University of Durham
EXAMINATION PAPER

Examination session:	Year:	Examination code:
May/June	2019	PHYS2621-WE01

Title:
Stars and Galaxies

Time allowed:	3 hours		
Additional material provided:	None		
Materials permitted:	None		
Calculators permitted:	Yes	Models permitted:	Casio fx-83 GTPLUS or Casio fx-85 GTPLUS
Visiting students may use dictionaries:	No		

Instructions to candidates:

- Attempt **all** questions. The short-answer questions at the start of each section carry 50% of the total marks for the paper. The remaining 50% of the marks are carried by the longer questions, which are equally weighted.
- 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.
- Slip your booklets for Sections B and C, in order, inside your booklet for Section A, before they are collected by the invigilator.

Information

Section A: Observational Techniques
Section B: Stars
Section C: Galactic Astronomy

A list of physical constants is provided on the next page.

Revision:	

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:	$k_\mathrm{B} = 1.38 \times 10^{-23}\ \mathrm{J\,K^{-1}}$
Bohr magneton:	$\mu_\mathrm{B} = 9.27 \times 10^{-24}\ \mathrm{J\,T^{-1}}$
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:	$R = 8.31\ \mathrm{J\,K^{-1}\,mol^{-1}}$
Avogadro's constant:	$N_\mathrm{A} = 6.02 \times 10^{23}\ \mathrm{mol^{-1}}$
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

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SECTION A: OBSERVATIONAL TECHNIQUES

1. (a) State four advantages of a modern CCD detector compared to the photographic plate. [4 marks]

   (b) A certain 30.0 meter diameter telescope has a focal ratio of $f\,/\,4.00$.

   (i) Calculate the effective focal length of the telescope. [1 mark]

   (ii) Calculate the plate scale of the telescope. Give your answer in units of arcseconds mm^{-1}. [3 marks]

   (c) The star Vega is observed with a stellar interferometer operating at a wavelength of 700 nm. When the telescopes are separated by 55.0 m, Vega is *just* resolved.

   (i) Calculate the angular size of Vega on the sky. Give your answer in units of milli-arcseconds. [1 mark]

   (ii) Calculate the distance to Vega if it has a parallax of $0.12''$. Give your answer in units of parsecs. [1 mark]

   (iii) Calculate the radius of Vega. Give your answer in units of the solar radii. [2 marks]
   [The radius of the Sun is $R_{\odot} = 7.00 \times 10^{8}$ m]

2. (a) Describe four effects of the Earths atmosphere on electromagnetic radiation passing through it, and one way in which each of these effects can be minimised when observing. [8 marks]

(b) Describe how the dark current, sky background and variations in the sensitivity of a CCD from pixel to pixel are measured and corrected for in an astronomical image. [4 marks]

(c) In October 2017, the extra-solar asteroid "Umauma" passed through the solar system. When it was discovered, the asteroid had a V-band magnitude of $\mathrm{m_V} = 21.4$ and was moving across the sky at a rate of $0.02''\,\mathrm{s}^{-1}$.

The asteroid was observed with the 8.00 meter diameter Very Large Telescope. If the exposure time is adjusted so that the image of the asteroid remains within a $1.00'' \times 1.00''$ pixel, calculate the photometric signal-to-noise ratio obtained in a single exposure.

In your calculation, assume that the observations are carried out in $1''$ seeing in the V-band, which is centered at $0.550\,\mu\mathrm{m}$ and the filter width is $\Delta\lambda = 0.05\,\mu\mathrm{m}$. Assume each pixel is $1.00'' \times 1.00''$ and that the sky brightness is 21.4 magnitudes arcsec^{-2}, the CCD has a gain of 1.00, the dark current and read noise are negligible and that the combined efficiency of the atmosphere plus CCD is 50%. A star with magnitude zero has a flux density of $3.92 \times 10^{-8}\,\mathrm{W\,m^{-2}\,\mu m^{-1}}$. [8 marks]

SECTION B: STARS

3. (a) A star is identified with a surface temperature of 6,000 K and a radius of 6000 km. Calculate the luminosity of the star. Evaluate what type of star has been identified. Justify your reasoning. [4 marks]

(b) In an eclipsing binary system, the time taken for the light to drop from uneclipsed to fully eclipsed is 3.5 hrs. The relative velocity of the smaller star with respect to the larger star is 40 km s^{-1}. Calculate the radius of the smaller star. [4 marks]

(c) Calculate the temperature at which radiation pressure exceeds gas pressure in the core of a star. In your calculation assume a particle density of $n = 1.00 \times 10^{31}$ m^{-3}. [4 marks]

[Hint: The radiation constant is $a = 7.57 \times 10^{-16}$ J m^{-3} K^{-4}]

(d) A horizontal-branch star has a mass of 1.00 $M_\odot$, luminosity of 3.00 $L_\odot$, and lifetime of 1.00×10^8 yrs. Assuming 7.59 MeV of energy is produced during each triple-alpha reaction, calculate the fraction of the mass of the star that is converted into carbon from helium over the horizontal-branch lifetime. [4 marks]

[Hint: 1 eV is 1.60×10^{-19} J; mass of helium: $m_{\mathrm{He}} = 6.65 \times 10^{-27}$ kg]

(e) The Schwarzschild condition for convection is satisfied in different regions for stars of different masses. Draw a cross section of a high-mass main-sequence star (15 $M_\odot$) and highlight where convection is believed to occur in this star. Why does convection occur in this region? [4 marks]

(f) What are protostars and what physical process is largely responsible for generating their radiative output? Why are protostars challenging to identify at optical wavelengths? [4 marks]

(g) List the four forms of pressure that prevent the collapse of a main-sequence star, a white dwarf star, and a neutron star. [4 marks]

4. (a) The instability strip is the region on the Hertzsprung-Russell diagram, where the majority of pulsating stars are found to lie. Draw a Hertzsprung-Russell diagram and highlight the main sequence, the instability strip, and the regions where red giants and white dwarfs lie. [6 marks]

(b) The period of radial pulsations of a star in the instability strip can be shown to be approximately,

$$\Pi \approx \sqrt{\frac{3\pi}{2\gamma G\rho}} \ ,$$

where Π is the period, γ is the ratio of the specific heats and ρ is the density. Assume $\gamma = 5/3$ in your calculations.

