THE UNIVERSITY
of LIVERPOOL

SUMMER 2003 EXAMINATIONS

Degree of Bachelor of Science : Year 3
Degree of Master of Physics : Year 3

ADVANCED OBSERVATIONAL ASTRONOMY

TIME ALLOWED : Three Hours

INSTRUCTION TO CANDIDATES

Answer **all** questions.

Question 1 carries 40% of the total marks.

Questions 2 and 3 each carry 30% of the total marks.

The marks allotted to each part of a question are indicated in square brackets.

In the event of a student answering both parts of an either/or question and not clearly crossing out one answer, only the answer to part (a) of the question will be marked.

You are allowed to quote the following relation without proof:

The Planck function is

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{(e^{h\nu/kT} - 1)}$$

1. (a) Explain the method of construction and principles of operation of **Volume Phase Holographic** (VPH) gratings used in astronomical spectrographs. Discuss two advantages and one disadvantage of this type of grating when compared with conventional ruled gratings. [**5**]

(b) The 21cm line of Neutral Hydrogen is described as a *Hyperfine Structure Line*. Explain what this means in terms of the quantum numbers of the hydrogen atom. [**3**]

(c) Explain the physical mechanism which gives rise to *thermal bremsstrahlung* radiation. Outline two types of observation which can distinguish *thermal bremsstrahlung* from *synchrotron* radiation. [**6**]

(d) Give the definition of the terms **Responsive Quantum Efficiency** (RQE) and **Detective Quantum Efficiency** (DQE) when applied to an astronomical detector. An observer must choose between a Charge Coupled Device detector with an RQE of 80% and a readout noise of 5 electrons; and a noise-free Photon Counting Detector with an RQE of 15%, for spectroscopic observations of stars on a 1.0 metre aperture telescope. Spectral pixels are 1nm and all the light from the star falls within two spatial pixels along the slit. Slit losses are negligible, and the total efficiency of the optical system taking into account all losses due to atmospheric absorption, optical surfaces, obscuration, and vignetting is 20%. For a star of magnitude 18 in the V passband, calculate the Signal-to-Noise ratio above which the CCD reaches the desired Signal-to-Noise in the shorter time.
You may assume that a star of zero magnitude yields 10^8 photons/s/m^2/nm at the top of the atmosphere. You may neglect the contribution of sky background to the noise. [**10**]

(e) Explain why it is possible to build soft X-ray telescopes using grazing incidence optics. Sketch a Wolter Type I telescope, and explain how the collecting area of such a telescope can be increased. [**6**]

(f) Describe three types of detectors which are sensitive to Gamma rays. Explain how Laue diffraction can be used to construct a low resolution Gamma ray telescope. The spectral energy distribution of Gamma rays from a Gamma Ray Burst source shows a line at an energy of 350 keV. Explain the origin of this line. [**10**]

2. Answer **either** (a) **or** (b)

(a) (i) By summing the amplitude of the diffracted light from all slits in a grating, show that the disperser equation for a plane ruled reflection grating is $a(\sin i + \sin d) - m\lambda = 0$, where a is the grating ruling spacing, i and d are the angles of incidence and diffraction respectively, m is the spectral order and λ is the wavelength. [**6**]

An optical astronomical telescope has an aperture of 2 metres, and a focal length of 10 metres. We intend to design a spectrograph for use with an optical fibre feed, where the optical fibres present a diameter on the sky of 1 second of arc. Input and ouput focal ratios of the optical fibres are identical. The spectrograph will use a ruled reflection grating with a groove spacing of 1μm, and will use a collimator lens with an aperture of 100mm. The angle between the camera and collimator optical axes is 35 degrees. We will use the spectrograph in first order at a wavelength of 0.5μm.

(ii) What must the focal length of the collimator lens be? [**2**]

(iii) Using the disperser equation, derive two solutions for the angles of incidence and diffraction at the grating, and thus the blaze angle of the grating for efficient diffraction at 0.5μm. [**12**]

(iv) The spectrograph is operated *blaze to collimator*, so that the spectrograph beam expands as it comes off the diffraction grating in to the camera. What must the aperture of the camera lens be to accept all of the light from the grating? [**2**]

(v) Calculate the spectral resolving power of the spectrograph, assuming that it is not limited by the sampling of the detector. [**8**]

2 (continued).

(b) (i) Describe the principle of the *superheterodyne* radio receiver. What is the difference between a superheterodyne receiver designed to operate at above 40 GHz and one designed to be used at lower frequency? [**4**]

(ii) Demonstrate mathematically that a balanced receiver employing *Dicke switching* between a resistive load and the sky can reduce the effect of gain instabilities in a total power receiver. Sketch a schematic receiver circuit employing such switching. [**12**]

(iii) Describe three alternative methods of producing a comparison signal for switching used in radio spectral line observations, and describe the circumstances in which each can be used. [**6**]

(iv) Describe the principles of the *acousto-optic spectrometer*, for use at radio wavelengths. [**2**]

State the Bragg condition for the diffraction of a light wave through a Bragg cell. [**2**]

