

1 An Overview of Multimessenger Astrophysics

1.1 Introduction

- Multimessenger astrophysics integrates observations from different cosmic messengers: electromagnetic radiation, cosmic rays, neutrinos, and gravitational waves.
- The field addresses fundamental questions about the Universe, such as the nature of dark matter and the processes powering extreme cosmic phenomena.

1.2 Astrophysics and Astroparticle Physics

- Astrophysics focuses on macroscopic systems like stars and galaxies, while astroparticle physics connects these phenomena with particle physics.
- Cosmic rays provide a bridge, allowing particle physics experiments to probe astrophysical environments.

1.3 Multimessenger Astronomy

- By combining data from different messengers, multimessenger astronomy provides a comprehensive view of cosmic events.
- Examples include the detection of neutrinos and gravitational waves from neutron star mergers.

1.4 Experimental Results Not Covered in This Book

- Certain topics, such as low-energy cosmic rays and detailed gamma-ray spectra, are excluded to maintain the focus on high-energy phenomena.

1.5 Cosmic Rays

- Cosmic rays are charged particles, primarily protons and nuclei, accelerated to high energies by astrophysical processes.
- Their energy spectrum spans many orders of magnitude, with notable features like the "knee" and "ankle."

1.6 Gamma Rays of GeV and TeV Energies

- Gamma rays provide insights into the most energetic processes in the Universe, such as supernova remnants and active galactic nuclei.
- Observations rely on space telescopes (e.g., Fermi-LAT) and ground-based Cherenkov detectors (e.g., HESS, MAGIC).

1.7 Neutrino Astrophysics

- Neutrinos, produced in nuclear reactions and cosmic accelerators, are unique messengers as they interact weakly and travel unimpeded.
- High-energy neutrinos detected by IceCube are linked to blazar flares and cosmic ray sources.

1.8 Gravitational Waves

- The detection of gravitational waves has opened a new window into astrophysics, revealing insights into black hole mergers and neutron star collisions.
- Observatories like LIGO and Virgo lead this field.

1.9 The Dark Universe

- Dark matter and dark energy constitute over 95% of the Universe's mass-energy content.
- Indirect searches for dark matter focus on signals like gamma rays or neutrinos from annihilation or decay.

1.10 Laboratories and Detectors for Astroparticle Physics

1.10.1 Space Experiments

- Satellites like AMS-02 and Fermi-LAT operate above the atmosphere, detecting high-energy particles and photons.

1.10.2 Experiments in the Atmosphere

- Balloon-borne detectors capture cosmic rays in the upper atmosphere, providing complementary measurements to space experiments.

1.10.3 Ground-Based Experiments

- Ground-based observatories, such as Cherenkov telescopes and extensive air shower arrays, study cosmic rays and gamma rays indirectly.

1.11 Underground Laboratories for Rare Events

- Shielded from cosmic ray background, underground facilities search for rare processes, such as neutrinoless double beta decay and dark matter interactions.
- Examples include the Gran Sasso Laboratory and SNOLAB.

2 Primary Cosmic Rays and Galactic Properties

2.4 A Toy Telescope for Primary Cosmic Rays

- A toy telescope concept simplifies cosmic ray detection by focusing on key parameters: charge, momentum, and energy.
- Proportional counters and scintillators measure the particle's energy loss (dE/dx), which depends on the charge squared (Z^2).
- The relation for specific energy loss:

$$-\frac{dE}{dx} \propto Z^2, \quad (1)$$

where Z is the particle charge.

2.5 Differential and Integral Flux

- The differential flux $\Phi(E)$ quantifies particles per unit area, time, energy, and solid angle:

$$\Phi(E) = \frac{d^2 N}{ATdEd\Omega}. \quad (2)$$

- The integral flux $\Phi(> E_0)$ represents particles with energy above E_0 :

$$\Phi(> E_0) = \int_{E_0}^{\infty} \Phi(E) dE. \quad (3)$$

2.6 The Energy Spectrum of Primary Cosmic Rays

- Cosmic ray energy spectra follow a power-law distribution:

$$\Phi(E) \propto E^{-\alpha}, \quad (4)$$

where α is the spectral index.

- Features like the "knee" and "ankle" mark transitions in the spectrum, indicating changes in source or propagation effects.

2.7 The Physical Properties of the Galaxy

2.7.1 The Galactic Magnetic Field

- Galactic magnetic fields (average strength $\sim 4\mu G$) influence cosmic ray propagation via diffusion and confinement.
- The Larmor radius r_L of a charged particle is:

$$r_L = \frac{pc}{ZeB}, \quad (5)$$

where p is momentum, B is the magnetic field strength, and Ze is charge.

