NJESR/December-2023/Volume-5/Issue-12 E-ISSN-2582-5836

DOI-10.53571/NJESR.2023.5.12.9-18

Variation In Cosmic Rays Due To Life Cycle Of The Sun And Impact On Environment On The Earth Surface: An Introduction.

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Received:26November2023/Revised:6December2023/Accepted:20December2023/Published:29December2023)

Abstract:
Astroparticles, commonly referred to as cosmic rays, represent energetic particles or clusters of particles, predominantly comprised of protons or atomic nuclei, traversing space at velocities nearing the speed of light. Originating from diverse sources such as the Sun, regions beyond our Solar System within the Milky Way galaxy, and even distant extragalactic origins, these particles encounter Earth’s atmosphere, initiating cascades of secondary particles, with a fraction penetrating to the planet’s surface. However, the majority of these particles are either redirected into space by Earth’s magnetosphere or deflected by the heliosphere. The Sun assumes a critical role in regulating the cosmic ray influx reaching Earth, primarily influenced by its solar cycle and magnetic field dynamics. Understanding this intricate interplay holds significance across various disciplines, including space weather forecasting, climate research, and strategic planning for prolonged space missions. The fluctuations in cosmic ray intensity encompass a spectrum of complex implications for Earth and its inhabitants.

Keywords: Heliosphere, Sunspots, Red Giant Phase, CCN

1.1 Introduction

Astroparticles, also known as cosmic rays, are energetic particles or particle clusters, predominantly composed of protons or atomic nuclei, traversing space at velocities approaching the speed of light. These particles originate from various sources, including the Sun, regions beyond the confines of the Solar System within our Milky Way galaxy, and even distant extragalactic sources. Upon encountering the Earth’s atmosphere, cosmic rays initiate cascades of secondary particles, with a portion penetrating to the planet’s surface. However, the majority of these particles are either redirected into space by the Earth’s magnetosphere or deflected by the heliosphere.

The identification of cosmic rays is credited to Victor Hess, who conducted balloon experiments in 1912 and was subsequently honoured with the 1936 Nobel Prize in Physics for his contributions. In the realm of cosmic rays, two primary classifications emerge: primary cosmic rays and secondary cosmic rays.

1.2 Primary Cosmic Rays

These cosmic rays trace their origin to primary cosmic rays, initially generated in diverse astrophysical phenomena. Comprising predominantly protons and alpha particles (constituting 99% of their composition), primary cosmic rays also include a minor proportion of heavier nuclei (approximately 1%) and an exceptionally minute fraction of positrons and antiprotons. Satellite experiments have revealed the presence of positrons and a few antiprotons within primary cosmic rays, constituting less than 1% of the particle population in primary cosmic rays. These findings suggest that these particles do not originate from significant quantities of antimatter formed during the Big Bang or from complex antimatter structures within the universe. Rather, they seem to consist solely of these two elementary particles, freshly produced in energetic processes.

Preliminary data from the Alpha Magnetic Spectrometer (AMS-02), currently operational aboard the International Space Station, indicates that positrons within cosmic rays exhibit isotropic arrival patterns. In September 2014, updated findings, based on nearly double the original dataset, were presented at CERN and published in Physical Review Letters. These new measurements of the positron fraction, extending up to 500 GeV, reveal a peak value of approximately 16% of total electron-positron events at energy of 275 ± 32 GeV. Beyond 500 GeV, the ratio of positrons to electrons diminishes, while the absolute flux of positrons declines before reaching 500 GeV, but still peaks at energies significantly higher than those of electrons.

These results have prompted speculation regarding the production of positrons through annihilation events involving massive dark matter particles. Additionally, cosmic ray antiprotons exhibit markedly higher average energies compared to their proton counterparts. Their characteristic energy maximum upon arrival at Earth, approximately 2 GeV, suggests a distinct production mechanism from cosmic ray protons, which typically possess only one-sixth of the energy. Despite extensive investigations, there is currently no evidence of complex antimatter atomic nuclei, such as antihelium nuclei, within cosmic rays. Efforts to detect such particles are actively ongoing. A precursor to the AMS-02, known as AMS-01, was deployed aboard the Space Shuttle Discovery on STS-91 in June 1998. However, no antihelium was detected, leading to the establishment of an upper limit for the antihelium-to-helium flux ratio at 1.1×10^6.

