Introduction: What is particle astrophysics?

- Particle astrophysics is the use of particle physics techniques (experimental or theoretical) to address astrophysical questions.
- Topics included:
  - early-universe cosmology (inflation, baryogenesis, dark energy)
  - cosmic rays
  - γ-ray astronomy
  - high-energy neutrino astronomy
  - low-energy neutrino astronomy
  - dark matter (see PHY326/426)

I will focus on high-energy particle astrophysics.
PHY418 Syllabus

• Introduction
  • brief outline of those topics I am not going to cover in detail

• High-energy particle astrophysics: the observations
  • cosmic rays
  • radio emission
  • high-energy photon emission (X-rays and γ-rays)
  • neutrinos

• Acceleration mechanisms
  • Fermi second-order
  • diffusive shock acceleration
  • magnetic reconnection

• Sources
  • case studies of the principal source types

PHY418 Resources

• There isn’t an ideal course text—so I have basically written one
  • too long to photocopy for you but you can download the pdf from the website (or from the MOLE reading list)
  • www.hep.shef.ac.uk/cartwright/phy418
  • this also contains copies of slides

• The nearest thing to a “proper” course text is Malcolm Longair, *High Energy Astrophysics* 3rd edition, CUP
  • several copies in IC
  • different organisation and emphasis compared to course
  • rather more detail in the mathematics
  • it is in SI units—note that a lot of texts at this level are in cgs
PHY418 Assessment

- End-of-semester exam (85%)
  - One compulsory question (30 marks)
  - Any two from four optional questions (20 marks each)
  - A practice exam will be provided since this is a new module

- Also short class tests (15%)
  - designed to test your ability to apply the taught material to problems
  - similar to exam questions (but without bookwork)
  - 3 (two during Observations, and one after Acceleration Mechanisms)
  - open notes format

INTRODUCTION TO PARTICLE ASTROPHYSICS

Early-universe cosmology
Early-universe cosmology

- In the early universe, energies are extremely high
  - appropriate physics is very high-energy particle physics
    - GUTs, string theory??
  - consequences in early universe
    - inflation (breakdown of GUT?)
    - baryogenesis (matter-antimatter asymmetry)
  - consequences in later universe
    - dark energy (vacuum energy? scalar field?)
    - dark matter (lightest supersymmetric particle? axion?)
- Particle physics of early universe is very difficult to test
  - energies are much too high for feasible accelerators

Inflation

- Observational evidence shows that the universe is
  - geometrically flat ($k = 0$ in Robertson-Walker metric)
  - extremely uniform at early times ($\Delta T/T \sim 10^{-5}$ in CMB)
  - not precisely uniform (with nearly scale invariant fluctuations)
- These properties are unexpected in the classical Big Bang model
  - no reason in GR why overall geometry should be flat
    - and if it is not flat originally it evolves rapidly in the direction of increased curvature
  - no expectation that the CMB temperature should be uniform
    - horizon distance expands faster than universe, so causally connected regions at ~400000 years correspond to only ~2° on sky now
  - if initial conditions force it to be uniform, no explanation for the fact that it is not quite uniform

notes section 1.2.1
Inflation

- Observational features can be accounted for by **inflation**
  - period of very fast (~exponential) expansion in very early universe
  - expansion $\dot{a} \propto e^{Ht}$ or $\dot{a} \propto a^n$, $n > 1$, will force geometry towards flatness and ensure that visible universe is causally connected
  - quantum fluctuations provide the anisotropies
    - with the right spectrum

Inflation and the inflaton

- Exponential expansion requires equation of state $P = -\mathcal{E}$ (vacuum energy)
  - this can be approximated by a **scalar field** (the **inflaton**) $\phi$:
    
    $$\mathcal{E}_\phi = \frac{1}{2\hbar c^3} \dot{\phi}^2 + V(\phi);$$
    $$P_\phi = \frac{1}{2\hbar c^3} \dot{\phi}^2 - V(\phi);$$
  - if the kinetic term is small this is *almost* a vacuum energy
  - this is very similar to the Higgs field (but expected mass of inflaton $\gg$ Higgs mass)
  - most extensions to Standard Model (e.g., supersymmetry) predict more Higgs fields
  - various models of inflationary cosmology exist
    - testable using CMB polarisation, cf. BICEP2
Baryogenesis

