High Energy Astrophysics

Introduction

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Today’s introduction

- The sky at different wavelengths

- What is ‘High Energy Astrophysics’?

- Course description:
  - Aims and objectives
  - Course structure & topics
  - Recommended textbooks
  - Brief overview
  - Course evolution
The sky at different wavelengths

- Major part of what we observe is due to High Energy Astrophysics (HEA)
The sky at Optical Wavelengths

Whole sky at 500-600 nm

- Until 1945 Astronomy meant Optical Astronomy (frequency range 300-800nm)
  - Black-Bodies in the range 3000-10000K

- Optical waveband has a central role in Astrophysics:
  - large fraction matter Universe in stars \(~10M_{\text{Sun}}\) with long lifetime
    - these stars mainly emit in the optical region

- Optical spectrum very rich of emission and absorption features

Stars and nebulae
mainly in the
Galactic plane

Globular Clusters
and Galaxies

Dust strong
radiation absorber

Magellanic
Clouds
Radio Continuum (408 MHz, 73cm)

- Image dominated by radio emission of relativistic electrons spiralling in the interstellar magnetic field → Synchrotron emission

- High latitudes: isotropic distribution of mainly small angular diameter discrete extragalactic radio sources → Active Galactic Nuclei

→ Radio emission provides information about hot relativistic plasmas in the Universe
The sky at Millimetre Wavelengths

COBE / DMR - (53 GHz, 5.7mm)

- Differential map: intensity relative to mean temperature of the Cosmic Microwave Background Radiation $\rightarrow$ $T=2.736$ K

- Image dominated by the CMB ‘dipole’ component due to Earth motion ($\Delta T/T \approx 10^{-3}$)

- Galactic plane emission associated with extensive regions of ionised hydrogen $\rightarrow$ Hot electrons Free-Free emission (Bremsstrahlung)

http://lambda.gsfc.nasa.gov

CMB Dipole (6mK)

Galactic Free-free
The sky at Far-Infrared Wavelengths

IRAS (12, 60, 100µm)

- Dominated by galactic plane emission:
  → Thermal emission of heated dust grains → Regions with active star formation

- Top-right to bottom-left:
  → residual of thermal radiation from zodiacal dust on ecliptic plane

http://mwmw.gsfc.nasa.gov
The sky at Near-Infrared Wavelengths

COBE / DIRBE (1.25, 2.2, 3.5μm)

- Dust is transparent at these wavelengths:
  → Possible to look deep in regions obscured in the optical → galactic centre

- Emission mainly due to stars in galactic plane and galactic centre

http://mwmw.gsfc.nasa.gov
The X-ray sky

ROSAT / PSPC - (0.25, 0.75, 1.5 KeV)

- Concentration of bright sources towards the Galactic plane and the Galactic centre:
  → Supernovae Remnants, X-ray binary systems, stars with active stellar coronae
- High latitudes: isotropic distribution:
  → Active galaxies and Clusters of Galaxies (diffuse hot gas thermal free-free)
- Background of diffuse emission:
  → Integrated emission of discrete extragalactic X-ray sources
- Bright diffuse patches → Region of hot gas in our Galaxy
The \( \gamma \)-ray sky

CGRO / EGRET (\( >100\text{MeV} \))

- Galactic plane diffuse gamma-ray emission from interstellar gas:
  \( \rightarrow \) Produced by decay of \( \pi \) particles generated in collisions between cosmic ray protons / nuclei and interstellar gas

- High latitudes discrete sources: \( \rightarrow \) Quasars and pulsars in supernovae remnants

- Background at lower energies (\( <100\text{MeV} \)):
  \( \rightarrow \) Non-thermal processes like Inverse Compton Scattering and Bremsstrahlung
- The sky at different wavelengths
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What is High Energy Astrophysics? 1/2

- Area of astrophysics that involves:
  - High energy particles or plasmas:
    - Relativistic particles emitting non-thermal radiation (also Radio)
    - Very hot radiating gases and plasmas
  - High energy emitted radiation:
    - X-rays and $\gamma$-rays

- More in general:
  - Phenomena that involve physics under the most extreme conditions:
    - Very high densities, very large masses, relativistic velocities ...

