A Comprehensive Investigation of Cosmic Rays: Galactic and Extragalactic Origins, Detection Techniques, and Atmospheric Interactions: Article Review

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• **Abstract**

Cosmic rays represent one of the most compelling phenomena in high-energy astrophysics, originating from both Galactic and extragalactic environments and spanning energies from mega-electron volts to beyond 10^{20}electron volts. This review synthesizes current knowledge on their composition, sources, spectral features, and detection techniques. Galactic Cosmic Rays are primarily accelerated in supernova remnants and superbubbles, while extragalactic contributions are linked to active galactic nuclei and gamma-ray bursts. The cosmic ray spectrum exhibits distinct structures, including the knee at $\sim 3 \times 10^{15}$ eV and the ankle at $\sim 10^{18}$ eV, marking the transition between Galactic and extragalactic origins. Recent direct detection experiments (AMS-02, DAMPE, CALET) have revealed additional spectral features such as hardening near 500 GeV and softening around 10 TeV, challenging the traditional single power-law description. Ground-based observatories (Pierre Auger, LHAASO, HAWC) complement these findings by probing ultra-high-energy regimes and providing evidence for anisotropies in arrival directions. The results emphasize that cosmic ray behavior reflects a complex interplay of acceleration mechanisms, propagation effects, and source diversity. Conclusions highlight the necessity of integrating space-based and ground-based observations to reduce uncertainties in energy calibration and composition, particularly in the transition region between the knee and the ankle. This combined approach is essential for advancing our understanding of cosmic ray origins and their role in shaping high-energy astrophysical processes.

Keywords: Cosmic ray; Cosmic ray spectrum; Galactic cosmic rays; Extragalactic cosmic rays; Particle acceleration

1. Introduction

dentifying the origin of cosmic rays (CRs) is considered a fundamental issue in high-energy astrophysics. Although research has firmly demonstrated that the majority of these rays are generated within our Galaxy, the specific mechanisms behind their sources remain the subject of ongoing debate[1]. Cosmic rays are energetic particles that arise from diverse astrophysical sources, including supernova explosions, pulsars, and active galactic nuclei. They are composed of protons, electrons, alpha particles, and heavier nuclei, with energies spanning from a few mega-electron volts (MeV) up to several exa-electron volts (EeV). First identified by Victor Hess in 1912 through balloon experiments, these rays have since been observed to strike Earth incessantly from all directions[2]. Most galactic cosmic rays consist mainly of protons and helium nuclei, whereas their extragalactic counterparts—referred to as ultra-high-energy cosmic rays (UHECRs)—originate beyond the Milky Way and display energies surpassing eV. When these particles penetrate Earth's atmosphere, they collide with atmospheric matter, generating cascades of secondary particles such as muons, electrons, and photons[3]. When cosmic rays collide with Earth's atmosphere, they generate extensive air showers composed of secondary particles such as muons, neutrinos, and gamma rays. These interactions offer valuable insights into the composition, origin, and spatial distribution of cosmic rays. Given their significance, multiple detection techniques have been devised to study them both directly in space and indirectly from the ground. Instruments like AMS-02 aboard the International Space Station and balloon-borne experiments such as BESS and CREAM capture primary cosmic rays before atmospheric interaction. In contrast, facilities including the Pierre Auger Observatory and the Telescope Array register secondary particles from large air showers at Earth's surface, while Cherenkov telescopes and cloud chambers serve as complementary tools for monitoring cosmic ray activity[4]. There are two types of Cosmic rays Primary cosmic rays refer to particles that are directly accelerated within astrophysical environments and reach Earth without prior interaction with its atmosphere. They constitute the initial flux of cosmic radiation arriving at our planet before generating secondary products. Their composition is largely dominated by nuclei of elements akin to those present in stars, offering valuable clues about stellar nucleosynthesis and the broader processes of cosmic chemical evolution, When primary cosmic rays strike molecules in Earth's atmosphere, they initiate nuclear reactions that generate a cascade of secondary particles. These particles develop into extensive air showers detectable by both ground-based and subterranean instruments. While a fraction of the secondary cosmic rays succeed in reaching the planet's surface, many either decay rapidly or are absorbed within the atmospheric layers[5]. This study focuses on the enduring challenge of pinpointing the primary origins of cosmic rays. Despite decades of investigation, the source of these energetic particles remains contested, with proposed candidates including supernova remnants, pulsar wind nebulae, active galactic nuclei, and gamma-ray bursts. Such uncertainty underscores a major gap in our comprehension of cosmic ray generation across different energy regimes. Accordingly, the aim of this work is to deliver a thorough and critical synthesis of recent research on cosmic ray sources, combining theoretical frameworks with observational findings to clarify the current understanding, identify consensus and divergence within the field, and outline future directions that may contribute to resolving this fundamental astrophysical issue.