Derive an expression relating the change in the exit angle of the diffracted beam to the change in the frequency of the sound wave in the acousto-optic medium. [**4**]

3. Answer **either** (a) **or** (b)

(a) (i) What is meant by the *equivalent width* of an absorption line in the spectrum of a star? [**2**]

(ii) Describe three sources of broadening of absorption lines in a stellar spectrum. For each broadening mechanism explain what physical parameters the mechanism depends upon, and give with justification a functional form for the dependence of the *full width at half maximum* of the broadening upon these parameters. [**12**]

(iii) What is meant by the *curve of growth* of a spectral absorption line? Sketch the curve of growth of the CaII K absorption line in main sequence stars, and identify on this sketch three regions of different dependence upon the absorber column density, briefly explaining the physics which give rise to these dependences. [**8**]

(iv) Explain how the true profile of a stellar absorption line may be derived from an observed spectrum and an accurately determined instrumental response profile, both in digital form. Discuss how noise in the observed spectrum affects the derived profile, and describe a strategy at the data analysis stage for reducing the effect of this noise. [**8**]

3 (continued).

(b)

(i) Describe the principles of operation of a *bolometer*, illustrating your answer with a sketch of a block diagram showing the components of a bolometer. [**6**]

(ii) The performance of a bolometer is characterised by the Noise Equivalent Power (NEP). Give the definition of Noise Equivalent Power. [**2**]
Describe the two major contributions to the component of the NEP which is due to the detector, and show that there is a trade-off between NEP and detector response time when determining the thermal conductance between the absorber and the heat sink in a bolometer. [**6**]

(iii) In a *semiconductor bolometer*, the resistance can be characterised by $R = R_0 exp[(T_0/T)^{0.5}]$, where T is the temperature and R the resistance, and T_0 and R_0 are constants which are properties of the material. Derive a form for the temperature coefficient of resistance $\alpha = (T/R)(dR/dT)$. Explain why it is advantageous to make α as large as possible. [**3**]

(iv) Describe the principles of operation of *transition edge sensors* and explain their advantages compared with *semiconductor bolometers* at far infrared wavelengths. [**8**]

(v) Explain the principle of operation of a *quantum calorimeter*, and describe an application of *transition edge sensors* as *quantum calorimeters* discussing the factors which affect the design of the calorimeter. [**5**] (i) Describe the principles of operation of a *bolometer*, illustrating your answer with a sketch of a block diagram showing the components of a bolometer. [**6**]

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Physical Constants

EEP, November 1995

Quantity	*Symbol*	*Value*	*Units*
Speed of light	c	2.998×10^{8}	m s^{-1}
Permeability of free space	μ_0	$4\pi \times 10^{-7}$	H m^{-1}
Permittivity of free space	ϵ_0	8.854×10^{-12}	F m^{-1}
Charge on electron	e	1.602×10^{-19}	C
Planck's constant	h	6.626×10^{-34}	J s
Gravitational constant	G	6.673×10^{-11}	N m^{2} kg^{-2}
Atomic mass unit	u	1.660×10^{-27}	kg
Rest mass of electron	m_e	9.109×10^{-31}	kg
Rest mass of proton	m_p	1.673×10^{-27}	kg
Rest mass of neutron	m_n	1.675×10^{-27}	kg
Boltzmann's constant	k	1.381×10^{-23}	J K^{-1}
Avogadro's number	N_A	6.023×10^{23}	mol^{-1}
Universal gas constant	R	8.314	J K^{-1} mol^{-1}
Stefan-Boltzmann constant	σ	5.67×10^{-8}	W m^{-2} K^{-4}
Radiation constant	a	7.56×10^{-16}	J m^{-3} K^{-4}
Bohr magneton	μ_B	9.274×10^{-24}	A m^{2}
Nuclear magneton	μ_N	5.051×10^{-27}	A m^{2}
Acceleration due to gravity	g	9.81	m s^{-2}
Standard atmospheric pressure	1 atm	1.013×10^{5}	N m^{-2} (Pa)
Thomson cross section	σ_T	6.65×10^{-29}	m^{2}
Rydberg's constant for Hydrogen	R_H	1.09678×10^{7}	m^{-1}

Astronomical Constants

Quantity	*Symbol*	*Value*	*Units*
Earth mass	$M_\oplus$	5.980×10^{24}	kg
Earth radius	$R_\oplus$	6.378×10^{6}	m
Solar mass	$M_\odot$	1.989×10^{30}	kg
Solar radius	$R_\odot$	6.960×10^{8}	m
Solar luminosity	$L_\odot$	3.862×10^{26}	W
Solar effective temperature	$T_{eff\odot}$	5770	K
Astronomical unit	AU	1.496×10^{11}	m

Conversions

Quantity	*Symbol*	*Value*	*Units*
Gauss	G	10^{-4}	T
Erg	erg	10^{-7}	J
Electron volt	eV	1.602×10^{-19}	J
Parsec	pc	3.086×10^{16}	m
		3.262	light years
Jansky	Jy	10^{-26}	W m^{-2} Hz^{-1}