Examples

- Physical processes in the interiors of neutron stars
- X-ray emission from accretion processes in X-ray binaries, etc.
- Acceleration of high energy particles in astronomical environments
- Massive black-holes in active galactic nuclei
- Origin of enormous fluxes of high energy particles from active galaxies
What is High Energy Astrophysics? 2/2

- HEA covers area of research undertaken by astrophysicists and physicists interested in high energy phenomena of all types

Deeper understanding of the behaviour of matter in physical conditions which cannot be reproduced in the laboratory. Often the astrophysical environment is the only one where these problems can be addressed.

- HEA is in very quick evolution:
  - Many mysteries have been recently solved and many others have arisen
  - This is a very exciting time for HEA!
Today’s introduction

- The sky at different wavelengths ✓
- What is ‘High Energy Astrophysics’? ✓

- Course description:
  - Aims and objectives
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Course aims & objectives

- To give an **introduction** to a wide range of exciting topics of modern astrophysics involving high energy processes

- To gain **basic knowledge** about the **sky** produced by high-energy processes or observed at high-energies

- To understand the **basic physical processes** creating the observed emission

- To get a **basic understanding** about the wide range of astrophysical high-energy **sources**

- To understand the **relative importance of competing** high-energy processes for a variety of sources

- To learn the **methods and observing techniques** to study high energy emission
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- **Classes:** 24 lectures
- **Assessment:** 1 hour 30 minutes examination in May/June
Recommended textbooks

HEA General

- Longair, "High Energy Astrophysics", CUP (2011)
- Vol 2: "The Stars, the Galaxy and the interstellar medium", (1992)


More on Physical Processes

- Frank, King & Raine, "Accretion power in astrophysics", CUP (2002)
Additional textbooks and material

Specific research topics

- Smith, “Observational Astrophysics”, CUP

Web resources

- On-line books (Many links will be given)
- Experiments websites

Course lecture slides

Available on the web:

- http://www.jb.man.ac.uk/~gp/
- Blackboard
Things to understand

Before we can identify astrophysical sources and interpret their emission, we need to understand how and what types of emissions can be created across the whole electromagnetic spectrum.

Essential Physics:
- Special relativity
- Radiative transfer
- Accretion (later on)

Astrophysical objects

Radiation processes:
- Black-Body radiation
- Bremsstrahlung (Free-free emission)
- Compton & Inverse Compton Scattering
- Synchrotron emission
- Self-absorption
Radiation process example: Synchrotron Radiation

Radiation emitted by very high energy electrons gyrating in a magnetic field

Equation of motion

Emitted radiation

Polarisation

Spectrum

\[ F(\omega/\omega_c) \propto \sqrt{\omega} \exp(-\omega/\omega_c) \]
Synchrotron Radiation from Extragalactic Radio Sources

- Optical emission

M31

- Radio emission ($\lambda=6\text{cm}$)

M51

Total intensity + B-Vectors (Effelsberg)

Total intensity + B (VLA)

MPIfR Bonn
Radiation process example: Inverse Compton Scattering

\[ h' = \gamma h (1 + \beta \cos \vartheta) \]
\[ h' \approx 2 \gamma h \]

\[ h' = \gamma h (1 - \beta \cos \vartheta_1) \]
\[ h_1 \approx 4 \gamma^2 h \]
Inverse Compton Scattering in Astrophysics

- Blazar spectrum

- Two broad peaks → Synchrotron Self-Compton process
**Supernovae and their remnants**

- SN 1994D in NGC 4526
- Kepler's SNR (SN 1604)

Supernova in another Galaxy

Supernova Remnant in our Galaxy (IR, Opt, X)

