Evolution of electron zebra stripes in the Earth's inner magnetosphere

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1. Abstract

We focus on the charged particle in space that exhibits a complex interaction under the influence of the Earth's magnetic field. For certain conditions, these charged particles may get trapped into the Earth's magnetosphere and execute distinct periodic motion unless an external perturbation acts on it. The external perturbation affects the trajectory of the charged particles and leads to the redistribution of their configuration in the space. The energetic particles with energies ranging from 100 keV to a few MeV are trapped in about 1-7 R_E forming a doughnut-like two-belt structure namely: (i) the inner radiation belt which is located at about ~1-2.5 R_E and (ii) the outer radiation belt which is located at about 3-7 R_E. The inner belt mainly consists of protons and is relatively stable, while the outer belt is highly dynamic with relativistic electrons. The region between the inner and outer belt is generally devoid of energetic charged particles and is named as slot region. The outer belt electrons continuously decay and reform with each reformed belt may have different physical properties and intensities. The energy versus L-value spectrum of electrons in the inner belt was previously expected to be monotonic and smooth. Later, multi-peaked structures of electron intensities are observed in the energy spectra at $L<3$. The peak-to-valley ratio of the intensities was observed to reach 10 times or more. Currently, we are testing plausible global mechanisms for the formation of such structures and their variation that could be responsible to alter the magnetic field configuration in the inner magnetosphere down to $L = 1.1$.

2. Introduction

The charged particles emanating from the Sun exhibits a complex interaction under the influence of the Earth's magnetic field and get trapped in the Earth's magnetosphere when certain conditions are satisfied. The energetic particles with about 100's of keV to a few MeV energies get trapped in the Earth's magnetic field in about 1-7 R_E regions known as radiation belts. The schematic diagram of a typical two-belt structure of radiation belts is shown in figure 1. It consists of two distinct regions of energetic particles' population; (i) inner belt, which mainly consists of energetic protons that extend from ~1-2.5 R_E, and (ii) outer belt, which is mainly composed of energetic electrons and has its inner edge around 3 R_E. The outer belt is highly dynamic with its outer edge usually just beyond geosynchronous orbit. The region between the inner and outer belt is generally devoid of energetic charged particles and is known as the slot region.

Explorer I and III spacecraft recorded very critical measurements of the energetic charged particles in space. These were discovered by James Van Allen in 1958 and were named as Van Allen Radiation belts in his memory. The radiation belt particles are very harmful to human life and electronic circuits of sensitive instruments in space. Moreover, the radiation belt electrons and ions showed interesting characteristics like non-monotonic distribution during the disturbed intervals under the influence of electric fields, flux variation by an order of one or more, interaction with the variety of frequencies of waves leading to the acceleration or loss

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processes in the magnetosphere. This made a study of radiation belts a very interesting topic especially using newer sophisticated instruments that are specially designed to survive the severe energetic particle bombardment.

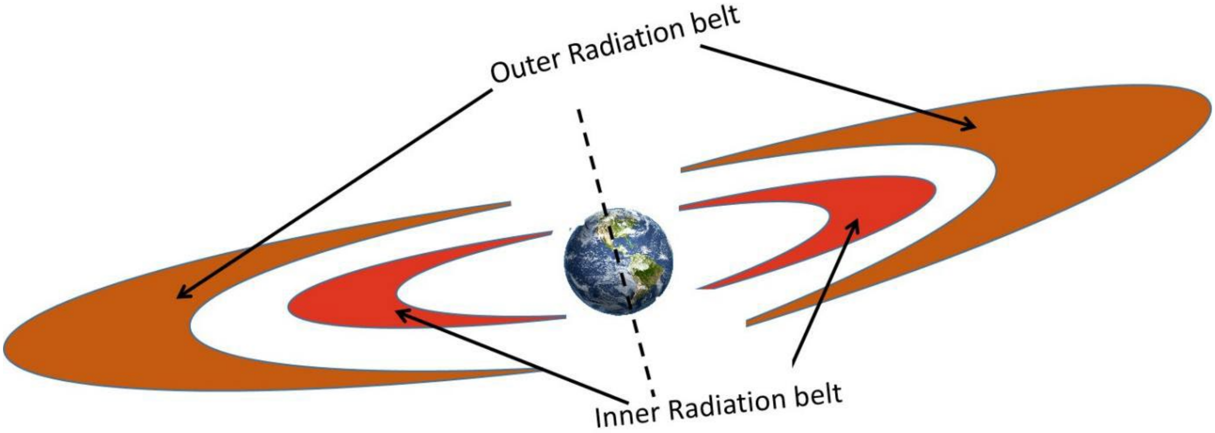

Figure 1: Schematic diagram of the two-belt structure of the Earth's radiation belts.

Our studies focus on the dynamic electron radiation belts that continuously undergo the decay process and again refill irregularly with different physical properties like shape, position, and intensity of fluxes. This newly formed radiation belt may be completely different from the previous one. In the early 1960's it was believed that the distribution of the 100's of keV to a few MeV electrons is monotonous and well-ordered. Later, Imhof et al.,$^{1)}$ first showed the presence of some sharp peaks in the electron flux intensities after a geomagnetic storm. They observed a single peak in the energy spectrum at 1.5 MeV using low altitude-satellites. A new era to study such distinct features in the Earth's radiation belt emerged with this observation. Several researchers observed similar fine structures at $L<2$ and multiple peaks with high intensities were studied to explain the global mechanism for its occurrence.

Since the beginning of the space era, the behavior or energetic charged particle population with 100's of keV to a few MeV energies has always puzzled the scientific community. The unusual characteristics of charged particle population and its extent of flux intensities have led to a major loss of some of the previous satellite missions in the 1990s. At low L-values where the fluxes of energetic protons are high, the older satellite missions, like DEMETER spacecraft, could not distinguish the contamination of protons while measuring electron fluxes. In 2012, the newly-launched Van Allen Probes mission re-opened another era to re-examine and improve the understanding of radiation belt ions and electrons.