1.2 Secondary Cosmic Rays

Secondary cosmic rays arise through the decay of primary cosmic rays upon interacting with an atmosphere. This category encompasses various particles, including photons, hadrons, and leptons such as electrons, positrons, muons, and pions. Notably, the latter three particles were initially identified through cosmic ray observations. Upon entering the Earth's atmosphere, cosmic rays interact with atoms and molecules, primarily oxygen and nitrogen. This interaction initiates a cascade of secondary radiation known as an air shower, which encompasses a variety of lighter particles, including x-rays, protons, alpha particles, pions, muons, electrons, neutrinos, and neutrons. All secondary particles resulting from these collisions maintain trajectories within approximately one degree of the original path of the primary particle. Commonly generated particles in such interactions include neutrons and charged mesons, such as positive or negative pions and kaons. Subsequently, some of these particles decay into muons and neutrinos, capable of reaching the Earth's surface.

High-energy muons possess the ability to penetrate shallow mines to some extent, while most neutrinos traverse the Earth without significant interaction. Others decay into photons, initiating electromagnetic cascades. Consequently, photons, electrons, and positrons typically dominate within air showers. These particles, along with muons, are readily detectable using various types of particle detectors, including cloud chambers, bubble chambers, water-Cherenkov detectors, and scintillation detectors. The simultaneous observation of a secondary particle shower across multiple detectors serves as evidence that all particles originated from the same event. Detection of cosmic rays impacting other celestial bodies within the Solar System is achieved indirectly by monitoring high-energy gamma ray emissions using gamma-ray telescopes.

The relationship between cosmic rays and the Sun's evolutionary stages is multifaceted, particularly in light of the Sun's impact on the heliosphere, which subsequently influences the cosmic ray influx reaching Earth. This interconnection is primarily governed by four key factors that intricately link cosmic rays to the terrestrial environment.

1.3 Solar Activity And Cosmic Rays

The Sun undergoes an 11-year solar cycle, characterized by fluctuations in solar activity levels, manifesting as alterations in sunspot counts, solar flare occurrences, and coronal mass ejections. At the peak of solar activity, known as solar maximum, the Sun's magnetic field strengthens and becomes more turbulent, enhancing its capability to divert cosmic rays away from the inner solar system. Conversely, during periods of solar minimum, the Sun's magnetic field weakens, resulting in heightened penetration of cosmic rays into the inner solar system and towards Earth. This reciprocal relationship between solar activity and cosmic ray intensity, recognized as the solar modulation of cosmic rays, has been extensively documented in scientific literature. The primary components contributing to solar activity predominantly include the solar cycle, sunspots, solar flares, and coronal mass ejections (CMEs).

1.3.1 Solar Cycle

The Sun experiences an approximate 11-year cycle, recognized as the solar cycle, wherein its magnetic activity waxes and wanes. This phenomenon is chiefly discernible through the fluctuating abundance of sunspots observable on the solar surface.

1.3.2 Sunspots

Sunspots, characterized by their darker and cooler appearance on the Sun's surface, are regions linked with intense magnetic fields. The quantity of sunspots serves as a pivotal gauge of solar activity, with a higher count indicating heightened solar activity.

1.3.3 Solar Flares And Coronal Mass Ejections (CMEs)

In times of elevated solar activity, the Sun frequently generates solar flares and coronal mass ejections (CMEs). Solar flares manifest as intense surges of radiation, whereas CMEs entail the expulsion of plasma and magnetic fields from the Sun's corona. These phenomena are intricately tied to the dynamics of the Sun's magnetic field.

