DEPARTMENT OF PHYSICS & ASTRONOMY
3459 EXAM-2
10:00 - 13:00 : December 11th 2007

Please read the exam guidelines, rules, instructions and marking criteria at `http://moodle.ucl.ac.uk/mod/wiki/view.php?id=13963&page=Final+exam` (linked from the *Exams and Coursework* page).

This exam is worth 50% of your final mark for the course. The duration of the exam is 3 hours. Students should upload the Java source code files for their solution using Moodle under the section headed "Exam 2".

High energy cosmic rays strike the upper atmosphere, resulting in particle "air-showers" that can be detected by instruments on the Earth's surface. The data from these cosmic ray detectors can be used to reconstruct the energies and arrival directions of the incident cosmic rays. An important goal is to try to determine the astrophysical sources of these extremely high energy particles.

You will write Java classes and methods to read data from two URLs, analyse the data and present the results. The two URL's are :

(1) `http://www.hep.ucl.ac.uk/undergrad/3459/exam-data/detections.txt`

(2) `http://www.hep.ucl.ac.uk/undergrad/3459/exam-data/sources.txt`

File (1) contains details of detected cosmic rays. Each line is of the form :

`LOG10-ENERGY THETA PHI`

where `LOG10-ENERGY` is the logarithm to the base 10 of the reconstructed cosmic ray energy in electron-Volts (eV), and `THETA` and `PHI` are the polar (θ) and azimuthal (ϕ) arrival angles of the cosmic ray, defined in a suitable celestial spherical coordinate system. All angles are in radians, with θ in the range $[0, \pi]$ and ϕ in the range $[0, 2\pi]$.

File (2) contains details of known astrophysical objects. Each line is of the form :

`TYPE THETA PHI`

where `TYPE` is a name representing the type of object and can take one of three values : `AGN` (Active Galactic Nucleus), `GRB` (Gamma-Ray Burst) and `ABH` (Accreting Black Hole). `THETA` and `PHI` are the polar and azimuthal angles of the object in the sky in the same coordinate system as the cosmic ray detections.

A simple way of determining whether cosmic ray arrival directions match a particular type of object is to compute the average minimum angular separation S_t between the cosmic rays and the objects of type t :

$$S_t = < \alpha^t_{min} > \quad .$$

For a given cosmic ray, α^t_{min} is the angle subtended between the cosmic ray arrival direction and the nearest object of type t. The average is then taken over the cosmic rays of interest. You will find the requisite formulae to compute these angles at the end of this paper.

- Determine the values S_t for the three types of astrophysical object, using all of the cosmic rays. Print out the type of astrophysical object showing the greatest correlation with the cosmic ray arrival directions. [**30/50 marks**]
- Determine the values S_t for the three types of astrophysical object, for two subsets of cosmic rays : those with energy $< 10^{18}$ eV, and those with energy $\geq 10^{18}$ eV. Compare the S_t values for the lower and higher energy cosmic rays. [**10/50 marks**]
- Modify your existing code and define appropriate interfaces so that :
  - Different separation functions S_t could be easily implemented.
  - The detected cosmic rays could have their energies and directions corrected by arbitrary functions before being analysed.

  Note that you do *not* need to provide specific implementations of alternative separation or correction functions. [**10/50 marks**]

The following results may be useful :

For a direction defined in spherical polar coordinates (θ, ϕ) you can find the corresponding Cartesian unit direction vector (x, y, z) using the following equations :

$$x = \sin\theta\cos\phi$$
$$y = \sin\theta\sin\phi$$
$$z = \cos\theta$$

The angle α subtended between two vectors of unit length $\vec{a}$ and $\vec{b}$ is given by :

$$\alpha = \cos^{-1}(\vec{a}\cdot\vec{b})$$

where :

$$\vec{a}\cdot\vec{b} = a_x b_x + a_y b_y + a_z b_z$$

END OF PAPER