University of Durham

EXAMINATION PAPER

May/June 2012 Examination code: 042621/01

LEVEL 2 PHYSICS: STARS AND GALAXIES

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

Time allowed : 3 hours

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 50% of the total marks for the paper. Answer **any three** of the four optional questions. 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:	$\epsilon_0 = 8.85 \times 10^{-12}\ \mathrm{F\,m^{-1}}$
Magnetic constant:	$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H\,m^{-1}}$
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:	$\sigma = 5.67 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$
Astronomical Unit:	$\mathrm{AU} = 1.50 \times 10^{11}$ m
Parsec:	$\mathrm{pc} = 3.09 \times 10^{16}$ m
Solar Mass:	$M_{\odot} = 1.99 \times 10^{30}$ kg
Solar Luminosity:	$L_{\odot} = 3.84 \times 10^{26}$ W

SECTION A. OBSERVATIONAL TECHNIQUES

Question 1 is compulsory. Question 2 is optional.

1. (a) Calculate the focal ratio of an 8-m telescope which has a plate scale of 2.34 arcsec/mm. [4 marks]

   (b) What is the absolute magnitude of a star measured to have apparent magnitude, $m = 9.5$, and an annual parallax of $p = 0.5$ arcsec? [4 marks]

   (c) What is the angular resolution of a radio dish of 100 m diameter, when observing at a frequency of 1.4 GHz? What is the angular diameter (in arcseconds) of a uniform circular source of physical diameter 1 parsec, when seen at a distance of 1 kiloparsec. If the brightness temperature of this source is 100 K, what is the measured antenna temperature? [4 marks]

2. (a) Write down the four major sources of statistical error in a CCD measurement of a star magnitude. [4 marks]

   (b) Which errors are usually governed by Poisson statistics and which are governed by Gaussian statistics? [2 marks]

   (c) For Poisson noise, if a process produces an average of N counts what will be the standard deviation? [1 mark]

   (d) Write down the general equation for the signal-to-noise (S/N) of a star's flux, f, measured using a CCD detector in a set exposure time, t. Include all the above four sources of noise. [3 marks]

   (e) ATLAS is a new CCD imaging survey aiming to reach the same depth as the previous SDSS survey. Both survey telescopes and instruments are identical except that the ATLAS CCD pixels are two times smaller in each of their linear dimensions. Relative to SDSS, what ATLAS exposure time will be required to reach the same S/N as SDSS in a passband where the observations are purely read-out noise limited? Assume that the star flux is completely contained in just one pixel for SDSS and 4 pixels for ATLAS. [4 marks]

   (f) In another passband, the sky noise is more significant relative to the readout noise. The readout noise is ± 2.5 analogue-to-digital units (ADU) for both SDSS and ATLAS CCDs and the sky background is 50 ADU in an SDSS pixel in a set exposure time. If the star flux is now assumed small compared to the sky background, what is the difference in the limiting magnitudes of ATLAS and SDSS, given identical limiting S/N and exposure time? Assume the same observing conditions for ATLAS and SDSS, a gain of 2 electrons/ADU and zero dark current for both ATLAS and SDSS CCDs and that the star flux is completely contained in one SDSS pixel and 4 ATLAS pixels. [6 marks]

SECTION B. STARS

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

3. (a) Calculate the radius of a white dwarf that is 10% of the luminosity of the Sun but has a surface temperature of 35,000 K. What pressure force prevents a white dwarf from collapsing? [4 marks]

   (b) Calculate the range of wavelengths that correspond to the Balmer series (n=2) of Hydrogen. Recall that

$$E = -13.6eV\left(\frac{1}{m^2} - \frac{1}{n^2}\right).$$

   [4 marks]

   [Hint: 1 eV is 1.60×10^{-19} J]

   (c) What are protostars? Why are protostars challenging to identify at optical wavelengths? [4 marks]

   (d) Briefly explain how sun spots are produced. Why is the umbra of a sun spot dark when compared to the penumbra and the solar surface? [4 marks]

   (e) State the generalised version of Kepler's third law. Use this law to determine the orbital period of a system comprised of two stars of 1 solar mass each that lie 1 AU apart. Assume a circular orbit and give your answer in years. [4 marks]

   (f) Estimate the time it would take for a photon to escape from the Sun on a "random walk". Assume a mean-free path of 0.009 m and scattering with a 10^{-8} s delay each time the photon is scattered. Give your answer in years. [4 marks]

   [Hint: the radius of the Sun is 6.96×10^{8} m]

   (g) By equating the gravitational force with the centrifugal force, show that the minimum rotation period of a spherical spinning pulsar of uniform density can be written as

$$P_{\min} = \left(\frac{3\pi}{G\rho}\right)^{\frac{1}{2}},$$

   where ρ is the density. [4 marks]

4. (a) Draw a Hertzsprung-Russell diagram to illustrate the evolution of a low-mass (1 $M_\odot$) and high-mass (25 $M_\odot$) star. Clearly label the axes, mark the track of the main sequence, and draw tracks to indicate the post-main sequence evolution of these stars up to (and including) the giant-branch phase. What limits the maximum luminosity of a star of a given mass? [6 marks]