1.3.4 Solar Modulation Of Cosmic Rays

The Sun's magnetic field's effect on cosmic ray intensity is termed solar modulation, a pivotal element in comprehending the fluctuating levels of cosmic rays observed within Earth's vicinity and in near-Earth space. Solar modulation holds significant implications, influencing space weather dynamics and posing hazards to astronauts and spaceborne equipment. Moreover, it potentially impacts atmospheric chemistry and, conceivably, Earth's climate, although the extent of this influence remains subject to ongoing scientific inquiry.

In conclusion, the interaction between solar activity and cosmic rays constitutes a dynamic and intricate phenomenon. The Sun's 11-year cycle serves as a crucial determinant in regulating the intensity of cosmic rays reaching Earth, underscoring the interconnectedness between solar and cosmic processes.

1.4 Long-Term Changes

Overextended timescales, as the Sun progresses through its lifecycle, alterations in its magnetic field and solar wind—a continuous flow of charged particles emanating from the Sun's atmosphere—can undergo substantial modifications. As the Sun matures and eventually transitions into a red giant, which is projected to occur billions of years hence, its attributes will undergo dramatic shifts. These transformations have the potential to modify the Sun's interaction with cosmic rays, potentially influencing their intensity and repercussions on the solar system. Understanding the Sun's lifecycle and its evolving characteristics is paramount in elucidating the long-term alterations and their ramifications for cosmic rays. Over the span of billions of years, the Sun will undergo notable metamorphoses, impacting not only the solar system but also its interplay with cosmic rays. The primary stages in the Sun's life cycle are the main sequence phase and the red giant phase.

1.4.1 Main Sequence Phase

Presently, the Sun resides in the main sequence phase of its lifecycle, a stage it has maintained for approximately 4.6 billion years. Throughout this phase, the Sun undergoes nuclear fusion within its core, where hydrogen is converted into helium, generating the energy and light that sustains life on Earth. It is anticipated that the Sun will persist in this stable state for an additional 5 billion years or thereabouts.

1.4.2 Red Giant Phase

As the Sun depletes its hydrogen reservoir, it will transition into the red giant phase, a transformation projected to transpire roughly 5 billion years hence. During this phase, the Sun will undergo significant expansion, potentially engulfing the inner planets, potentially including Earth. Consequently, its surface will cool, imparting a reddish hue to its appearance. As the Sun progresses through its evolutionary trajectory, notable transformations are anticipated in its solar wind and magnetic field. During its transition into a red giant, the solar wind may intensify and exhibit greater variability. Concurrently, alterations in the magnetic field, a pivotal agent in shaping the solar wind and regulating cosmic ray modulation, are anticipated, although accurately forecasting these changes poses a considerable challenge.

As the Sun expands and cools during the red giant phase, a weakening of its magnetic field is envisaged. A diminished magnetic field would render it less effective in shielding the solar system from cosmic rays. Consequently, the heliosphere, the Sun's protective bubble, might experience a reduction in its ability to deflect cosmic rays. This scenario could culminate in an escalation of cosmic ray influx into the solar system. Moreover, significant modifications in the heliosphere's nature may ensue. A potential contraction or diminished efficacy of the heliosphere could result in alterations to the heliopause—the boundary where the solar wind interacts with the interstellar medium—potentially reshaping the dynamics of cosmic ray interactions within the solar system.

The heightened penetration of cosmic rays could engender diverse repercussions for the solar system. Planetary atmospheres, such as that of Mars, could be subject to alterations or depletion due to increased cosmic radiation exposure. Furthermore, the augmented cosmic radiation could pose substantial challenges for extant or nascent life forms. Over the long term, as the Sun progresses beyond its main sequence phase, the evolving characteristics of cosmic ray interactions are likely to be influenced. The attenuation of the Sun's magnetic field and the modifications in the solar wind during the red giant phase may exacerbate cosmic ray penetration. These transformations constitute integral facets of the natural evolution of Sun-like stars, underscoring the dynamic nature of cosmic phenomena.

