marks]

   (d) One of the main goals of this survey is to determine the variability of active galactic nuclei. The detected count rate of these objects is proportional to $\lambda^{1.0}$ over the optical band. Which filter will make the most significant detections and is hence best to study variation? [2 marks]

   (e) Another goal is to detect supernovae which have a detected count rate that is proportional to $\lambda^{-1.0}$ over the optical band. Which filter will make the first significant detection of any supernova as it brightens? [2 marks]

   (f) The effect of the Full Moon is such that it increases the detected sky background by a factor of 100 in the g band but this scattered sunlight is proportional to $\lambda^{-2.5}$ over the optical band. Which band will detect a brightening supernova during Full Moon first? [5 marks]

SECTION B. STARS

Question 3 is compulsory. Questions 4 and 5 are optional.

3. (a) Draw a Hertzsprung-Russell diagram. Clearly label the axes, mark the track of the main-sequence and the position of the Sun. For a coeval population of stars, mark on the diagram the position of the first stars leaving the main sequence. [4 marks]

   (b) Compute the effective temperature of a star with 10^{-3} times the luminosity of the Sun, and a radius equal to that of the Earth. [4 marks]

   [Luminosity of the Sun = 3.85×10^{26} W, radius of the Earth = 6.38×10^{6} m]

   (c) Compute the mean free path of a photon in the core of the sun, given that the density there is 1.5×10^{5} kg m^{-3}, and the Rosseland mean opacity is 0.2 m^{2} kg^{-1}. [4 marks]

   (d) Explain what the Mixing Length is in the theory of convection in the Sun. Give an estimate for its value. [4 marks]

   (e) Write down all the input and output particles of the main pp chain for fusion of hydrogen into helium in the Sun. Make sure that the nuclear conservations laws are obeyed. [4 marks]

   (f) Give three of the reasons considered for the observed deficit of electron neutrinos detected from the Sun. Which is the correct one? [4 marks]

   (g) Estimate the ratio of the pulsation periods for two stars, both of one solar mass, but one with a radius equal to that of the Earth, and the other with a radius equal to one astronomical unit. [4 marks]

   [Radius of the Earth = 6.38×10^{6} m, 1 astronomical unit = 1.50×10^{11} m]

   (h) Estimate the mass ratio of two stars in circular orbits about their centre of mass with velocities equal to 10 m s^{-1} and 0.1 m s^{-1}. Which velocity is that of the more massive star? [4 marks]

4. (a) What is the Jeans Mass? [2 marks]

(b) Show that the Jeans Mass, M_J, for a spherically symmetric gas cloud satisfies the relation:

$$M_J = \left(\frac{3k_BT}{2\mu m_pG}\right)^{\frac{3}{2}}\left(\frac{3}{4\pi\rho}\right)^{\frac{1}{2}}$$

where T is the temperature of the cloud, μ is the (dimensionless) mean molecular mass and ρ is the average density of the cloud. [6 marks]

(c) For a cloud of H_2 with a temperature of 70 K and density 1.0×10^{-18} kg m^{-3}, calculate the minimum mass needed for it to collapse. [4 marks]

(d) After some collapse, the cloud fragments to form protostars of average mass double that of the Sun. Assuming that the temperature of the cloud remains constant, what must the density of the cloud be at the onset of fragmentation? [4 marks]

(e) Typically, stars with a range of mass between 20 and 0.1 times that of the Sun are formed. Make an estimate of the time until the cloud is disrupted and give a plausible reason for the disruption. [4 marks]

[You may assume that the main sequence lifetime of a star is proportional to mass$^{-3.5}$]

[Mass of the Sun = 1.99×10^{30} kg.]

5. (a) Write down equations for the two forces on an electron-proton pair that have to be balanced in order to derive the Eddington luminosity of an accreting system. [4 marks]

   (b) Use these equations to derive the Eddington luminosity:

$$L_E = \frac{4\pi G M m_{\mathrm{p}} c}{\sigma_T}$$

   where M is the mass of the accreting object, and σ_T is the Thompson cross section. [4 marks]

   (c) Calculate the Eddington luminosity (measured in solar luminosities) for an neutron star 2.5 times the mass of the sun. [2 marks]

   (d) Estimate the mass accretion rate for a neutron star of radius 15 km radiating at this luminosity. [6 marks]

   (e) Give two reasons why this limit is not appropriate for an accreting binary system where the infalling matter forms an accretion disk. [4 marks]

[Luminosity of the Sun = 3.85×10^{26} W, Mass of the Sun = 1.99×10^{30} kg, Thompson cross section, $\sigma_T = 6.65 \times 10^{-29}$ m^2]

SECTION C. GALACTIC ASTRONOMY

Question 6 is compulsory. Question 7 is optional.

6. (a) Briefly describe Hubble's classification sequence of galaxies. State two characteristics each of elliptical and spiral galaxies. [4 marks]

   (b) Which physical mechanism produces the 21 cm line in atomic hydrogen? How can this line be used to measure the rotation curve in a spiral galaxy? Discuss one advantage of this method over the usage of optical measurements. [4 marks]

   (c) Which physical process produces the X-rays detected in clusters of galaxies? How can such X-ray observations be used to determine cluster masses? [4 marks]

   (d) Describe two key observations and their interpretation that suggest the presence of a super massive black hole in the centres of massive galaxies. [4 marks]

   (e) Assume that the Sun, and a pulsar in the Milky Way's disc, are both on a circular orbit with radius $r = 8.0$ kpc around the centre of the Milky Way. The distance between Sun and pulsar is $d = 3.0$ kpc. Compute the cosine of the pulsar's galactic longitude l. [4 marks]

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7. (a) The Milky Way is said to have a flat rotation curve. What does this mean, and how has it been established? [2 marks]

   (b) Demonstrate that the observed flat rotation curve requires the Milky Way to have a dark matter halo with radial density distribution $\rho_{\rm dm}(r) \propto r^{-2}$. Neglect the contribution from stars and gas. [4 marks]

   (c) The average nearest neighbour distance between stars at the location of the Sun is 1 parsec. Estimate the mean density in stars, $\rho_\star$, assuming all stars have mass $M = 1M_\odot$. Use this to compute the ratio $\rho_\star/\rho_{\rm dm}$ of the density in stars over the density in dark matter at the solar location. Assume that the circular velocity $V_c = 220$ km s^{-1} and that the Sun is at distance $r_\odot = 8$ kpc from the Milky Way's centre. [4 marks]

   (d) Briefly describe the 'winding problem' of spiral arms. What is the solution to this problem? [2 marks]

   (e) The Milky Way has a central black hole with mass $M_{\rm BH} = 1 \times 10^6\, M_\odot$. Demonstrate that this does not contribute significantly to the rotation speed at $r_\odot$. [4 marks]

   (f) A star is on a circular orbit around the Milky Way's central black hole, with the Sun in the orbital plane. It's radial velocity v_d Doppler shifts between +620 km s^{-1} and -620 km s^{-1} along its orbit. The measured maximum angular extent of the orbit is $\theta = 0.58 \pm 0.01$ arc seconds. Use this to determine $r_\odot$ in kpc, and its uncertainty. Neglect the uncertainty in $M_{\rm BH}$ and v_d. [4 marks]

   [$M_\odot = 1.989 \times 10^{30}$ kg, 1 pc$= 3.0856 \times 10^{16}$ m]