(b) Derive an expression for the energy (E) available from the gravitational collapse of a spherically symmetrical star of constant density to show that $E = -\frac{3}{10}\frac{GM^2}{R}$, where M is the mass of the star and R is the post-collapse radius. Assume that the star is in virial equilibrium but state any other assumptions that you make in your derivation. Demonstrate that the gravitational collapse of the 2 $M_\odot$ core of a massive star is sufficient to power a supernova with a total energy output of 10^{46} J. State what you assumed for the post-collapse radius of the stellar core. [10 marks]

[Hint: the gravitational potential of a point mass is $dU = -\frac{GMdm}{r}$, where $dm = 4\pi r^2 \rho dr$ is a shell at radius r of density ρ and thickness dr]

(c) Why are a large number of neutrinos produced during the collapse of the stellar core in massive stars? Why were neutrinos detected several hours before the optical emission of SN1987A? [4 marks]

5. (a) What is the name of the main nuclear-fusion chain that occurs at the centre of the Sun? What direct observational evidence provides strong support for nuclear fusion as the power source of the Sun? [4 marks]

(b) Give an equation for the main-sequence lifetime of stars. List all terms used. Use this equation to calculate the main-sequence lifetime of the Sun assuming a nuclear-fusion efficiency conversion of 0.7% and that only 10% of the mass of the Sun is used for main-sequence nuclear fusion. Give your answer in years. [6 marks]

(c) The Coulomb barrier energy is the energy that particles require to get within the range of strong interactions. Calculate the ratio of the typical particle kinetic energy in a star to the Coulomb barrier energy. Assume a core temperature of 10^7 K, a pure Hydrogen gas, and that the range of the strong nuclear force is comparable to nuclear dimensions (i.e., 10^{-15} m). [6 marks]

(d) Why does nuclear fusion appear to be unfeasible on the basis of the classical approach taken above? Briefly explain what quantum effect needs to be considered to provide a better understanding of how nuclear fusion works, outlining the main principles behind this effect. [4 marks]

SECTION C. GALACTIC ASTRONOMY

Question 6 is compulsory. Question 7 is optional.

6. (a) Spiral galaxies are usually bluer than elliptical galaxies. Briefly discuss two reasons why. Describe two other differences between spirals and ellipticals. [4 marks]

   (b) Briefly describe the three main stellar components of a spiral galaxy. Which of these does the Sun belong to? [4 marks]

   (c) Which physical mechanism produces the X-rays observed from clusters of galaxies? How are these observations used to show that clusters contain dark matter? Include in this discussion how one determines the amount of baryonic matter in the cluster. [4 marks]

   (d) What is gravitational lensing? How did the MACHO collaboration use gravitational lensing to constrain the nature of the dark matter in the Milky Way? What was their conclusion? [4 marks]

   (e) The orbit of a star around the Milky Way's central black hole is observed to be circular, with a period of $P = 10.5$ years. The maximum extent of this orbit on the sky as seen from the location of the Sun is 0.19 arc sec and the maximum observed velocity difference along the orbit is 4400 km s^{-1}. Compute the Sun's distance to the galactic centre in kpc. [4 marks]

7. Assume that the Sun is on a circular orbit around the centre of the Milky Way, with radius $R_\odot = 8$ kpc and velocity $V_c = 220$ km s^{-1}.

   (a) Demonstrate that for a star on a circular orbit the mass enclosed by the orbit is $M(R) = RV_c^2/G$. Show that the enclosed Milky Way mass at the Sun's location is $M(R_\odot) = 0.90 \times 10^{11}\, M_\odot$. [4 marks]

   (b) Assume the Milky Way's rotation curve is flat up to $R_h = 140$ kpc. Compute the enclosed mass $M(R_h)$. If the rotation speed started declining at $R > R_\odot$, argue whether this would make $M(R_h)$ larger or smaller. [2 marks]

   (c) Briefly explain the winding problem in spiral galaxies, and its resolution. [3 marks]

   (d) The pattern speed of the Milky Way's spiral arms is measured to be $\Omega_p = 20$ km s^{-1} kpc^{-1}. Sketch the circular velocity of stars and of the spiral arms, as a function of radius, up to $R = 15$ kpc. [3 marks]

   (e) The width of the spiral arm at the Sun's location is $d = 1$ kpc. How long does it take for a star like the Sun to move through the arm? Express your answer in years. Argue from this whether the Sun enters the arm on its convex (outside) or concave (inside) side. [4 marks]

   (f) An HI gas cloud of mass $M = 1 \times 10^6\, M_\odot$ at $R = R_\odot$ is compressed as it enters a spiral arm, and starts forming stars. It forms 10 massive O-stars, each emitting ionising photons at a rate of $\dot{N} = 10^{48}$ per second. Assuming the stars start emitting as soon as the cloud enters the spiral arm, examine whether the ionising luminosity of the stars is enough to fully ionise the cloud before it leaves the arm. [4 marks]