2.7.2 The Interstellar Matter Distribution

- Cosmic rays interact with interstellar gas (density $n_H \sim 1 \text{ cm}^{-3}$), producing secondary particles.
- Key components include molecular clouds, atomic hydrogen, and ionized gas regions.

2.8 Low-Energy Cosmic Rays from the Sun

- Solar energetic particles (SEPs) dominate the low-energy cosmic ray spectrum.
- SEPs are produced during solar flares and coronal mass ejections, with energies typically below 100 MeV.
- Solar modulation affects cosmic rays entering the heliosphere, reducing their intensity at low energies.

2.9 The Effect of the Geomagnetic Field

- The Earth's magnetic field shields against low-energy cosmic rays, depending on latitude and rigidity.
- The rigidity cutoff R_c determines the minimum momentum required for a particle to penetrate:

$$R_c \propto \frac{B_E R_E^2}{r^2}, \quad (6)$$

where B_E is the Earth's magnetic field strength, R_E is the Earth's radius, and r is the distance from the center.

3 Direct Cosmic Ray Detection: Protons, Nuclei, Electrons, and Antimatter

3.1 Generalities on Direct Measurements

3.1.1 Generalities and "Data Mining"

- Direct measurements of cosmic rays involve capturing particles before they interact with the atmosphere.
- Instruments onboard satellites or balloons collect data on particle type, energy, and direction.
- "Data mining" analyzes large datasets to identify trends and rare events in cosmic ray spectra.

3.1.2 Energy and Momentum Measurements

- Magnetic spectrometers measure momentum by tracking particle trajectories in a magnetic field.
- Calorimeters determine energy via particle energy deposition.
- The relationship between rigidity R , charge Z , and momentum p is given by:

$$R = \frac{pc}{Ze}, \quad (7)$$

where e is the elementary charge and c is the speed of light.

3.2 The Calorimetric Technique

3.2.1 Hadronic Interaction Length and Mean Free Path

- Hadronic particles interact with nuclei in the detector material, producing showers of secondary particles.
- The hadronic interaction length λ_h determines the probability of interaction per unit depth:

$$P = 1 - e^{-x/\lambda_h}, \quad (8)$$

where x is the thickness of the material.

3.2.2 The Electromagnetic Radiation Length

- Electromagnetic showers are characterized by the radiation length X_0 , the distance over which particle energy decreases by $1/e$.
- For photons and electrons, X_0 depends on material properties:

$$X_0 \propto \frac{1}{Z(Z+1) \ln(287/\sqrt{Z})}, \quad (9)$$

where Z is the atomic number.

3.3 Balloon Experiments

- Balloon experiments are crucial for high-altitude cosmic ray detection, operating above most of the atmosphere.
- Notable examples include BESS (Balloon-borne Experiment with a Superconducting Spectrometer) and TRACER (Transition Radiation Array for Cosmic Energetic Radiation).
- Advantages include lower costs compared to satellites and the ability to deploy large instruments.

3.5 The AMS-02 Experiment on the International Space Station

- AMS-02 is a state-of-the-art magnetic spectrometer onboard the ISS, designed to measure cosmic ray composition and spectra.
- It can distinguish between particle types (protons, nuclei, positrons) and detect rare antimatter events.
- Key results include precise measurements of the positron fraction and hints of dark matter annihilation signals.

3.6 Abundances of Elements in the Solar System and in Cosmic Rays

- Cosmic ray abundances differ from solar system abundances due to propagation effects and nucleosynthesis.
- Secondary cosmic ray nuclei (e.g., Li, Be, B) are more abundant in cosmic rays due to spallation during propagation.

3.9 Antimatter in Our Galaxy

- Antimatter particles (e.g., positrons, antiprotons) are rare but detectable components of cosmic rays.
- Possible sources include dark matter annihilation, pulsars, and secondary production during propagation.
- Observations from AMS-02 show unexpected features in the positron spectrum.

3.10 Electrons and Positrons

3.10.1 The Positron Component

- The positron flux in cosmic rays exhibits an excess above 10 GeV, possibly linked to nearby pulsars or dark matter.
- The positron fraction $f(e^+)$ is defined as:

$$f(e^+) = \frac{N(e^+)}{N(e^+) + N(e^-)}, \quad (10)$$

where $N(e^+)$ and $N(e^-)$ are the positron and electron fluxes.

