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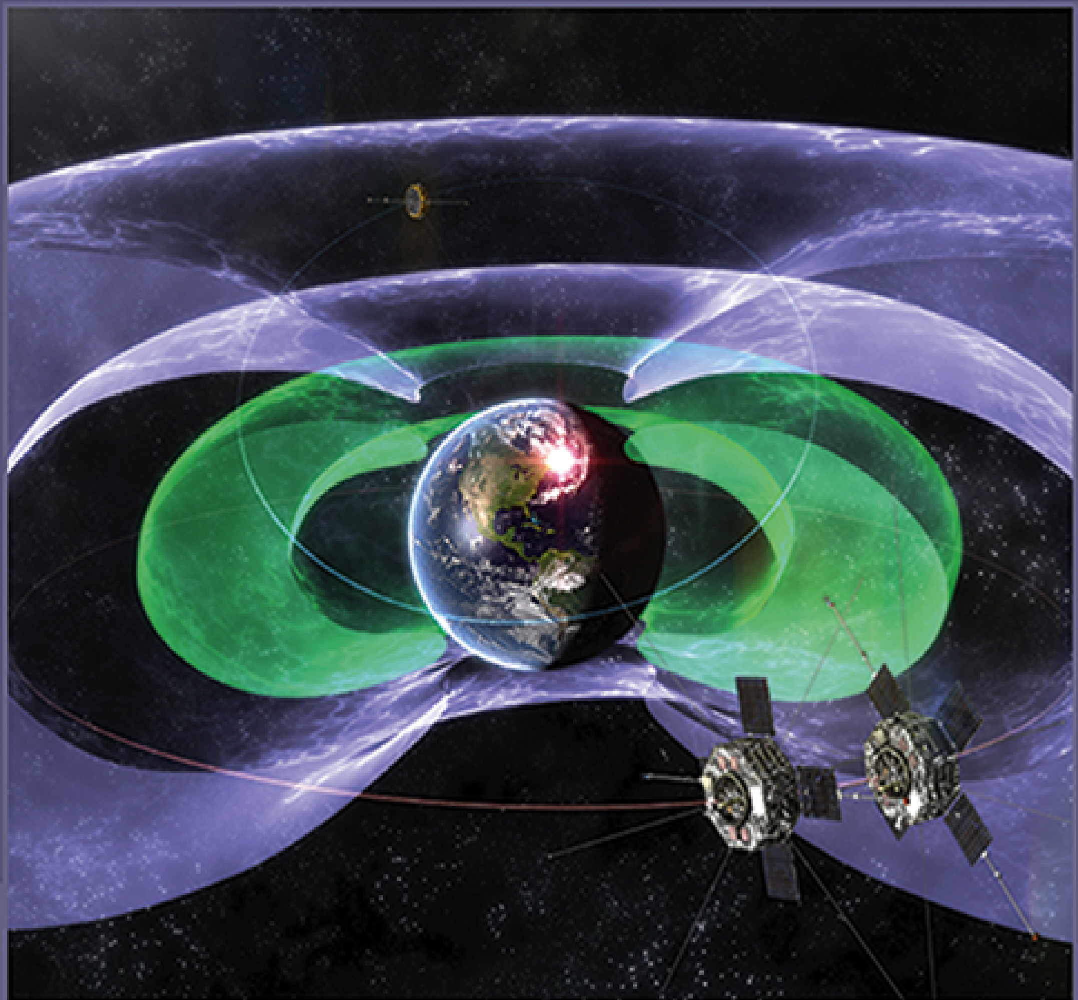
Dynamics of the Earth's Radiation Belts and Inner Magnetosphere



Danny Summers, Ian R. Mann, Daniel N. Baker,
and Michael Schulz
Editors

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CONTENTS

Section V: Radiation Belt Injections, Dropouts, and Magnetospheric Variability

Time Scales for Localized Radiation Belt Injections to Become a Thin Shell

Rebuilding Process of the Outer Electron Radiation Belt: The Spacecraft Akebono Observations

The Shock Injection of 24 March 1991: Another Look

Section VI: Wave-Particle Interactions

Generation Processes of Whistler Mode Chorus Emissions: Current Status of Nonlinear Wave Growth Theory

Plasma Wave Observations at Earth, Jupiter, and Saturn

AGU Category Index

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Ian R. Mann
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Cover Image: Schematic illustration of Earth’s radiation belts and orbiting satellites. Image credit: Andy Kale, University of Alberta,Edmonton, Alberta, Canada.

