Royal International Global Journal of Advance and Applied Research
Peer Reviewed International, Open Access Journal.
ISSN: 2998-4459 | Website: https://rlgjaar.com Volume-2, Issue-3 | March - 2025

Original Article

Study on Van Allen belt

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Manuscript ID:
RIGJAAR-2025-0203021

ISSN: 2998-4459

Volume 2

Issue 3

Pp. 103-105

March 2025

Submitted: 15 Feb 2025

Revised: 20 Feb 2025

Accepted: 15 Mar 2025

Published: 31 Mar 2025

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Quick Response Code:

Web. https://rlgjaar.com

DOI:
10.5281/zenodo.16149102

DOI Link:
https://doi.org/10.5281/zenodo.16149102

Abstract

The discovery of the Earth's Van Allen radiation belts by instruments aboard Explorer 1 in 1958 marked the first major scientific breakthrough in the Space Age. These belts consist of two distinct zones containing trapped high-energy (MeV) particles: primarily protons in the inner belt and electrons in the outer belt. This observation led to foundational models that explain the sources and losses of these particles. For instance, the inner zone protons were attributed to Cosmic Ray Albedo Neutron Decay (CRAND), whereas radial diffusion was proposed as a primary mechanism for the transport of outer zone electrons. Particle loss mechanisms, including pitch angle scattering into Earth's atmosphere, have also been identified. The study of Van Allen belts has significantly enhanced our understanding of energetic particle dynamics, not only around Earth but also at other magnetized planets, exoplanets, and in various astrophysical and laboratory plasma environments. In recent years, computational models of radiation belts have advanced substantially, particularly during the Van Allen Probes mission. These improvements have enabled more accurate and assimilative forecasting of radiation belt behavior. Moreover, machine learning techniques are being developed and integrated into space weather models to predict changes in radiation belts more effectively. Given the impact of radiation belt variability on satellites and other space-based technologies, enhanced predictive capabilities are becoming increasingly vital. In the future, radiation belt modeling is expected to become crucial to space operations, as weather forecasting is related to terrestrial activities.