(i) Calculate the ratio of the densities of a white dwarf star with an observed radial pulsation period of 3.0 seconds compared to that of a red giant star with a period of 3.0 years. [3 marks]

(ii) The white dwarf star has a mass of 1.0 $M_\odot$ and luminosity of 1.0×10^{23} W while the red giant star has a mass of 3.0 $M_\odot$ and luminosity of 1.0×10^{31} W. Calculate the ratio of the surface temperatures of the two stars. State any simplifying assumptions you make in your calculation. [7 marks]

(c) What physical process drives radial pulsations in stars and where in stars do the pulsations originate? Why don't all stars show strong radial pulsations? [4 marks]

SECTION C: GALACTIC ASTRONOMY

5. (a) In Figure 1, galaxies occupy two regions labelled 'region I' and 'region II'. $M_\star$ is the total stellar mass of a galaxy and $\dot{M}_\star$ its star formation rate. These two regions correspond relatively well to spiral and elliptical Hubble types. Which region(s) corresponds to spirals and which to ellipticals? Explain your reasoning in terms of the optical properties of spirals and ellipticals. [4 marks]

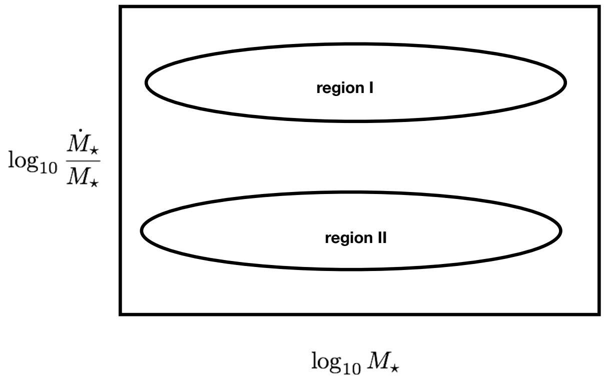

Figure 1: Location of galaxy populations 1 and 2 in a plot of stellar mass, $M_\star$ versus specific star formation rate, $\dot{M}_\star/M_\star$.

(b) In the interstellar medium of a galaxy, molecules are detected in the cold gas. Explain why hot gas does not contain molecules. [4 marks]

(c) Describe the physical process that produces the X-rays detected from clusters of galaxies. Is this gas mostly neutral or mostly ionised? Explain your reasoning. [4 marks]

(d) Briefly describe three observational manifestations of an Active Galactic Nucleus (AGN). Does the Milky Way galaxy harbour an AGN? Explain your reasoning. [4 marks]

(e) Describe the physical process that powers active galactic nuclei (AGN). How can you use the observed luminosity of an AGN to estimate the black hole mass? [4 marks]

6. (a) The Milky Way's rotation curve is flat. Why is this evidence for dark matter? [2 marks]

   (b) Obtain an expression relating the circular velocity, $V_c(r)$, at distance r from the centre in a spherically symmetric density distribution to the mass enclosed in the sphere of radius r, $M(r)$. Assume that the Sun is on a circular orbit with radius $d = 8.00$ kpc and circular velocity $V_c = 2.00 \times 10^2$ km s^{-1}. Evaluate your relation between V_c and M to compute the mass enclosed by the Sun's orbit. Express the result in solar masses. [4 marks]

   (c) The light from the Milky Way's disc follows an exponential distribution, $\Sigma(R) = \Sigma_\odot \exp(-(R-d)/R_c)$. In this expression, $\Sigma(R)$ is the luminosity per unit area at distance R from the centre of the Milky Way and $R_c = 3.00$ kpc. Prove by integration in polar coordinates that the total disc light, L, enclosed by the Sun's orbit is,

$$L = 2\pi R_c^2 \Sigma_\odot \exp(\delta) \left(1 - \exp(-\delta) - \delta \exp(-\delta)\right) ,$$

   where $\delta \equiv d/R_c$. [4 marks]

   (d) Take $\Sigma_\odot = 30.0$ L$_\odot$ pc^{-2}. Compute the luminosity of the disc enclosed by the Sun's orbit, L, in units of the Solar luminosity. [2 marks]

   (e) Use the result from part (d) to compute the total stellar mass, $M_\star$, enclosed by the Sun's orbit, assuming all Milky Way stars have the same mass and luminosity as the Sun. [2 marks]

   (f) Starting from the relation between stellar mass and stellar luminosity on the main sequence of the Hertzsprung-Russell diagram, discuss how $M_\star$ from part (e) would change if the average stellar mass of Milky Way stars were lower than that of the Sun. [2 marks]

   (g) Investigate whether the results obtained in (b) and (e) support the evidence that most of the enclosed mass is dark matter. [4 marks]

[Hint: up to a constant, $\int x \exp(-x) dx = -\left(x \exp(-x) + \exp(-x)\right)$.]