3.10.2 Considerations on the e^+, e^- Components

- Electrons lose energy rapidly through synchrotron radiation and inverse Compton scattering.
- Observed spectra are shaped by both source distribution and propagation effects in the Galaxy.

4 Indirect Cosmic Ray Detection: Particle Showers in the Atmosphere

4.1 Introduction and Historical Information

- Cosmic ray detection through particle showers in the atmosphere dates back to early studies of cosmic rays by Victor Hess and others.
- Extensive air showers (EAS) are produced when primary cosmic rays interact with atmospheric nuclei, creating cascades of secondary particles.

4.3 The Electromagnetic (EM) Cascade

4.3.1 Heitler's Model of EM Showers

- Heitler's model provides a simplified description of electromagnetic cascades initiated by high-energy photons or electrons.
- The shower develops as particles undergo pair production ($\gamma \rightarrow e^+ + e^-$) and bremsstrahlung ($e \rightarrow e + \gamma$).
- The number of particles in the shower doubles approximately every radiation length X_0 .

Key Equation for Shower Development

The number of particles N at depth X is given by:

$$N(X) \approx 2^{X/X_0}, \quad (11)$$

where X is the depth and X_0 is the radiation length.

4.3.2 Analytic Solutions

- Energy conservation in the shower leads to an exponential decrease in particle energy.
- The average energy per particle is:

$$E_{\text{avg}} = \frac{E_0}{N(X)}, \quad (12)$$

where E_0 is the initial energy.

4.4 Showers Initiated by Protons and Nuclei

4.4.1 The Muon Component in a Proton-Initiated Cascade

- Proton showers produce muons through the decay of charged pions ($\pi^+ \rightarrow \mu^+ + \nu_\mu$).
- Muons are the dominant component at ground level due to their long lifetime and minimal energy loss.

4.4.2 The EM Component in a Proton-Initiated Cascade

- Secondary electrons and photons form an electromagnetic sub-cascade within the hadronic shower.

4.4.3 Depth of the Shower Maximum for a Proton Shower

- The depth of maximum development X_{max} is greater for proton showers compared to pure EM showers.
- X_{max} scales with the logarithm of the primary energy:

$$X_{\text{max}} \propto \ln(E). \quad (13)$$

4.4.4 Showers Induced by Nuclei: The Superposition Model

- Nuclei-induced showers are treated as a superposition of A independent proton showers, where A is the mass number.
- The total energy E_0 is divided among the nucleons:

$$E_{\text{nucleon}} = \frac{E_0}{A}. \quad (14)$$

5 Diffusion of Cosmic Rays in the Galaxy

5.1 The Overabundance of Li, Be, and B in Cosmic Rays

5.1.1 Why Li, Be, B Are Rare on Earth

- Lithium, beryllium, and boron (Li, Be, B) are light nuclei that are relatively rare in terrestrial and stellar environments due to their low binding energy, making them easily destroyed in stellar interiors.

5.1.2 Production of Li, Be, and B During Propagation

- Li, Be, and B are produced by spallation reactions when primary cosmic rays (e.g., C, O nuclei) collide with interstellar matter.
- The production rate is proportional to the cross-section of spallation reactions σ :

$$Q_s \propto \sigma_{pp} n_H, \quad (15)$$

where n_H is the hydrogen density in the interstellar medium.

5.2 Dating of Cosmic Rays with Radioactive Nuclei

5.2.1 Dating “Lived” Matter with ^{14}C

- Cosmic-ray dating uses the decay of unstable isotopes like ^{14}C to estimate the age of matter exposed to cosmic rays.
- The lifetime τ of a radioactive nucleus is:

$$\tau = \frac{1}{\lambda}, \quad (16)$$

where λ is the decay constant.

5.2.2 Unstable Secondary-to-Primary Ratios

- Ratios like $^{10}\text{Be}/^9\text{Be}$ are used to estimate cosmic ray residence times in the Galaxy.

5.3 The Diffusion-Loss Equation

5.3.1 The Diffusion Equation with Nuclear Spallation

- The diffusion-loss equation balances sources, propagation, and losses of cosmic rays:

$$\frac{\partial N}{\partial t} = Q - \nabla \cdot (D \nabla N) - \frac{N}{\tau}, \quad (17)$$

where N is the particle density, Q is the source term, D is the diffusion coefficient, and τ is the loss time.

5.3.2 Numerical Estimate of the Diffusion Coefficient D

- The diffusion coefficient depends on energy as:

$$D(E) \propto \left(\frac{E}{E_0} \right)^\delta, \quad (18)$$

where δ is an empirical parameter.