- Supernovae are explosions of massive stars, important because:
  - Birth event of neutron stars and stellar black-holes
  - Powerful sources of heating for ambient interstellar gas
  - Radio sources (Synchrotron in SNR magnetic fields)
  - Optical, UV and X-ray line emission
  - Intensive X-ray sources (Bremsstrahlung of hot gas)
  - Possible sources of high energy particles (Cosmic rays)
  - Origin of most of the heavy elements in nature
- SNRs in X-rays

- We will identify different phases in the SN remnant evolution
- A class of SNRs will present emitting central pulsars
Old Supernova Remnants

- Puppis A Remnant

- The SN explosion created and ejected the neutron star in one direction and much of the debris in the other

→ A fast moving neutron star as a cosmic cannonball!
Neutron Star Hypothetical internal structure

- Atmosphere
- Envelope
- Outer Crust
- Inner Crust
- Outer core
- Inner core
Pulsars

M1 - Crab Nebula (SN 1054)

- Pulsars are rapidly rotating neutron stars with intense magnetic fields:
  → Pulsar as superconductor rotating in its own strong magnetic field
  → Emission from magnetic poles, from radio waves to gamma-rays
    → Lighthouse effect: pulses observed when beams point towards us
    → Pulsed emission with very stable periods from 1.5ms to 8.5sec
- Binary pulsars to test General Relativity:
  → Gravitational waves emission
P-Pdot diagram

Pulsar Evolution

\[ \tau = \frac{P}{2\dot{P}} \]

Pulsar Characteristic Age

Braking index for magnetic dipole radiation

\[ n = 3 \]

Not always the case

Pulsar Magnetic Field

\[ B \approx 3.2 \times 10^{15} \sqrt{\dot{P}} \]

C.M. Espinoza (2009)
Pulsar Group - Manchester
**Accretion & X-Ray Binaries**

- Example of X-ray eclipsing binary star system: giant + rotating neutron star
  - Energy source is the infall of matter from primary star → Accretion
  - X-ray thermal emission of very hot gas that falls onto the neutron star magnetic poles

- There are X-ray sources where the invisible secondary star has mass greater upper limit for stable neutron star:
  → Black-Holes as candidates
Gamma-Ray Bursters (GRBs)

CGRO - 2704 BATSE

- Objects that emit short and extremely powerful flashes of gamma rays, two types:
  → Short duration GRBs (0.1-1 sec) & Long duration GRBs (10-100 sec)
- Isotropic distribution: → Extragalactic origin, located within distant galaxies
- Origin GRBs: → Possible scenarios: hypernovae and neutron star merger
Active Galactic Nuclei (AGNs)

Centaurus - A

- Active galaxies → Quasars, Blazars, Seyfert and Radio galaxies:
  → They can emit from Radio to X-ray (synchrotron form two radio lobes)
- Non-thermal emission near nucleus from Optical to far UV:
  → Continuum radiation that excites ions and atoms → strong UV lines
- Intense and often variable X-ray sources:
  → Expulsion of jets of ultra-relativistic plasma from the nuclei
- Energy demands and timescales extreme (nuclear energy not adequate):
  Active galactic nuclei → Super-massive Black-Holes
Instrumentation in HEA

- Wolter type X-ray Mirrors

- Mirrors can only be used at grazing incidence with X-ray photons
Evolution of this course

- This course is in a continuous **evolution** because of these extremely fast evolving topics

- The new textbooks as well as new experimental results will be used to **update** specific topics

- Don’t worry! All the **references** will be given at the beginning of each topic

- The **lecture slides** will contain all the information needed for your exam
  BUT they will not be necessarily enough for a proper understanding!
  → Further reading is important during this learning process

- **Problems** will be given at the end of the Thursday lecture and will be solved together the following Monday during the first part of the lecture

- Remember: this course is **FOR YOU** → it is vital your **feedback** to me!
  → e-mail me about suggestions, ask for better explanations, etc.
Introduction

Next lecture

Essentials

- Electromagnetic spectrum
- Radiation propagation & definitions
- Radiative transfer
- Thermal and Black-Body radiation
- Special relativity formulae