1.5 The Heliosphere

The heliosphere constitutes an extensive expanse of space primarily governed by the solar wind and the influence of the Sun's magnetic field, extending far beyond the orbit of Pluto. The Sun's solar wind forms a protective barrier known as the heliosphere, encompassing the solar system and shielding the inner planets from certain influences of galactic cosmic rays. Evolving solar wind dynamics will inevitably impact the dimensions and configuration of the heliosphere, potentially modifying its efficacy in safeguarding against cosmic rays. Essentially, the heliosphere serves as a vast protective bubble generated by the solar wind—a flow of charged particles, primarily electrons and protons, emanating from the Sun. This expansive bubble envelops the planets, dwarf planets, asteroids, and comets comprising our solar system. Integral components of the heliosphere include key boundary regions, notably the termination shock, heliopause, and bow shock.

1.5.1 Termination Shock

At this juncture, the velocity of the solar wind descends below the speed of sound, leading to a significant deceleration and subsequent heating of the solar wind.

1.5.2 Heliopause

Situated at the outermost periphery of the heliosphere, the heliopause marks the threshold where the pressure exerted by the solar wind is counteracted by the pressure of the interstellar medium, denoting the cessation of the solar wind.

1.5.3 Bow Shock

Potentially extending beyond the heliopause, the bow shock represents the point at which the heliosphere experiences a sudden deceleration upon encountering the interstellar medium, akin to the formation of a water wave at the bow of a moving vessel. The solar wind, accompanied by the Sun's magnetic field, establishes a magnetic barrier capable of deflecting or decelerating high-energy particles originating from beyond our solar system, termed galactic cosmic rays. The efficacy of the heliosphere in safeguarding the solar system from cosmic rays is dynamic, fluctuating with the solar cycle and variations in solar activity. During periods of heightened solar activity, the heliosphere expands, providing enhanced protection, whereas, during solar minimums, it contracts, potentially permitting greater penetration of cosmic rays.

As the Sun progresses through its evolutionary timeline spanning billions of years, alterations in its energy output and the properties of the solar wind are anticipated. In its red giant phase, the solar wind is expected to exhibit differences both in composition and intensity. These transformations may precipitate adjustments in the dimensions and configuration of the heliosphere. A more vigorous solar wind could engender heliospheric expansion, while a weakened solar wind might induce contraction. A diminished or less dense heliosphere would display reduced efficacy in deflecting cosmic rays, potentially resulting in heightened infiltration of these high-energy particles into the inner solar system. Such scenarios could bear implications for space weather, potentially impacting satellites, astronauts, and even terrestrial climate dynamics. In essence, the heliosphere assumes a pivotal role in shielding our solar system from galactic cosmic rays. Its size, configuration, and efficacy as a protective barrier are contingent upon the solar wind, which, in turn, hinges upon solar activity.

1.6 Cosmic Ray And Earth Environment

Fluctuations in cosmic ray intensity carry numerous ramifications for Earth. For instance, there is a hypothesis suggesting that cosmic rays contribute to cloud formation by facilitating the nucleation of cloud condensation nuclei. This phenomenon theoretically holds the potential to influence Earth's climate, although the magnitude of its impact remains a subject of ongoing scientific inquiry and discourse. Furthermore, elevated cosmic ray levels could impact space travel, technology, and biological systems owing to their ionizing properties. The fluctuations in cosmic ray intensity and their consequences for Earth encompass a diverse array of effects, spanning potential climatic influences to impacts on technology, space travel, and biological systems.

1.6.1 Impact On Cloud Formation And Climate

The influence of cosmic rays on cloud formation and climate involves the dynamics of cloud condensation nuclei (CCN) and their subsequent effects on cloud coverage and Earth's climate.

1.6.1.1 Cloud Condensation Nuclei (CCN)

Cosmic rays are proposed to contribute to the generation of CCN, which serve as nuclei for water vapour condensation, thereby initiating cloud formation. The underlying hypothesis posits that cosmic rays, upon entering Earth's atmosphere, can ionize atmospheric particles, facilitating the formation of CCN.