2. Composition of Cosmic Rays

Cosmic rays are composed chiefly of protons and atomic nuclei, with hydrogen and helium nuclei representing the most prevalent components. Classified as primary cosmic rays, these particles originate from astrophysical processes and traverse interstellar space at velocities approaching the speed of light[6].

Beyond protons and helium nuclei, cosmic rays also contain heavier atomic species such as carbon, oxygen, and iron, along with electrons and their antimatter counterparts, positrons. The relative proportions of these components vary with particle energy, with heavier nuclei becoming increasingly significant at higher energies. When primary cosmic rays interact with interstellar gas and radiation fields, they generate secondary particles including muons, pions, and neutrinos. These secondary products contribute to the cosmic ray flux detected near Earth and provide essential clues about the processes governing cosmic ray propagation and acceleration[7].

Cosmic rays comprise a wide spectrum of high-energy particles generated by astrophysical sources both inside and outside our galaxy. In general, they are divided into two principal categories: Galactic Cosmic Rays (GCRs) and Extragalactic Cosmic Rays (EGCRs). Each class exhibits distinct characteristics and origins, warranting closer examination[8]. There are two type of Cosmic ray Sources:

2.1 Galactic Cosmic Rays (GCRs)

Galactic Cosmic Rays (GCRs) are energetic particles that originate outside the solar system. Their composition is largely dominated by protons (~87%), followed by helium nuclei (~12%), with heavier ions contributing only about ~1%. The exact proportions vary depending on particle energy, yet the energy spectra of different species display similar trends when expressed per nucleon. According to the prevailing model of GCR origin and propagation, these particles are accelerated by shock waves generated in supernova explosions and then diffuse through the galaxy, interacting with interstellar gas. This process also incorporates material from the interstellar medium (ISM), meaning that the chemical makeup of GCRs mirrors that of the ISM. Recent observations and experimental missions provide strong support for diffusive shock acceleration, especially in the case of GCR protons interacting with molecular gas. In such frameworks, roughly 12–16% of the kinetic energy from supernova ejecta is available for cosmic-ray acceleration. Highly efficient production sites are thought to include superbubbles—compact regions spanning only a few parsecs where numerous stars undergo supernova explosions within a relatively short timescale of a few million years[9]. Liu et al. (2022), in their review published in Reviews of Modern Plasma Physics, argue that supernova remnants represent the most plausible sources of Galactic Cosmic Rays (GCRs). They highlight that shock waves produced by stellar explosions are capable of accelerating particles to energies on the order of the TeV scale. While this mechanism accounts for a substantial portion of the observed energy spectrum, it does not adequately explain

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cosmic rays with energies exceeding 10^ eV, thereby motivating alternative hypotheses that invoke additional galactic sources[10].

Complementing this perspective, Alvarez-Muñiz et al. (2024) in the Particle Data Group (PDG) Report provide a detailed overview of the cosmic-ray energy spectrum, identifying key spectral features such as the “knee” and the “ankle.” Their review also addresses aspects of chemical composition, the role of heavy elements, propagation processes, and anisotropy. This work serves as a cornerstone reference, offering a broad framework for interpreting the physical characteristics of cosmic rays across diverse energy ranges[11].

Further insights are offered by Tatischeff et al. (2021) in Monthly Notices of the Royal Astronomical Society (MNRAS), who examined the chemical composition of GCRs using data from AMS-02, Voyager 1, and SuperTIGER. Their findings underscore the significant contributions of massive stars and supernovae in shaping the elemental makeup of cosmic rays, thereby reinforcing the view that these astrophysical sources are central to the production of the majority of cosmic rays within the galaxy[12].

2.2. Extragalactic Cosmic Rays (EGCRs)

Extragalactic cosmic rays represent one of the most striking astrophysical manifestations of high-energy processes in the universe. These charged particles originate beyond the Milky Way and traverse immense cosmological distances before arriving at Earth. Current studies suggest that they are generated in extreme astrophysical environments, notably within active galactic nuclei (AGN) powered by supermassive black holes, where relativistic jets accelerate particles to extraordinary energies. They are also associated with gamma-ray bursts (GRBs), which arise from the collapse of massive stars or the merger of neutron stars, releasing vast amounts of energy and charged particles. These cosmic rays are distinguished by their ultra-high energies, with some particles surpassing 10^20 electron volts—the highest energies observed in nature. Although rare and challenging to detect due to their long propagation paths, ongoing research seeks to characterize their properties and pinpoint their origins. Such efforts are essential for advancing our understanding of high-energy astrophysics and the extreme physical conditions that shape the universe[13].