Keywords: *Van Allen belt, characteristics of Van Allen belt.*

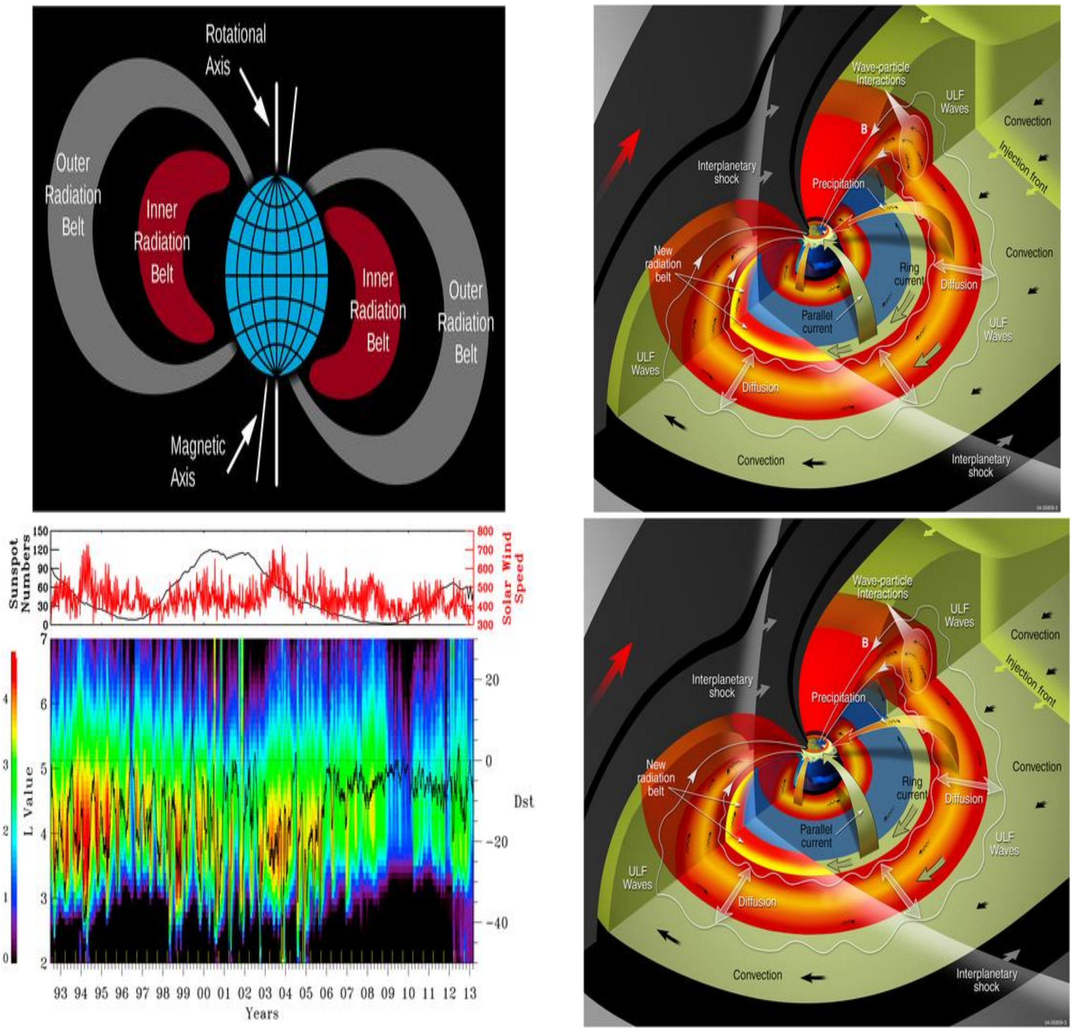
Introduction

The Van Allen radiation belts consist of populations of relativistic electrons and protons trapped within the Earth's magnetic field. Among these, energetic electrons, often referred to as “killer” electrons, are of particular concern because of their potential to cause significant anomalies in satellites through deep-dielectric charging. Early space missions underestimated the flux levels of these particles, as the initial instrument designs were based solely on measurements of cosmic rays and transient solar particles. In fact, the Unexpectedly high fluxes of trapped particles were first identified through dead-time saturation in Geiger counters aboard Explorer 1 [5]. At the time, prevailing theories, influenced by the growing knowledge of solar-terrestrial interactions and earlier observations of auroral soft radiation, suggested that the trapped particles originated from ionized solar gas injected into the geomagnetic field. Local acceleration mechanisms have been proposed to explain the high energy of these particles. However, subsequent studies introduced alternative hypotheses. One such idea posits that the penetrating component of trapped radiation might result from the radioactive decay of mesons produced in the Earth's atmosphere, a phenomenon tied to cosmic-ray albedo. Notably, the neutron component of this albedo was identified as a potential source of inner-zone protons, with Singer [2,3] emphasizing the role of high-energy neutrons in generating this radiation. The complete formation mechanism of the Van Allen Belt remains complex and has not been fully described. For example, the plasma turbulence phenomena observed in auroral zones are not fully understood. Nonetheless, it is now widely accepted that plasma instabilities and quasilinear pitch angle scattering, particularly in whistler-mode and ion cyclotron waves [4,5,6], play a significant role in limiting the fluxes of stably trapped energetic particles. These processes operate within the Earth’s magnetic field, which exhibits a dipolar “mirror” configuration [7,8,9], as illustrated in Figures 1.

How to cite this article:
Khatiwada, C. P. (2025). Study on Van Allen belt. Royal International Global Journal of Advance and Applied Research, 2(3), 103–105. https://doi.org/10.5281/zenodo.16149102

Results

Research conducted during the Van Allen Probes mission has significantly advanced our understanding of the Earth's radiation belts. The mission confirmed the existence of two main belts: the inner belt, which was rich in protons, and the outer belt, which was dominated by electrons. Additionally, a temporary third belt was observed under certain geomagnetic conditions, highlighting the complexity of the belt dynamics. The electron flux levels of the outer belt were highly variable, often responding to solar wind variations and geomagnetic storms. Electrons of approximately 100 keV, often referred to as seed populations, are injected during substorms and enhanced convection events. These are subsequently accelerated to megaelectronvolt energies through interactions with whistler-mode chorus waves, a process known as local acceleration, as shown in Fig 1. Further modifications in the electron distribution occur because of ultra-low frequency (ULF) waves, which transport electrons radially. Inward transport leads to acceleration, whereas outward transport causes deceleration and potential loss to space or the atmosphere. Wave-particle interactions play a critical role in the evolution of belts. Specifically, plasmaspheric hiss and electromagnetic ion cyclotron (EMIC) waves contribute to electron scattering, leading to atmospheric loss. Phenomena such as radiation belt "dropouts"—sudden depletions of high-energy electrons—are linked to this scattering and magnetopause shadowing. Detailed satellite observations also revealed a non-uniform spatial distribution of particles, showing both azimuthal and radial structures, especially following bursty flows from the magnetotail. The Van Allen probe data facilitated the development of hybrid data-driven and physics-based models, enhancing the prediction accuracy for radiation belt behavior and supporting space weather forecasting. These advances have important implications for the design of radiation-hardened satellite systems, as illustrated in fig 1. Nevertheless, integrating radiation belt physics into global geospace models remains challenging. Future progress depends on coupling radiation belt dynamics with larger systems, such as solar wind, plasmasphere, and ionosphere, using coordinated satellite and ground-based observations.



Figures 1: Van Allen belt formation, Van Allen Belts, and arrival of interplanetary shock with new radiation, formation of Van allen belt with year and sunspot number and various magnetospheric waves and energetic particles.

Conclusion

In the Van Allen Probes era, significant advances have been made in understanding and modeling the physical processes controlling the Earth's radiation belt electron dynamics. Electron injections due to substorms or enhanced convection, inward radial diffusion, and time-domain structures play an important role in providing seed electron populations (~100s keV) that can be further accelerated to MeV through local acceleration. Rapid transport of the seed electron population from the tail may be highly azimuthally structured in bursty bulk flows. The most efficient local heating is provided by whistler-mode chorus waves through diffusive or non-diffusive scattering, which leads to growing radial peaks in the electron phase-space density in the heart of the outer radiation belt. Subsequently, radial diffusion due to ULF waves plays an essential role in redistributing electrons, thus accounting for further acceleration (or deceleration) depending on whether the transport is directed radially inward or outward. There remain outstanding open questions in radiation belt physics and challenges in radiation belt modelling. In addition to the challenges discussed above, a major issue is the effective coupling of radiation belt models into global geo spatial models for space weather forecasting. This requires proper incorporation of the interaction of radiation belt dynamics with other systems such as the solar wind, tail plasma sheet, plasma sphere, and ionosphere. It is hoped that future investigations will address these open questions by combining multisatellite data sets with ground-based resources.

Acknowledgement

The author declares that there is no acknowledgement regarding this paper.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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