The University Of Sheffield.

DEPARTMENT OF PHYSICS & ASTRONOMY **Autumn Semester 2012–13**

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**

(a) Draw the energy spectrum of charged cosmic rays, indicating the "knee" and the "ankle" and specifying their respective energies. Your diagram should have appropriate axis labels. [4]

(b) Explain why charged cosmic rays cannot themselves be used to identify their own astrophysical sources, and why TeV γ-rays and neutrinos may be used to do so instead. [4]

(c) Explain why radio emission from an astrophysical object can sometimes be a signature for the presence of high-energy particles in that object. Your account should specify which high-energy particles are involved, and explain their connection to the radio emission. [6]

(d) Compare and contrast *Fermi second-order acceleration* and *diffusive shock acceleration* (also known as Fermi first-order acceleration). [6]

(e) *Briefly* explain the following terms:

(i) spallation; [2]

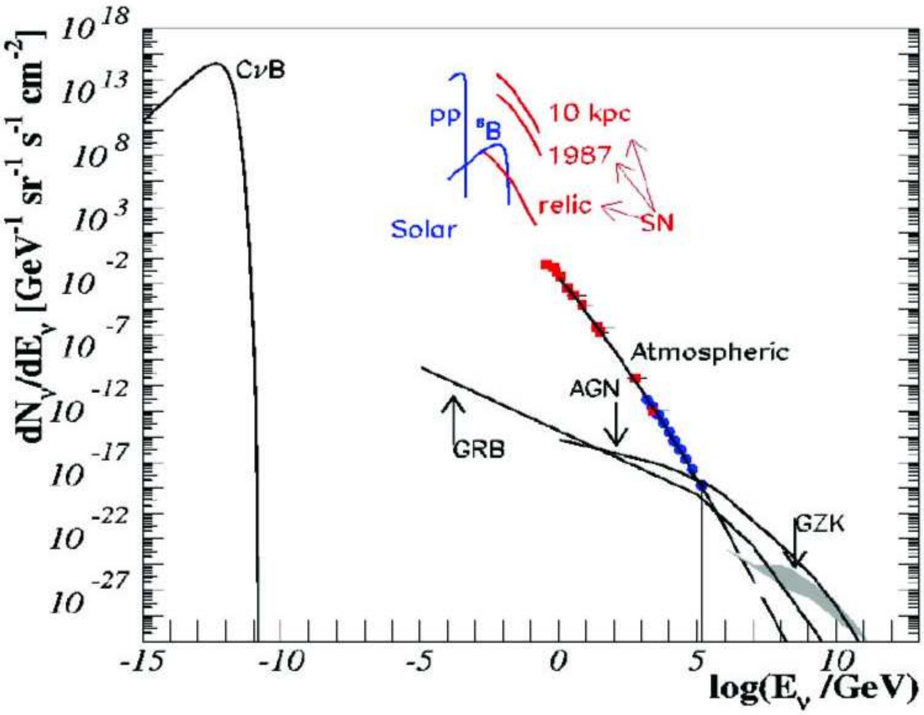
(ii) nitrogen fluorescence; [2]

(iii) collisionless shock; [2]

(iv) magnetic reconnection; [2]

(v) BL Lac object. [2]

2. (a) The image below shows the spectra of various types of astrophysical neutrinos.



(i) Explain how the neutrinos at the high end of this plot, with energies above 1 GeV, are produced in the atmosphere and in astrophysical sources. Given that the production mechanism is the same in both cases, why is the slope of the spectrum steeper for atmospheric neutrinos than it is for neutrinos from astrophysical sources? [5]

(ii) Explain what is meant by "GZK neutrinos" at the bottom right of this plot, and justify the fact that the GZK spectrum starts at about 10^7 GeV, stating any assumptions that you make. [You may need some or all of the following masses: proton 938.3 MeV/c^2, neutron 939.6 MeV/c^2, Δ^+ 1232 MeV/c^2, π^0 135.0 MeV/c^2, $\pi^\pm$ 139.6 MeV/c^2, $\mu^\pm$ 105.7 MeV/c^2, $e^\pm$ 0.511 MeV/c^2. The mean photon energy for a blackbody spectrum at temperature T is $2.7k_\mathrm{B}T$ where k_B is Boltzmann's constant.] [9]