- The universe contains matter, but not antimatter
  - evidence: no annihilation signatures
- The amount of (baryonic) matter is small
  - ratio of baryons to photons $\sim 6 \times 10^{-10}$
- At some point in the very early universe, non-zero baryon number must be generated
- Sakharov conditions:
  - $B$ must be violated
  - reactions must take place out of thermodynamic equilibrium
  - $C$ and $CP$ must be violated

$B$ violation occurs in Standard Model
- via transitions called sphalerons which conserve $B - L$ but violate $B$ and $L$ separately (by 3 units)
- these are quantum tunnelling transitions which are suppressed to non-existence in the present universe but would have occurred easily at sufficiently high energies

Out-of-equilibrium conditions are natural
- in a rapidly expanding and cooling early universe

$C$ and $CP$ violation are observed in weak interactions
- level of $CP$ violation insufficient for observed asymmetry
- $CP$ violation may also occur in neutrino sector
Baryogenesis models

- **GUT baryogenesis**
  - takes place via heavy gauge bosons $X$ and $Y$
  - problem—may allow production of heavy GUT relics such as magnetic monopoles

- **Electroweak baryogenesis**
  - takes place at electroweak phase transition (~100 GeV)
  - problem: requires first-order phase transition to satisfy out-of-equilibrium condition, and this requires a light Higgs (<75 GeV/c$^2$, cf. 126 GeV/c$^2$)

Leptogenesis models

- Generate non-zero *lepton* number, convert to $B$ via sphaleron transitions
  - lepton number violation is testable at low energies via double $\beta$ decay
  - occurs if neutrinos are *Majorana particles* (neutrino and antineutrino are the same particle with different “handedness”)
  - expected in “seesaw models” which use massive right-handed neutrino to explain why (left-handed) neutrino mass so small compared to other fermions
  - possible link to axion dark matter
    - lightest of the “heavy” neutrino states could be linked to axion symmetry-breaking scale $f$ (see later)
Dark energy

- There is a great deal of observational evidence from astrophysics and cosmology that the expansion of the universe is currently accelerating
  - requires a component with equation of state $P = w \rho$ where $w < -1/3$
    ($w = -1$ is a vacuum energy or cosmological constant, $\Lambda$)

- Vacuum energy is “natural” because of spontaneous pair creation (uncertainty principle)
  - but “natural” value of $\Lambda$ is $\sim 10^{120}$ times too large!
Models of dark energy

- Vacuum energy plus weak anthropic principle
  - if $\Lambda$ had its “natural” value, we would not exist, therefore $\Lambda$ must be “unnaturally” small
  - works best in multiverse models such as chaotic inflation (there are then many other universes with “natural” $\Lambda$ and no life)
- Scalar field (as in inflation)
  - in this case the effective value of $\Lambda$ will evolve over time
  - in some “tracker” models it is constrained to stay close to the density of radiation or matter
- Modified gravity
  - especially in models with extra dimensions

Dark matter

- Much observational evidence that most matter in the universe is (a) non-luminous and (b) non-baryonic
  - non-luminous:
    - rotation curves of galaxies
    - gravitational potential of galaxy clusters
    - weak lensing maps
  - non-baryonic
    - comparison of light-isotope abundances with gravitational mass
    - comparison of X-ray luminosity of clusters with gravitational potential
    - power spectrum of CMB anisotropies
notes section 1.6
Dark matter properties

- From observations, dark matter must
  - not absorb or emit light (and hence, not interact electromagnetically)
  - because it is not seen, in emission or absorption, at any wavelength, and from CMB power spectrum which implies it does not interact with photons
  - not be hadronic (i.e. strongly interacting)
  - from discrepancy between light-element abundances and gravitational mass measurements
  - be non-relativistic at $z \sim 3000$
  - so that it can be bound in galaxy-sized potential wells when structures form
  - be stable or very nearly so
  - because mass measurements in local universe agree with CMB

- No Standard Model particle satisfies this list
  - neutrinos are closest, but are relativistic at $z \sim 3000$ ("hot")

Dark matter candidates

<table>
<thead>
<tr>
<th>Motivation</th>
<th>WIMPs</th>
<th>SuperWIMPs</th>
<th>Light $G$</th>
<th>Hidden DM</th>
<th>Sterile $\nu$</th>
<th>Axions</th>
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</thead>
<tbody>
<tr>
<td>Naturally Correct $\Omega$</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Possible</td>
<td>No</td>
<td>No</td>
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<tr>
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<td>Freeze Out</td>
<td>Decay</td>
<td>Thermal</td>
<td>Various</td>
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<td>Temperature</td>
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<td>Cold/Warm</td>
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<tr>
<td>Early Universe</td>
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<td>Direct Detection</td>
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<tr>
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</tbody>
</table>

