The University Of Sheffield.

DEPARTMENT OF PHYSICS & ASTRONOMY **Autumn Semester 2013–14**

PARTICLE ASTROPHYSICS **2 hours**

Answer Question ONE (Compulsory) and TWO further questions.

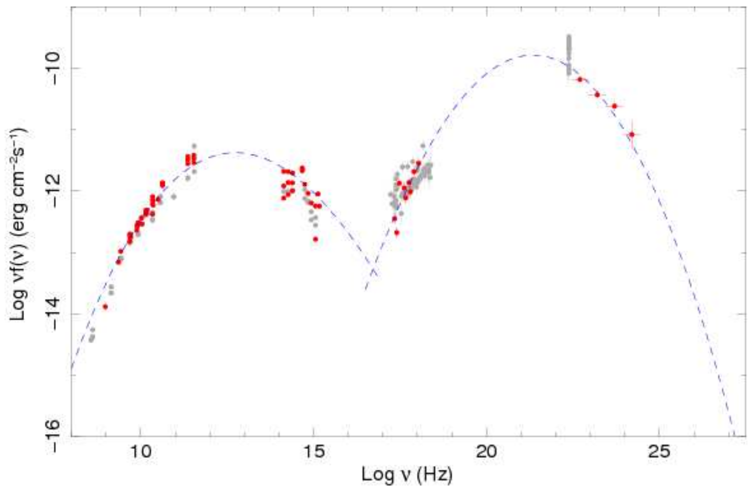
If you attempt more than the required number of questions, please indicate the questions on which you would like to be assessed on the front cover of your answer book, and cross out any work on which you do not wish to be assessed.

Question 1 is marked out of 30, and all other questions are marked out of 20. The breakdown on the right-hand side of the page is meant as a guide to the marks that can be obtained from each part.

A formula sheet and list of physical constants is attached to this paper.

1. **COMPULSORY**

The plot below shows the spectral energy distribution (SED) of a flat-spectrum radio quasar. Note that the y-axis of the plot is $\nu f(\nu)$, not simply $f(\nu)$.



(a) The dashed line shows a model fit to the emission from this object, which consists of two components. State what these components are and briefly explain how the radiation is produced in each case. [6]

(b) Would you expect the radio emission from this source to be polarised? Briefly justify your answer. [2]

(c) The SED shown above is the result of a coordinated multiwavelength observing campaign involving a number of different types of detector/telescope. For *either* the data between 10^{16} and 10^{18} Hz *or* those between 10^{21} and 10^{25} Hz, make an annotated drawing of a detector that might have been used to make these observations, explaining the purpose of each component. [6]

(d) Show that if two particles collide to create a final state of mass M, their energies and momenta are related by

$$2(E_1E_2 - p_1p_2\cos\theta) = M^2 - m_1^2 - m_2^2,$$

in units in which $c = 1$. [4]

Hence estimate the minimum energy that a cosmic ray proton must have in order to create a π^0 when colliding with a stationary proton, $p + p \rightarrow p + p + \pi^0$. [2]
[Note that the mass of the proton is 938 MeV/c^2, and of the π^0 135 MeV/c^2.]

(e) *Briefly* explain the following terms:

(i) bremsstrahlung; [2]

(ii) cyclotron radiation; [2]

(iii) quasi-parallel shock; [2]

(iv) coded-mask aperture; [2]

(v) Fermi second-order acceleration. [2]

2. (a) Explain why GeV-energy cosmic rays and γ-rays are observed using space-based platforms, whereas TeV-energy cosmic rays and γ-rays are observed from the ground. [2]

(b) Compare and contrast a typical installation for the ground-based observation of ultra-high-energy charged cosmic rays with one designed for the ground-based observation of ultra-high-energy γ-rays. Your account should include an explanation of the underlying physics behind the similarities and differences that you discuss. [8]

(c) The Cherenkov radiation emitted per unit time at angular frequency ω by a particle of charge Ze travelling at speed βc through a medium of refractive index n is given by