(b) Neutrino telescopes such as IceCube sometimes test their angular resolution by looking for the neutrino shadow of the Moon. If the neutrino-nucleon charged-current cross-section is given by $\sigma_\mathrm{CC} = \sigma_0 E_\nu$, where $\sigma_0 = 6.8 \times 10^{-39}$ cm^2 GeV^{-1} and E_ν is the neutrino energy in GeV, and the Moon has a radius of 1737 km and a mean density of 3.53 g cm^{-3}, estimate the reduction in the flux of 10 TeV neutrinos at the centre of the Moon's shadow, stating any assumptions that you make. [6]

3. (a) Compare and contrast particle identification by *time of flight*, dE/dx and *Cherenkov radiation.* [8]

(b) You are building a space-based cosmic-ray experiment which will use time of flight to separate positrons from protons. Your two TOF counters are 2.00 m apart and each counter has a resolution of 120 ps. Up to what kinetic energy will your experiment be able to separate positrons and protons reliably (on an event-by-event basis, rather than by fitting distributions)? [6]

(c) Ground-based cosmic-ray experiments do not detect the primary particle, but rather the extensive air shower produced when the primary particle interacts high in the Earth's atmosphere. Discuss how, and to what extent, these experiments can identify particles, with relevance to (i) distinguishing between photons and hadrons and (ii) distinguishing between protons and heavy nuclei. [6]

4. For a relativistic particle making a return crossing of a highly relativistic shock, the particle energies before and after the return crossing are related by

$$\frac{E_f}{E_i} = \frac{1 - \beta_{\rm rel}\mu_1}{1 - \beta_{\rm rel}\mu_2}, \tag{1}$$

where $\mu = \cos\theta \simeq \beta_{\|}$ and all quantities are measured in the upstream rest frame.

(a) Assuming that the shock is highly relativistic, so that $(1-\beta_s) \ll 1$, show that the relative γ factor between the two sides of the shock, $\gamma_{\rm rel}$, is given by $\gamma_{\rm rel} = \gamma_{\rm s}/\sqrt{2}$, where $\gamma_{\rm s}$ is the γ factor of the shock in the upstream rest frame (or of the upstream gas in the shock rest frame). [4]

[You may assume that $\beta_2 = \frac{1}{3}$. The addition formula for relativistic velocities is $\beta_{1+2} = (\beta_1 + \beta_2)/(1 + \beta_1\beta_2)$, where $\beta = v/c$.]

(b) Hence show that equation (1) is equivalent to

$$\frac{E_f}{E_i} = \frac{1}{2}\gamma_s^2 \left(1 - \beta_{\rm rel}\mu_1\right)\left(1 + \beta_{\rm rel}\bar{\mu}_2\right), \tag{2}$$

where now $\bar{\mu}_2$ is measured by an observer in the *downstream* rest frame. [4]

[The Lorentz transformation for angles is $\cos\phi = (\cos\phi' + \beta)/(1 + \beta\cos\phi')$, where the primed frame is moving at speed βc relative to the unprimed frame.]

(c) By considering the extreme cases of (1) a seed particle from the thermal population of the upstream gas and (2) a highly relativistic seed particle from a population which is isotropic relative to the upstream gas, show that equation (2) leads to the conclusion that the first return shock crossing yields an energy gain of $E_f/E_i \sim \gamma_{\rm s}^2$. [8]

(d) Briefly explain (with or without mathematics) why this energy gain is not achieved on subsequent return trips through the shock. [4]

5. Write an essay on particle acceleration in shell supernova remnants. Your account should include discussion of the observational signatures of particle acceleration and a description of the corresponding theoretical models. [20]

END OF QUESTION PAPER