Extragalactic cosmic rays have been the subject of extensive academic investigation, recognized as one of the most significant manifestations of high-energy processes in the universe. Kotera and Olinto (2011), in their review published in the Annual Review of Astronomy and Astrophysics, examined the fundamental physics of ultra-high-energy cosmic rays, emphasizing active galactic nuclei (AGNs) and gamma-ray bursts (GRBs) as prime candidates for their origin. They argued that such extreme astrophysical environments are capable of accelerating particles to energies exceeding 10^20 electron volts, thereby offering a plausible explanation for the flux observed at Earth[14].

Anchordoqui (2019), in Physics Reports, provided a broad synthesis of ultra-high-energy cosmic ray research, highlighting the observational challenges posed by their rarity and the difficulty of reconstructing their trajectories through intergalactic magnetic fields. The review underscored the role of large-scale ground-based facilities, such as the Pierre Auger Observatory, in detecting anisotropies and establishing potential links to extragalactic sources[15].

Further evidence was presented by the Pierre Auger Collaboration (2017) in Science, which reported a large-scale anisotropy in the arrival directions of cosmic rays with energies above 8\times 10^18 electron volts. This discovery provided compelling support for the extragalactic origin of a substantial fraction of these particles and marked a critical step in bridging experimental observations with theoretical models that attribute their production to sources such as AGNs and GRBs[16].

3. Comsic Ray Spectrum

The cosmic ray spectrum has been observed over an extensive energy range, spanning from 10^{8} to 10^{20} eV, and is generally characterized by a power-law distribution. Within this spectrum, two notable structures emerge: the “knee,” located near 3\times 10^{15} eV, and the “ankle,” around 3 times 10^{18} eV. Galactic cosmic rays are commonly attributed to acceleration by shock fronts generated in supernova remnants; however, this mechanism alone does not adequately account for particle energies reaching the knee. The interval between the knee and the ankle, where cosmic rays are thought to shift from Galactic to extragalactic origins, remains insufficiently understood. Determining the mass composition in the knee region with high precision is essential for clarifying these questions, including identifying the termination of the Galactic cosmic ray spectrum. In addition, reliable calibration of cosmic ray energy and composition up to approximately 100 TeV—through comparison with direct measurements and refinement of hadronic interaction models used in air shower analyses—is vital for reducing systematic uncertainties[17].

High-precision measurements from direct detection experiments have revealed new structures in the low-energy region of the cosmic ray spectrum. A spectral hardening near ~500 GeV has been consistently confirmed by several experiments, while a softening around 10 TeV was initially reported by CREAM and subsequently validated by both DAMPE and CALET. Although the physical origin of these spectral features remains uncertain, they clearly indicate that the cosmic ray spectrum below the knee cannot be adequately described by a single power-law, contrary to earlier assumptions. The limited statistics available from direct experiments restrict their ability to probe cosmic rays beyond ~100 TeV. Consequently, the energy interval between $10^{١٤}$ and $10^{١٨}$ eV—which encompasses the knee and the transition from Galactic to extragalactic sources—is primarily investigated using large ground-based air shower arrays[18].

4. Cosmic ray detectors

The flux of cosmic rays—defined as the number of particles striking Earth per unit area, solid angle, and time—decreases steeply with increasing energy, following a power-law dependence (flux $\propto E^{-\gamma}$), where γ , the spectral index, is approximately 2.7 below ~3 PeV. For example, at 10^{11} eV, roughly one particle passes through a square meter each second. At 10^{15} eV (PeV scale), the rate

falls to about one particle per square meter per year, while at 10^{18} eV (EeV scale), the flux drops to nearly one particle per square kilometer per year. This rapid decline necessitates detectors of different sizes to achieve statistically meaningful measurements across the full energy spectrum. Measurements below 10^{14} eV are primarily conducted using satellite- or balloon-borne instruments. These provide higher accuracy since particles are detected directly before interacting with Earth's atmosphere. However, such space-based observations are limited to energies below 100 TeV due to the steeply falling flux and payload constraints on detector mass. Ground-based arrays complement these efforts, extending coverage up to the highest observed energies (10^{20}ev).

