### DEPARTMENT OF PHYSICS AND ASTRONOMY

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<th>PHY418</th>
<th>Particle Astrophysics</th>
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<th><strong>Autumn</strong></th>
<th>10 Credits</th>
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**Staff contact**
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### Outline Description
The LHC accelerates protons to kinetic energies of up to 7000 times their rest mass - a huge technological achievement. Yet, every second, over 500 million particles with energies greater than this collide with the Earth. Where do these particles come from, and how are they accelerated to these astonishing energies? These are, in fact, still open questions in astrophysics. In this module, we will look at the observational evidence for particle acceleration in astrophysical objects, the mechanisms available to accelerate particles, and some of the likely sources, including supernovae and supernova remnants, neutron stars, and active galaxies.

### Restrictions

### Prerequisites
PHY216 recommended, PHY304 or equivalent required

### Co requisites

### Approx Time allocation (hours)
22 Lectures, 2 problem solving classes, 74 independent learning

### Assessment (%) Examination 85, Class tests 15

### Aims
This course aims to
1. present the evidence for high-energy processes in astrophysics, in both the electromagnetic spectrum (from gamma rays to radio) and in high-energy particles (cosmic rays and neutrinos);
2. describe the techniques and instruments used to detect high-energy particles from astrophysical sources (gamma rays, neutrinos and cosmic rays);
3. discuss the mechanisms by which particles can be accelerated to high energies in astrophysical environments;
4. identify and describe those classes of astrophysical objects that provide such an environment, in particular supernovae and gamma-ray bursts, pulsars and supernova remnants, and active galactic nuclei;
5. discuss remaining open questions and future prospects in the field of particle astrophysics.

### Outcomes
On successful completion of this course, a student will be able to:
1. describe the mechanisms by which electromagnetic radiation is produced in the presence of a population of fast particles, namely synchrotron radiation, bremsstrahlung, the inverse Compton effect and neutral pion decays;
2. explain how cosmic rays, TeV gamma rays and neutrinos are detected by current and planned experiments;
3. summarise the observational evidence, from electromagnetic radiation and other observational signals, for the presence of populations of high-energy particles in some astrophysical objects;
4. derive expressions relating to diffusive shock acceleration in astrophysical environments;
5. explain the constraints that the observations place on the nature of astrophysical sources;
6. give a list of candidate source types, and describe the physical conditions therein and the observational evidence for populations of fast particles in these objects;
7. explain how observations can be used to distinguish different production mechanisms and discuss the importance of coordinated observing campaigns at different wavelengths;
8. summarise the current state of knowledge in the field and discuss possible future developments.

Recommended Books
(both recommended as supplementary reading but not required).

Syllabus

PROVISIONAL (new module)

1. Evidence for Astrophysical Accelerators
   1.1 Introduction: radiation from accelerated charged particles
   1.2 Radio astronomy
      Thermal and non-thermal continuum emission. Synchrotron radiation and evidence for fast electrons.
   1.3 X-ray and gamma-ray astronomy
      Detection of high-energy photons. Thermal bremsstrahlung and free-free emission.
   1.4 TeV gamma-rays
      Detection of TeV gamma-rays by atmospheric Cherenkov radiation. Identified sources.
   1.5 Cosmic rays
      Detection of cosmic rays by ground arrays or atmospheric fluorescence. Basic properties. Effect of the Galactic magnetic field.
   1.6 High energy neutrinos
      Detection of high-energy neutrinos by underwater or under-ice Cherenkov arrays. Backgrounds. Recent evidence from IceCube.

2. Acceleration Mechanisms
   2.1 General features
      Power law spectrum and energy range of cosmic rays. Effect of E and B fields on charged particles.
   2.2 Diffusive shock acceleration (aka Fermi first-order acceleration)
      Scattering of a particle off a moving magnetic field (Fermi second-order acceleration). Problems associated with this. Effect of considering particles diffusing across a shock front. Evidence for shock fronts in astrophysical objects.
   2.3 Production of high-energy photons
      Inverse Compton scattering and SSC vs decay of neutral pions.
   2.4 Production of high-energy neutrinos
      Decay of charged pions. Correlation or non-correlation of protons, neutrinos and high-energy gammas.
   2.5 GZK cutoff and implications
      Mechanism of GZK cut-off. Implications for range and energy of cosmic rays. Observational evidence.

3. Astrophysical Accelerators
   3.1 General considerations
      Requirements on size and B-field. Hillas plot.
   3.2 The Sun and the solar system
      Solar wind, planetary bow shocks, etc.
   3.3 Supernovae and gamma-ray bursts
      Properties of GRBs. Evidence for association of long/soft GRBs with luminous SNe Ic. GRB mechanisms.
   3.4 Pulsars, pulsar wind nebulae and supernova remnants
Spectral energy distributions of SNRs. Evidence for shock fronts and magnetic fields. Evidence for/against neutral pion decay signatures in some SNRs.

3.5 Active galaxies
   Introduction to active galaxies. Spectral energy distributions of AGN. Blazars as TeV gamma-ray sources. Possible correlation of UHE cosmic rays with nearby AGN.

4. Summary and Prospects
   4.1 Summary: the cosmos at very high energies
      Conclusions from study of high-energy particles and fast-particle signatures at lower energies.
      Remaining open questions.
   4.2 Prospects: new facilities and other improvements