GHP = Gauge Hierarchy Problem; NPFP = New Physics Flavour Problem
✓ = possible signal; ✓✓ = expected signal

Jonathan Feng, ARAA 48 (2010) 495 (highly recommended)
**WIMPs**

- Weakly Interacting Massive Particles
  - predicted by various extensions of the Standard Model, the most popular and widely studied being **supersymmetry** (SUSY)
  - in most variants of SUSY the lightest supersymmetric particle is absolutely stable
    - it is a “neutralino”, \( \chi^0 \) (a mix of the SUSY partners of the h, H, \( \gamma \) and Z)
  - These can be detected by identifying the recoil of an atomic nucleus struck by the WIMP
    - SUSY neutralinos can also be detected indirectly by identifying their annihilation products from regions of high WIMP density, e.g. the centre of the Sun
    - it is also possible that WIMPs could be produced at the LHC and identified as missing energy/momentum (they would not interact in the detectors)

**WIMP limits**

There are some claimed signals at low WIMP masses (not shown), but they are inconsistent with each other and with limits from other experiments.

Their interpretation is still unclear.

Axions

- The axion is a hypothetical particle arising from attempts to understand why the strong interaction conserves $CP$
  - in the Standard Model there is no reason why it should do so
- Axions are expected to be extremely light ($\mu$eV–meV), but are “cold” because they are not produced thermally
  - they arise from a phase transition in the very early universe
- Unlike WIMPs, axions do couple—extremely weakly—to photons and can be detected by the Primakoff effect
  - resonant conversion of axion to photon in highly tuned magnetic field
  - this coupling is the basis of the ADMX experiment (ask Ed Daw…)

Axion limits

Feng JI, 2010.
INTRODUCTION TO PARTICLE ASTROPHYSICS
Low energy neutrino astrophysics

Solar neutrinos

- Hydrogen fusion must involve neutrino emission:
  \[ 4 \, ^1\text{H} \rightarrow \, ^4\text{He} + 2\, e^+ + 2\nu_e \]
  - two protons get converted to two neutrons—must emit 2\, e^+ to conserve charge, then require 2\nu_e for lepton number
  - must be electron neutrinos as insufficient energy to produce \mu^+ or \tau^+
- Many routes to the final result
  - Q-values, and hence neutrino energies, vary
Solar neutrinos

- Detection techniques
  - inverse $\beta$ decay, e.g. $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$
    - low energy threshold, especially on $^{71}\text{Ga}$, but no directional or energy information
  - electron elastic scattering, $\nu + e^- \rightarrow \nu + e^-$
    - sensitive to all neutrino types, but mostly $\nu_\alpha$
  - capture on deuterium
    - CC: $\nu_\alpha + d \rightarrow p + p + e^-$
    - NC: $\nu + d \rightarrow p + n + \nu$
    - sensitive to all neutrino types

- Deuterium measurement established that solar neutrinos change flavour before detection (*neutrino oscillation*)

Supernova neutrinos

- 99% of the energy of a core-collapse supernova comes out as neutrinos
  - neutronisation pulse, $p + e^- \rightarrow n + \nu_\alpha$
  - thermal pair production

- Verified when neutrinos detected from SN 1987A
  - only 24, but enough to confirm energy scale

- Potential for a great deal of interesting physics in the event of a Galactic CCSN
  - thousands of neutrinos would be detected
Summary

- Particle astrophysics covers a very wide range of topics
  - early-universe cosmology
  - dark energy
  - dark matter
  - low-energy neutrino astrophysics
  - high-energy astrophysics
    - cosmic rays
    - radio emission from high-energy particles
    - high-energy photons
    - high-energy neutrinos

- This section has summarised the first four of these
- rest of course will focus on last topic

You should read sections 1.2, 1.3, 1.5.2, 1.5.3 and 1.6 of the notes

You should know about
  - inflation
  - baryogenesis
  - dark energy
  - dark matter
  - solar neutrinos
  - supernova neutrinos

Next: cosmic rays
- history
- detection techniques
- observed properties

Notes section 2.2

Energies and rates of the cosmic-ray particles