5.4 The Leaky Box Model and Its Evolutions

- In the leaky box model, cosmic rays are confined to a finite volume with a probability of escape.
- The escape time τ_{esc} is related to the diffusion coefficient:

$$\tau_{\text{esc}} \propto \frac{1}{D}. \quad (19)$$

5.5 Energy Dependence of the Escape Time τ_{esc}

- The escape time decreases with increasing energy:

$$\tau_{\text{esc}}(E) \propto E^{-\delta}. \quad (20)$$

5.6 Energy Spectrum of Cosmic Rays at the Sources

- The observed spectrum combines the source spectrum and propagation effects.
- The energy spectrum at the source is typically a power law:

$$\Phi(E) \propto E^{-\alpha}, \quad (21)$$

where α is the spectral index.

5.7 Anisotropies Due to the Diffusion

5.7.1 Evidence of Extragalactic Cosmic Rays Above 8×10^{18} eV

- Above 8×10^{18} eV, cosmic rays show an isotropic distribution, suggesting extragalactic origins.

5.7.2 The Compton–Getting Effect

- The Compton–Getting effect describes anisotropies in cosmic ray flux due to Earth’s motion relative to the cosmic ray source.
- The relative intensity change $\Delta I/I$ is:

$$\frac{\Delta I}{I} = \frac{v}{c} (\gamma + 2), \quad (22)$$

where v is the velocity of Earth and γ is the spectral index.

6 Galactic Accelerators and Acceleration Mechanisms

6.1 Second- and First-Order Fermi Acceleration Mechanisms

Particle acceleration occurs in astrophysical environments through interactions with magnetic fields and shock waves.

6.1.1 Magnetic Mirrors

Magnetic mirrors accelerate particles via reflection:

- Charged particles spiral in a magnetic field gradient, gaining velocity as they are reflected.
- Conservation of the magnetic moment μ is key:

$$\mu = \frac{p_{\perp}^2}{2mB}, \quad (23)$$

where $p_{\perp}$ is the perpendicular momentum, m is the particle mass, and B is the magnetic field strength.

6.1.2 The Second-Order Fermi Acceleration Mechanism

- Particles gain energy through collisions with moving magnetic clouds.
- The fractional energy gain per interaction is:

$$\frac{\Delta E}{E} \propto \frac{v^2}{c^2}, \quad (24)$$

where v is the cloud velocity and c is the speed of light.

6.1.3 The First-Order Fermi Acceleration Mechanism

- Particles crossing shock fronts gain energy proportionally to the relative velocity of the shock.
- The energy gain is more efficient than the second-order mechanism:

$$\frac{\Delta E}{E} \propto \frac{v}{c}. \quad (25)$$

6.1.4 The Power-Law Energy Spectrum from the Fermi Model

- Repeated energy gains create a power-law spectrum for cosmic rays:

$$N(E) \propto E^{-\alpha}, \quad (26)$$

where α depends on the compression ratio of the shock.

6.2 Diffusive Shock Acceleration in Strong Shock Waves

- Particles repeatedly scatter across shock fronts, gaining energy in each crossing.
- The acceleration time τ_{acc} depends on the shock velocity u_s :

$$\tau_{\text{acc}} \propto \frac{D}{u_s^2}, \quad (27)$$

where D is the diffusion coefficient.

6.3 Supernova Remnants (SNRs) and the Standard Model of Cosmic Ray Acceleration

6.3.1 SNRs as Galactic CR Accelerators

- Supernova remnants provide the energy and magnetic conditions required for cosmic ray acceleration.
- Observations suggest that SNRs can accelerate particles up to 10^{15} eV (the "knee" in the cosmic ray spectrum).

6.3.2 Relevant Quantities in SNR

- The Sedov-Taylor phase of SNR evolution determines particle acceleration.
- Maximum energy is influenced by:

$$E_{\text{max}} \propto BRu_s, \quad (28)$$

where B is the magnetic field strength, R is the radius, and u_s is the shock velocity.

6.4 Maximum Energy Attainable in the Supernova Model

- The maximum particle energy depends on the coherence length of the magnetic field and the lifetime of the shock.
- Estimated maximum energy:

$$E_{\text{max}} \propto ZBRu_s, \quad (29)$$

where Z is the particle charge.

6.5 The Spectral Index of the Energy Spectrum

6.5.1 The Escape Probability

- The spectral index depends on the probability of particle escape during acceleration.
- Escape time τ_{esc} influences the spectrum:

$$\tau_{\text{esc}} \propto \frac{1}{D(E)}, \quad (30)$$

where $D(E)$ is the energy-dependent diffusion coefficient.