Space-based detectors typically resemble those used in accelerator experiments. Systems equipped with strong magnetic fields can distinguish particles from antiparticles, while tracking elements record trajectories and calorimeters measure particle energies. Ground-based detectors, on the other hand, study extensive air showers (EAS) generated when cosmic rays interact with the atmosphere. Measurements of charged particle densities reveal the shower core, while lateral distributions provide information on shower size (total particle count) and age (development stage). Timing data determine the arrival direction, and muon density measurements help infer the primary particle's mass composition, offering sensitivity for distinguishing gamma rays from charged cosmic rays.

Ground-based arrays employ several detection techniques, including plastic scintillators, water Cherenkov tanks, and fluorescence telescopes. More recently, radio antenna arrays have proven effective for measurements beyond 10^{17} eV. Plastic scintillators detect charged particles by converting deposited energy into scintillation light in the blue wavelength range. Water Cherenkov detectors measure particle densities through Cherenkov radiation produced in water. Fluorescence telescopes capture light emitted when nitrogen molecules in the atmosphere are excited by shower particles, providing a longitudinal profile of shower development. While scintillators and Cherenkov detectors operate continuously, fluorescence telescopes are restricted to dark nights, resulting in a duty cycle of only ~10%[19].

4.1. Ground-based cosmic ray detectors

When primary cosmic rays penetrate Earth's atmosphere, they collide with nitrogen and oxygen nuclei, initiating cascades of secondary particles known as extensive air showers. These showers are composed mainly of gamma rays, electrons and positrons, as well as muons. Because muons are significantly heavier than electrons, they can travel deep into the atmosphere and even reach underground levels. Owing to relativistic time dilation, many muons produced at high altitudes survive long enough to arrive at the Earth's surface. Neutrinos are also generated in these interactions, but their extremely weak interaction with matter requires enormous detectors for observation.

The shower particles propagate at nearly the speed of light and can spread over areas ranging from tens of square meters to several square kilometers. The energy of the primary cosmic ray is distributed among thousands to millions of secondary particles. To investigate these showers, large ground-based detector arrays are employed, measuring the particles that reach the Earth's surface.

The Tibet-ASγ observatory is situated in Tibet at 30.1°N, 90.5°E, at an altitude of 4,300 m above sea level, corresponding to an atmospheric depth of 600 g cm^{-2}. It represents a collaborative effort among institutions from China, Japan, and Italy. The facility was designed to record extensive air showers (EAS) initiated by both cosmic rays and gamma rays in the energy range from several TeV up to 100 PeV.

The experimental setup consists of an array of 597 scintillation detectors, each with an active area of 0.5 m^2, distributed across 65,700 m^2. In addition, 64 underground Cherenkov muon detectors are installed in four pools, with 16 units per pool. The scintillator array measures the electromagnetic component of the EAS, providing information on the energy and arrival direction of the primary particle. Meanwhile, the muon detectors record the muonic component, enabling discrimination between gamma-ray and cosmic-ray primaries[20].

The Large High-Altitude Air Shower Observatory (LHAASO), located in Sichuan, China, at an elevation of 4,410 meters above sea level, is designed to investigate cosmic rays across a broad energy range, extending from below 1 TeV up to 100 PeV. The facility integrates multiple detection systems to achieve comprehensive measurements[21]:

- More than 5,000 electromagnetic detectors for recording secondary particles.
- Over 1,000 muon detectors to analyze the muonic content of air showers.
- A vast water Cherenkov detector array covering 78,000 m^2, subdivided into ponds containing thousands of cells equipped with photomultiplier tubes.
- Eighteen wide-field Cherenkov telescopes to capture Cherenkov radiation from air showers. By combining these complementary instruments, LHAASO is able to measure the energy, arrival direction, and composition of cosmic rays with high precision. This makes it one of the most advanced observatories worldwide for high-energy astrophysics research.

The High-Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory is located on the Sierra Negra Volcano in Puebla, Mexico, at an elevation of 4,100 meters above sea level. It is operated through an international collaboration involving institutions from Mexico, the United States, South America, and Europe.

HAWC explores energies ranging from below 1 TeV up to 1 PeV. The facility comprises 300 closely spaced water Cherenkov detectors distributed across an area of 22,000 m^2. Each detector tank contains 200,000 liters of water and is equipped with four photomultiplier tubes.

