UNIVERSITY OF SOUTHAMPTON PHYS3011W1

SEMESTER 1 EXAMINATION 2013/14

PHOTONS IN ASTROPHYSICS

Duration: 120 MINS

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*Answer **all** questions in **Section A** and two **and only two** questions in **Section B**.*

Section A carries 1/3 of the total marks for the exam paper and you should aim to spend about 40 mins on it. Section B carries 2/3 of the total marks for the exam paper and you should aim to spend about 80 mins on it.

A Sheet of Physical Constants will be provided with this examination paper.

An outline marking scheme is shown in brackets to the right of each question.

Only university approved calculators may be used.

Section A

A1. Three radio sources are observed to have different spectra. In the first the flux density $F \propto \nu^2$, where ν is the photon frequency. In the second $F \propto \nu^{2.5}$ and in the third the flux density is independent of frequency. What physical process is likely to be the source of the radiation in each case and what type of astronomical objects could produce that radiation? [3]

A2. The spectrum of a radio source is described by $F \propto \nu^{-0.8}$, where F is the flux density and ν is the photon frequency, from low freqencies up to a frequency $\nu = 10^9$Hz. Above $\nu = 10^9$Hz the spectrum becomes much steeper. It is known that the magnetic field strength in the source is 10^{-9} T. Write down an expression which relates the lifetime of the radiating particles to the magnetic field strength. [2]

Given that for synchrotron emission the radiated frequency, ν, is related to the gyrofrequency of the emitting electrons, ν_g, by $\nu = \gamma^2 \nu_g$ where γ is the relativistic Lorentz factor of the electrons, estimate the age of the radio source in years. [4]

A3. The H_β emission line (rest wavelength = 486.1nm) in a very nearby active galaxy has a width of 30nm. Show that this width cannot be due to thermal Doppler broadening. [2]

It is noted that the variations in the intensity of that emission line lag behind the variations in the continuum adjacent to the line by 6 days. Estimate the mass, in units of the solar mass, of the black hole in the centre of the galaxy. [3]

A4. An star of radius 10^4 km has a luminosity of 3×10^{25} W in the ultraviolet waveband, 1.8×10^{25} W in the optical waveband and 1×10^{25} W in the infrared waveband. It does not emit in any other waveband. What is the effective temperature of the star? [2]

A5. Briefly describe the interaction when TeV ($> 10^{12}$eV) photons interact with the atmosphere. With the aid of a diagram, determine a relationship between the refractive index of the atmosphere, n, and the accuracy with which the direction of arrival of a TeV photon can be determined. Hence estimate that accuracy, in degrees, if $n = 1.0005$. [4]

Section B

B1. (a) Explain, with the aid of fully labelled diagram, why radiation is emitted by an accelerated electric charge. [3]

Show that the transverse electric field E_T, detected at a distance R from a charge q is given by

$$E_T = \frac{q\ a\ sin\theta}{4\ \pi\ \epsilon_0\ R\ c^2}$$

where a is the acceleration of the charge, θ is the angle between the direction of acceleration and the line of sight and c is the speed of light. [3]

(b) Define a differential scattering cross-section. [1]

Show that the differential scattering cross-section for a particle of charge q and mass m is $\dfrac{q^4 sin^2(\theta)}{16\pi^2\epsilon_0^2 c^4 m^2}$

where c is the speed of light and θ is the angle between the incident and scattered radiation. [5]

Hence calculate the classical radius of the electron. [2]

(c) For scattering from particles which are of size $<< \lambda$, deduce the form of the wavelength dependence of the scattered radiation. Give an example of where this wavelength dependence may be observed. Describe also the state of polarisation of the scattered radiation. [4]

State how the intensity of the scattered light varies with wavelength, λ, for scattering by particles which are of size (i) $\sim \lambda$ and (ii) $>> \lambda$ and give a situation in which each type of scattering can be observed. [2]

B2. (a) Describe the operation of three types of detector used in the infrared and millimeter wavebands. Give the advantages and disadvantages of each type, and the approximate wavelength ranges over which they operate. [9]

Describe briefly the limitations, as a function of wavelength, imposed by observing from the ground, on the near-IR to millimetre wavebands. Mention how these limitations may, to some extent, be mitigated. [2]

(b) Why are planets used as flux density calibration sources in the far-infrared and sub-millimetre observing bands? The surface temperature of Mars is approximately 250K. Given that the wavelength of peak emission of the Cosmic Microwave Background is at 1.1mm, estimate the wavelength of the peak emission from Mars. [3]

At one point in its orbit the planet Mars has an apparent diameter of 20 arcseconds as seen from the Earth. Estimate the flux density, in Janskys, which would be detected from Mars by a spacecraft in Earth-orbit, observing at a wavelength of 500μm. Justify any assumptions which you might make. [1Jy = 10^{-26} W Hz^{-1} m^{-2}] [3]

(c) An astronomical object is observed through a filter of bandwidth $\delta\nu$. The total count rate from the object is N_S photons per second per Hz of bandwidth. The background count rate on the detector in an area of the same size as the object image is N_B photons per second per Hz of bandwidth. Derive an expression for the signal to noise ratio of the detection if the observation time is τ. [2]

If the object covers an area of 5 mm^2 on the detector, $N_S = 1$ per second per Hz, $N_B = 1000$ per second per Hz per square cm of detector area, $\delta\nu = 10^4$ Hz and $\tau = 10$ seconds, calculate the signal to noise ratio of the detection. [1]

B3. (a) Describe the operation of two types of detector commonly used in X-ray astronomy but not used in the infrared or longer wavelength bands. Give the advantages and disadvantages of each type, and the energy ranges over which they operate. [6]

For a particular detector, one free electron is produced for every 3 eV of photon energy. What is the percentage energy resolution for a photon of energy 10 keV? [2]

(b) For an electron of mass m and velocity v in a collision with an ion of charge Ze at an impact parameter b, write down the approximate duration, Δt, of the collision, during which time the bulk of the electron's emission will be liberated. [1]

Hence show that the energy liberated in that one collision is given approximately by

$$\frac{\sigma_T c (Ze)^2}{16\pi^2 \epsilon_0 b^3 v}$$

where σ_T is the Thomson scattering cross-section, and c is the speed of light. [3]

Suggest a criterion by which we might estimate the minimum impact parameter b_{min} and show how that parameter is related to the gas temperature, T. [2]

Hence show that, for a completely ionised pure hydrogen plasma with proton number density N, the power radiated per unit volume of plasma, P, is given by

$$P \propto N^2 T^{1/2}.$$ [6]

B4. (a) Describe two astronomical observations which demonstrate that gravitational waves must exist. [3]

Mention two circumstances in which gravitational waves might be detected but electromagnetic radiation would not be. [2]

Describe how gravitational wave detectors work. Include in your answer a discussion of the sources of noise and how such sources may be overcome. Comment on the advantages of space-based instruments, with reference to the types of source which only they can detect. [6]

(b) The transverse electric field E_T, detected at a distance R from a charge q is

$$E_T = \frac{q\ a\ sin\theta}{4\ \pi\ \epsilon_0\ R\ c^2}$$

where a is the acceleration of the charge, θ is the angle between the direction of acceleration and the line of sight and c is the speed of light. By analogy with the expression for E_T write down the transverse gravitational field produced by an accelerated mass, such as one of the stars in a binary stellar system. [2]

By considering the transverse field produced by both masses in a stellar system, or otherwise, show that the luminosity of a source of gravitational waves of moment of inertia, I, is given by

$$L \propto \left(\frac{d^3 I}{dt^3}\right)^2 .$$ [7]

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