6.5.2 A Shock Front in a Mono-Atomic Gas

- The compression ratio r for a mono-atomic gas is:

$$r = \frac{\gamma + 1}{\gamma - 1}, \quad (31)$$

where $\gamma = 5/3$ is the adiabatic index.

6.6 Success and Limits of the Standard Model of Cosmic Ray Acceleration

- The standard model explains the acceleration of cosmic rays up to 10^{15} eV.
- Challenges remain in explaining higher energies and exact source contributions.

6.9.1 A Simple Model Involving Pulsars

- Pulsars are rapidly rotating neutron stars with strong magnetic fields that accelerate particles to high energies.
- In the polar cap model, particles escape along open magnetic field lines, reaching energies beyond the "knee" in the cosmic ray spectrum.
- The maximum energy is determined by the electric potential difference ΔV :

$$E_{\text{max}} \propto e\Delta V \propto eBR^2\Omega^2, \quad (32)$$

where B is the magnetic field, R is the radius, and Ω is the angular velocity of the pulsar.

6.9.2 A Simple Model Involving Binary Systems

- Binary systems with compact objects (e.g., black holes or neutron stars) can accelerate particles through accretion-powered outflows or jets.
- Shock acceleration occurs as material ejected from the compact object interacts with the surrounding medium.
- The energy scale is determined by the shock velocity v_s and magnetic field B :

$$E_{\max} \propto Z B v_s, \quad (33)$$

where Z is the particle charge.

7 The Quest for Extragalactic Sources of UHE-CRs

7.4 The Quest for Extragalactic Sources of UHECRs

- Ultra-high-energy cosmic rays (UHECRs) are the most energetic particles observed, with energies exceeding 10^{18} eV.
- Potential extragalactic sources include active galactic nuclei (AGN), gamma-ray bursts (GRBs), and galaxy clusters.
- Identifying sources is complicated by magnetic deflections and energy losses during propagation.

7.5 Propagation of UHECRs

7.5.1 The Adiabatic Energy Loss

- UHECRs lose energy as the Universe expands, an effect described by the Hubble parameter H_0 .

7.5.2 The Propagation in the CMB: The GZK Cut-Off

- The Greisen–Zatsepin–Kuzmin (GZK) effect limits the energy of UHECRs due to interactions with cosmic microwave background (CMB) photons.
- Protons interact with CMB photons, producing pions and reducing their energy:

$$p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0 \text{ or } n + \pi^+. \quad (34)$$

7.5.3 e^+e^- Pair Production by Protons on the CMB

- Protons can lose energy through pair production:

$$p + \gamma_{\text{CMB}} \rightarrow p + e^+ + e^-. \quad (35)$$

- This process dominates energy losses below the GZK threshold.

7.5.4 Propagation in the Extragalactic Magnetic Fields

- UHECRs are deflected by extragalactic magnetic fields, smearing their arrival directions and complicating source identification.

7.6 Fluorescent Light and Fluorescence Detectors

- UHECR interactions with the atmosphere produce nitrogen fluorescence light, detectable by fluorescence telescopes.
- The fluorescence yield is proportional to the energy deposited by the shower particles.

7.7 UHECR Measurements with a Single Technique

- Experiments like HiRes and Telescope Array use fluorescence detection to reconstruct UHECR energy and composition.
- Strengths include high energy resolution but limited duty cycles due to dependence on clear, dark skies.

7.8 Large Hybrid Observatories of UHECRs

- Hybrid observatories, such as the Pierre Auger Observatory, combine fluorescence and surface detectors to improve measurement accuracy.
- Surface detectors provide high statistics, while fluorescence telescopes enable precise energy calibration.

7.9 Recent Observations of UHECRs

7.9.1 The Flux and Arrival Directions of UHECRs

- UHECR flux decreases sharply above $10^{19.5}$ eV, consistent with the GZK cut-off.
- Anisotropies in arrival directions suggest potential extragalactic sources.

7.9.2 The Chemical Composition of UHECRs

- Composition studies indicate a transition from lighter nuclei (protons) to heavier nuclei (e.g., iron) at the highest energies.
- Techniques include analyzing shower depth maxima (X_{max}).

7.9.3 Correlation of UHECRs with Astrophysical Sources

- Cross-correlation studies explore associations between UHECR arrival directions and known astrophysical sources (e.g., AGN).
- Results remain inconclusive due to magnetic deflections and limited statistics.