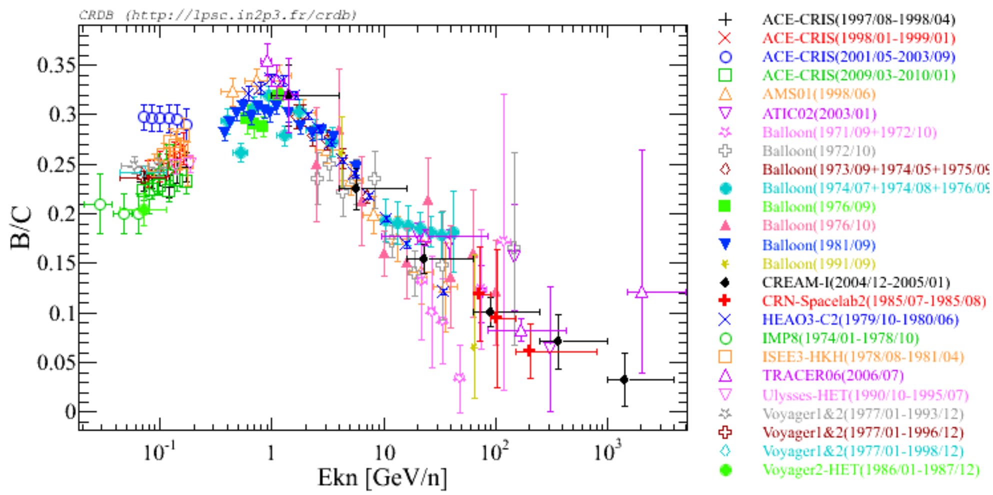
$$I(\omega) = \frac{\mathrm{d}E_{\mathrm{rad}}}{\mathrm{d}\omega \mathrm{d}t} = \frac{Z^2 e^2 \beta}{4\pi\epsilon_0 c}\left(1 - \frac{1}{n^2\beta^2}\right).$$

Hence explain why a cosmic-ray shower initiated by a heavy ion such as Fe can sometimes be identified in a Cherenkov telescope by the presence of a single bright pixel at the tip of the shower image. [4]

(d) Each of the pixels in the HESS-I telescopes subtends an angle of $6'$. If an iron nucleus interacts in the atmosphere at a height of 25 km, and its Cherenkov light is conned to a single pixel, estimate its kinetic energy, given that the atomic mass of iron is 56 u and assuming that for air at 25 km, $n - 1 = 1.01 \times 10^{-5}$. [6]

3. (a) Explain *two* methods by which the chemical or isotopic composition of cosmic rays can be measured, in each case carefully explaining the basis of the technique and any limitations that it has. [10]

(b) The plot below shows the ratio of boron to carbon abundance in cosmic rays, measured as a function of the kinetic energy per nucleon.



(i) Explain why the relative abundances of this particular pair of elements are useful in the understanding of cosmic rays. [4]

(ii) One set of data points at low energy, $E_k < 0.5$ GeV, seems to disagree with the rest of the data. Explain why this does not indicate a problem with this dataset. [2]

(c) Assuming that a cosmic ray with a gyroradius more than 1 kpc will random-walk out of the Galaxy over a time which is short compared to the Hubble time, estimate the maximum energy of cosmic ray protons of Galactic origin, given that the Galactic magnetic field is of order 1 μG (0.1 nT). Compare this with the observed spectrum of cosmic rays. [4]

4. (a) Derive the Rankine-Hugoniot shock jump conditions for a non-relativistic shock oriented perpendicular to the gas flow,

$$\rho_1 u_1 = \rho_2 u_2;$$
$$\rho_1 u_1^2 + p_1 = \rho_2 u_2^2 + p_2;$$
$$\frac{p_1 \gamma_g}{\rho_1(\gamma_g - 1)} + \frac{1}{2}u_1^2 = \frac{p_2 \gamma_g}{\rho_2(\gamma_g - 1)} + \frac{1}{2}u_2^2,$$

where ρ is the density, u the speed and p the pressure of the gas, the subscripts 1 and 2 refer to the two sides of the shock, γ_g is the ratio of specific heats, and all quantities are evaluated in the shock rest frame. You may assume the ideal gas law, $p = \rho(\gamma_g - 1)c_V T$ where c_V is the specific heat at constant volume. [8]

(b) Explain what is meant by the term *collisionless shock*. List the various types of collisionless shock that occur in the solar system and discuss the relevance of these solar-system shocks to theories regarding the acceleration of high-energy cosmic rays. [8]

(c) The fast component of the solar wind travels at about 750 km s^{-1}. Estimate how many shock crossings would be needed to accelerate a suprathermal ion with an energy of 0.1 MeV/nucleon up to typical Galactic cosmic-ray energies of order 100 GeV/nucleon, and comment briefly on your result. [4]

5. (a) Explain the difference between a pulsar wind nebula and a supernova remnant. [5]

(b) With particular reference to the Crab Nebula, discuss the problems of particle acceleration in pulsar wind nebulae, and explain why diffusive shock acceleration is probably not adequate to explain all the features of the Crab's high-energy emission. Describe at least two other mechanisms that have been proposed, and comment on their advantages and limitations. [15]

END OF QUESTION PAPER