1.6.1.2 Cloud Coverage And Climate

An elevation in CCN concentration can result in an augmentation of cloud cover. Clouds exert a multifaceted role in Earth's climate system, capable of either cooling by reflecting solar radiation back into space (known as the albedo effect) or warming by trapping heat within the atmosphere. The degree to which cosmic rays influence cloud cover and, consequently, Earth's climate remains a topic of ongoing investigation and deliberation within the scientific community. Despite some studies suggesting a correlation between cosmic ray intensity and cloud cover, establishing a definitive causative relationship remains elusive. Numerous climate scientists contend that the influence of cosmic rays on climate is relatively minor compared to other factors, notably greenhouse gas emissions.

1.6.2 Implications For Space Travel

The ionizing properties of cosmic rays present formidable obstacles to space travel. Their potential to affect spacecraft electronics raises concerns about malfunctions and data integrity. Furthermore, the prolonged exposure of astronauts to cosmic rays heightens the risk of radiation-induced health complications, given the particles' ability to penetrate human tissues. The imperative to mitigate these effects is paramount to ensuring the safety and viability of extended space missions. Numerous implications apply to space travel.

1.6.2.1 Radiation Exposure

In the realm of space exploration, cosmic rays present a formidable obstacle, particularly for missions venturing beyond Earth's protective magnetic field, such as voyages to Mars or further destinations. These energetic particles possess the capability to infiltrate spacecraft and endanger astronauts by inducing cellular damage or elevating the risk of cancer.

1.6.2.2 Shielding And Mitigation

Efforts to counteract the effects of cosmic ray exposure constitute a vital domain of inquiry within space travel research. This entails the exploration of various strategies, including the development of robust physical shielding, utilization of magnetic shields, and potential implementation of pharmaceutical countermeasures.

1.6.3 Effects On Technology

In the realm of technology, cosmic rays have the potential to induce errors or malfunctions in electronic devices. These energetic particles possess the capability to permeate electronic components, resulting in transient or permanent disturbances in their functionality. The mitigation of these effects assumes paramount importance in upholding the reliability and operational efficacy of technology, especially in space-based systems or environments at high altitudes where cosmic ray exposure is more pronounced.

1.6.3.1 Electronic Devices

Cosmic rays have the potential to interfere with or harm electronic systems, particularly during high-altitude flights and in space. The impact of energetic particles can induce single-event upsets (SEUs) in microelectronic circuits, resulting in malfunctions.

1.6.3.2 Risk Mitigation

The imperative to safeguard technology has spurred the creation of radiation-hardened electronics designed for deployment in spacecraft, satellites, and high-altitude aircraft.

1.6.4 Biological Implications

On our planet, the atmosphere and magnetic field offer significant shielding against cosmic rays. Nonetheless, at elevated altitudes and latitudes, nearer to the poles, cosmic rays may exert a slightly augmented influence on biological systems, potentially leading to DNA damage.

1.6.5 Long-Term Exposure Risks

Although the threat to individuals on Earth's surface remains minimal, prolonged exposure to elevated levels of cosmic rays (e.g., experienced by astronauts or frequent flyers) may potentially elevate the risks of cancer and other health ailments.

1.7 Conclusion

The Sun assumes a pivotal role in regulating the influx of cosmic rays reaching Earth, predominantly influenced by its solar cycle and magnetic field dynamics. Comprehending this interplay holds significance across multiple disciplines, encompassing space weather prediction, climate investigations, and strategic planning for extended space missions. The fluctuations in cosmic ray intensity encompass a spectrum of intricate implications for Earth and its inhabitants. While the relationship between cosmic rays, cloud formation, and climate remains under scientific scrutiny, their discernible impact on space exploration, technological infrastructure, and biological ecosystems underscores the formidable challenges faced in these domains. Consequently, cosmic rays persist as a focal point of investigation in both terrestrial and space sciences.

1.8 Acknowledgement

I am thankful to the Commissionerate of College Education, Rajasthan, Jaipur, and Dr. Bhimrao Ambedkar Government College, Sriganganagar, for giving me opportunities to work and providing the facility of an e-library.

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