The observatory is designed to record extensive air showers produced by both gamma rays and cosmic rays, with effective coverage from approximately 500 GeV to several hundred TeV. This makes HAWC a powerful instrument for investigating high-energy astrophysical phenomena[22].

4.2. Space-based cosmic ray detectors

The Alpha Magnetic Spectrometer (AMS-02) is a particle physics experiment installed on the International Space Station. Its primary objectives are to distinguish hadrons from leptons, separate particles from antiparticles, and provide detailed measurements of the chemical and isotopic composition of cosmic rays across an energy range extending from below 1 GeV to several TeV.

AMS-02 employs a permanent magnet to bend particle trajectories, enabling precise determinations of momentum and charge. Surrounding this core system are several specialized detectors:

- A Transition Radiation Detector for identifying electrons and positrons while suppressing proton background.

- Nine silicon tracker planes with approximately 200,000 channels for high-precision charge and momentum measurements.
- Time-of-Flight counters to determine particle velocity, direction, and charge.
- Anti-Coincidence Counters to reject side-entering cosmic rays.
- A Ring Imaging Cherenkov detector with more than 10,000 sensors for charge and velocity measurements.
- An Electromagnetic Calorimeter (ECAL) composed of lead and scintillating fibers, providing accurate energy and directional measurements of electrons and positrons.

By integrating these complementary instruments, AMS-02 achieves exceptional precision in particle identification, making it one of the most advanced space-based experiments for cosmic ray research[23].

The CALorimetric Electron Telescope (CALET), a joint mission of Japan, Italy, and the United States, has been operating on the International Space Station since 2015. Its primary aim is to measure electrons, gamma rays, and charged nuclei in cosmic rays to investigate their origin, acceleration, and propagation. The instrument covers energies from ~1 GeV to several TeV for gamma rays, and up to ~1 PeV for protons and nuclei. CALET consists of three main sub-detectors: the CHarge Detector (CHD) for measuring particle charge, the IMaging Calorimeter (IMC) for tracking and shower development, and the Total AbSorption Calorimeter (TASC) for full containment of electromagnetic showers. Together, these systems provide high-precision measurements of cosmic ray composition and energy, making CALET a key experiment in space-based astrophysics[24].

The DArk Matter Particle Explorer (DAMPE), launched in December 2015 into a Sun-synchronous orbit at 500 km, is a collaborative mission between China, Switzerland, and Italy. Its main objective is to measure electrons, photons, and cosmic rays with high energy resolution to search for possible dark matter signatures. DAMPE covers energies from 5 GeV to 10 TeV for electrons and photons, and from 100 GeV to 100 TeV for cosmic rays. The payload includes a plastic scintillator detector (PSD) for anticoincidence, a Silicon–Tungsten Tracker (STK) for tracking and photon conversion, a deep Bismuth Germanium Oxide (BGO) calorimeter for shower containment, and a Neutron Detector (NUD) to improve electron/proton separation. With a calorimeter depth of ~33 radiation lengths, DAMPE provides unprecedented precision in space-based cosmic ray measurements[25].

5. Results

Recent experimental and theoretical studies highlight several key findings in cosmic ray physics. Supernova remnants and superbubbles are identified as the most efficient accelerators of Galactic Cosmic Rays up to the knee region ($\sim 3 \times 10^{15}$ev), supported by data from AMS-02, Voyager, and ground-based observatories. Direct detection experiments such as DAMPE and CALET have revealed spectral features, including a hardening near 500 GeV and a softening around 10 TeV, indicating that the spectrum cannot be described by a single power-law. Ground-based facilities like the Pierre Auger Observatory and LHAASO provide strong evidence for an extragalactic origin of ultra-high-energy cosmic rays, particularly in the ankle region (10^{18} ev). Variations in elemental composition across energy ranges further emphasize the role of interstellar propagation and magnetic fields in shaping the observed flux.

6. Conclusion

Taken together, current results show that the cosmic ray spectrum reflects a complex interplay between Galactic and extragalactic sources, acceleration mechanisms, and propagation effects. Supernova remnants account for much of the Galactic contribution, while extragalactic environments such as active galactic nuclei and gamma-ray bursts are required to explain the highest observed energies. Spectral features at intermediate energies suggest contributions from multiple acceleration processes and local sources. Future progress will rely on combining direct space-based measurements with large ground-based arrays to reduce uncertainties in energy calibration and composition, particularly in the transition region between the knee and the ankle. This integrated approach is essential for advancing our understanding of high-energy astrophysical phenomena and the origin of cosmic rays.

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