A15809S1

Honour School of Mathematical and Theoretical Physics Part C
Master of Science in Mathematical and Theoretical Physics

RADIATIVE PROCESSES AND HIGH ENERGY ASTROPHYSICS

Trinity Term 2019

THURSDAY 20TH JUNE 2019, 14:30 to SATURDAY 22ND JUNE 2019, 14:30

You should submit answers to all questions.

Answer booklets are provided for you to use but you may type your answers if you wish. Typed answers should be printed single-sided and the pages securely fastened together.

You may refer to books and other sources when completing the exam but should not discuss the exam with anyone else.

The numbers in the margin indicate the weight that the Examiners anticipate assigning to each part of the question.

Do not turn this page until you are told that you may do so

1. (a) [5 marks] It is commonly argued that charged particles may be accelerated to relativistic energies by non-relativistic shocks via the so-called *first-order Fermi process*. With an annotated diagram, explain how this process occurs, and give quantitative examples of the maximum particle energies expected in Galactic and Extra-galactic scenarios.

   (b) [10 marks] Take the probability that an individual particle may re-cross the shock to be p, and the factor by which the particle's energy is increased at each crossing to be β. Show that the resulting distribution function for particle energies after the acceleration process may be written as

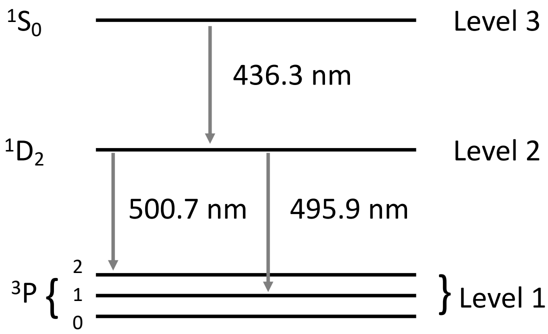
$$N(E)\,\mathrm{d}E \propto E^{-1+(\ln p/\ln\beta)}\,\mathrm{d}E.$$

   (c) [10 marks] In 2018, the *IceCube* experiment in Antarctica reported the detection of a muon neutrino with energy 290 TeV from the distant active galactic nucleus (AGN) TXS 0506+056 at redshift $z = 0.34$. Discuss how this detection may be used as evidence for the presence of protons at energies up to 10^{18} eV in the jet of the AGN, and explain why it is not expected that such protons would be detected directly from the AGN itself.

   Suppose that the plasma in the jet contains equal numbers of relativistic protons and electrons. What effect will this have on the synchroton luminosity of the AGN at radio frequencies? What other properties of the AGN might be affected by a large component of relativistic protons in the jet?

2. (a) [10 marks] Describe the processes that govern the relative number densities of ions of different excitation levels in typical astrophysical nebular conditions. You should consider spontaneous and collisional de-excitation processes, and explain how these processes allow astrophysicists to diagnose the temperature and density conditions in a nebula.

(b) [10 marks] The diagram shows several forbidden lines of doubly-ionized Oxygen, [O III]. These may be taken to comprise a three-level atom, with the doublet arising from the $2-1$ transitions to ^{3}P being taken as a single level with the mean photon energy of the two components of the doublet.



Derive equilibrium equations for the number densities of levels 3 and 2 relative to level 1. Under what conditions may these transitions be used as a diagnostic of the electron temperature? Show that, under such conditions, the observed emission line flux ratio may be expressed as

$$\frac{F_{32}}{F_{21}} = \frac{\nu_{32}}{\nu_{21}} \frac{A_{32}}{(A_{31}+A_{32})} \frac{\Omega_{13}}{\Omega_{12}} e^{-E_{32}/k_{\rm B}T_e}$$

where F_{ij} is the line flux; ν_{ij} is the line frequency; Ω_{ij} is the collision strength; A_{ij} is the transition probability; E_{ij} is the excitation energy and $T_{\rm e}$ is the electron temperature.

(c) [5 marks] Sketch a graph, with quantitative axes, of the line ratio as a function of electron temperature over the range of temperatures where this technique is useful. For a typical H II region and planetary nebula temperature, estimate the density limit at which the approximations assumed above break down.

Collision strengths and transition probabilities for [OIII]

Transition	Ω	$A\,(\mathrm{s}^{-1})$
$3 \rightarrow 2$	–	1.80
$3 \rightarrow 1$	0.34	0.23
$2 \rightarrow 1$	2.40	0.028

[The collisional de-excitation rate coefficient C_{ji} has the form

$$C_{ji} = 8.6 \times 10^{-12} \frac{\Omega_{ji}}{g_j} T_{\rm e}^{-1/2} \mathrm{m}^3\mathrm{s}^{-1}, \quad \text{where } g_j \text{ is the statistical weight.]}$$