3. Data Selection

To understand the behaviour of the charged particles, we employ the data obtained from Van Allen Probes. The Van Allen Probes launched into orbit on 30 August 2012, comprises twin identical spacecraft Probe-A and Probe-B. The two spacecraft have nearly identical orbits with an orbital period of ~9 hr, a perigee of ~600 km, and apogee of ~5.8 R_E and 10° inclination$^{3)}$. Such orbits allow spacecraft to cover the most hazardous region of the Earth's magnetosphere. We use level-3 unidirectional differential flux data obtained from the RBSPICE$^{4)}$ instrument onboard Van Allen Probes-A. It consists of 20–940 keV electrons having 64 bins of energy channels. The unidirectional data are binned into 17 pitch angle bins with 10° width, having the first and last pitch angle bin width of 15°. The high-resolution data binned into 64 energy channels serve as a great opportunity for studying various features in the energy spectrum of the electron radiation belt.

4. **Observation and Results**

Figure 2 presents the electron spectrogram taken by Van Allen Probes A at L<3.5 during the interval ranging from 01:35 UT to 06:07 UT on 27 January 2017. The colorbar represents the electron fluxes measured at 90° pitch angle. Several stripes are seen in the spectrogram, which is different from a monochromatically peaked structure as previously observed.1) The stripes that appear in the energy vs. L spectrogram are called "zebra stripes"5). Formation of such structures of electron flux distributions are not likely to be the consequence of the diffusion, in which particles in the denser region move to the tenuous region in the phase space. We are currently investigating the plausible sources that can give rise to the distribution of energetic electrons in the inner belt, in particular, the zebra stripes.

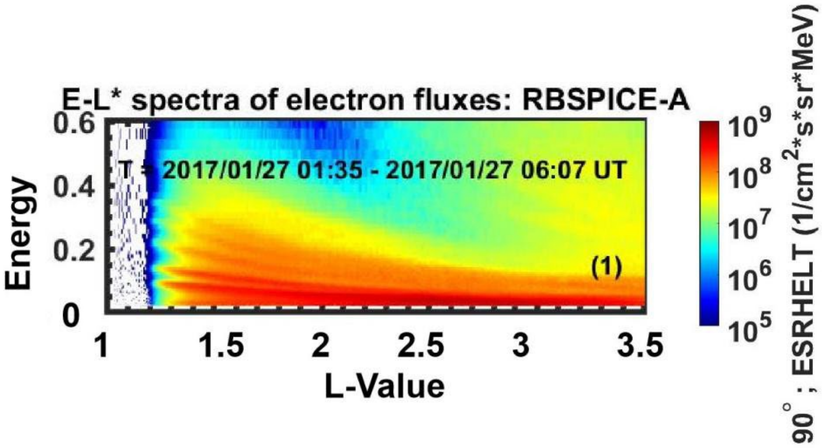

Figure 2: Electron "zebra stripes" observed on the energy versus L-value spectrogram is shown. They were recorded by RBSPICE-A on board the Van Allen Probe A on 27 January 2017.

Similar structures have been previously recorded by various satellites5,6). These patterns are suggested as an outcome of the interaction between the electrons and the induction electric field associated with Earth's rotation5), and resonant interaction of energetic electrons with ultralow frequency (ULF) waves in Earth's magnetic field1). Apart from these, the electric field generated due to the interaction of the fast solar wind with the Earth's magnetosphere is also suggested to play an important role in the dynamics of radiation belt electron1). Using numerical simulations Elkington et al.7) have shown that this electric field could also have an important and interesting effect on drift resonances of electrons with toroidal and poloidal ULF waves.

5. Discussion

We are studying the formation mechanism of the "zebra stripes" measured by the RBSPICE instrument onboard twin Van Allen Probes, which consist of 100's of keV electrons distributing over the entire inner radiation belt (<3 R_E). Based on the observed regular patterns automatically identified, we are currently investigating various physical processes that are responsible for the formation of stripes. Some global mechanisms could be likely to alter the electron drift in the longitudinal direction. As a first step, we are trying to identify the source location of the electrons with energy ranging from 0.02 to 0.6 MeV at L<3. One of the major plausible global mechanisms for the redistribution of energetic electrons is the complex interactions between the solar wind and Earth's magnetic field. We make a comprehensive analysis to understand the instability of the magnetic field lines up to L = 1.1.

Our studies on identifying the behavior of 100's keV electrons are believed to advance our understanding of space environments and their interactions with the human living environment-sphere. Human civilization has started to notice the destructive power of energetic particles after the advent of the space era. Hence, we aim to deepen our understanding of the variability of the radiation belts for the benefit of society and maximum use of a sustainable space environment, namely space humanosphere. The precipitating electrons, cause northern and southern lights. The magnetospheric and ionospheric current system results in huge electrical currents electrical currents that can disrupt communication and power grids. The radiation belts contain intensely charged particle particles that are potentially hazardous to astronauts and sensitive electronics on spacecraft. Our studies on energetic trapped charged particles in the near-Earth environment may contribute to forecasting and preventing adverse conditions in the space environment that can cause a variety of socioeconomic losses.

6. References

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Profile

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Graduated from the Department of Physics, Saurashtra University, in 2014 / Completed the doctoral course at the Indian Institute of Geomagnetism, Navi Mumbai and the degree is awarded by University of Mumbai (Ph.D. in Physics) in 2020 / Mission Research Fellow, RISH in 2021 (to present). At RISH, we study the Earth's radiation belt dynamics and its complex interactions with the solar wind.