PREFACE

These are exciting times for radiation belt research. After 11 years of planning and preparation, NASA's Radiation Belt Storm Probes (RBSP) blasted off from Cape Canaveral Air Force Station, Florida, at 4:05 A.M. EDT on 30 August 2012. The identical twin spacecraft (A and B) were launched aboard a United Launch Alliance Atlas V rocket from Space Launch Complex 41 following a smooth countdown. The probes, identically equipped with state-of-the-art instrumentation and heavily shielded against the effects of space radiation, were released from the Centaur upper stage of the rocket one at a time into different orbits, thus beginning a 2 year prime mission to study Earth's radiation belts. During the RBSP mission the twin spacecraft will traverse both the inner and outer Van Allen radiation belts that encircle the Earth twice per 9 hour orbit. Slightly different apogees and orbital periods will cause one spacecraft to lap the other 4 to 5 times per year. The wealth of data expected to be collected by RBSP on particles, plasma waves, and electric and magnetic fields should provide unprecedented insight into how the radiation belts evolve in time and space. The overall goal of RBSP is to understand, ideally to the level of predictability, how Earth's radiation belts vary in response to dynamical inputs originating from the Sun. This will require detailed understanding of particle acceleration mechanisms, particle loss processes, and particle transport in the inner magnetosphere. It will also require understanding how radiation belt behavior links to or couples with the other important plasma components in the inner magnetosphere, namely, the ring current, plasmasphere, and ionosphere.

An important facet of the RBSP mission is to explore the extremes of space weather, namely, the extreme conditions in the space environment surrounding Earth that can disrupt human technologies and possibly endanger astronauts. For instance, magnetic storms induced by solar events such as coronal mass ejections or high-speed solar wind streams can generate highly energetic (“killer”) electrons that can damage or even shut down Earth-orbiting satellites. Magnetic storms can also give rise to geomagnetically induced electric currents in the Earth that can interfere with technologies on the ground such as electric power grids. Energetic protons produced by solar storms can pose a serious hazard to both satellite electronics and astronauts. RBSP will produce a 24 hour space weather broadcast using selected data from its suite of instruments that will provide researchers a check on current conditions near Earth. RBSP data will be used by engineers to design radiation-hardened spacecraft and will enable forecasters to predict space weather events in order to alert astronauts and operators of spaceborne and ground-based technologies to potential hazards. The development of space weather science has intensified over the last 10–15 years, fueled by our increasing reliance on space technologies. In parallel with the coming of age of space weather science, there has been a resurgence in radiation belt research in the last decade that indeed has served as a prelude to the launch of RBSP.

In anticipation of the RBSP mission the AGU Chapman Conference Dynamics of the Earth’s Radiation Belts and Inner Magnetosphere was held during 17–22 July 2011 in St. John’s, Newfoundland and Labrador, Canada. This volume is based largely on the material presented at this Chapman Conference. The conference was held with the aim of drawing together radiation belt knowledge and refining science questions for RBSP and other upcoming missions; summaries of the conference are given by D. Summers, I. R.

Mann, and D. N. Baker (Eos, 92(49), 6 December 2011) and D. N. Baker, D. Summers, and I. R. Mann (*Space Weather*, 9, S10008, doi:10.1029/2011SW000725, 2011). Prevailing themes of the conference and this volume include radiation belt particle acceleration and loss processes, particle transport in the inner magnetosphere, radiation belt responses to different solar wind drivers, and the control of radiation belt dynamics by wave-particle interactions. A key conclusion of the conference is that, despite more than 50 years of radiation belt investigations, our knowledge of the radiation belts, both from observational and theoretical points of view, is far from complete. The RBSP era promises to significantly improve our understanding of the dramatic and puzzling aspects of radiation belt behavior. We hope that the present volume will serve as a useful benchmark at this exciting and pivotal period in radiation belt research in advance of the new discoveries that the RBSP mission will surely bring.

We would like to thank Brenda Weaver and Cynthia Wilcox of the AGU Meetings Department for their great help in ensuring the success of the Chapman Conference. We also thank Maxine Aldred, Colleen Matan, Maria Lindgren, and Telicia Collick of the AGU Books Department for their work in the production and timely completion of this book. Finally, we are most grateful to the more than 60 referees who reviewed the articles submitted to this volume.

Note added in proof: NASA has recently renamed the Radiation Belt Storm Probes (RBSP) mission. At a special ceremony held at the Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, on 9 November 2012, NASA renamed the mission as the Van Allen Probes in honor of James Van Allen, the discoverer of Earth’s radiation belts. The ceremony also highlighted the successful commissioning of the spacecraft.

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Introduction

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Earth's radiation belts have attracted much experimental and theoretical investigation since their discovery by James Van Allen in 1958. In this introductory article, we briefly scan developments in radiation belt science since 1958, both with respect to satellite observations and theory and modeling. We then provide an overview of the articles in this book, which mainly derive from the 2011 Chapman Conference on Dynamics of the Earth's Radiation Belts and Inner Magnetosphere. In the past decade, there has been a resurgence in radiation belt studies in parallel with the rapid development of space weather science. NASA's Radiation Belt Storm Probes (RBSP) mission, which has just been launched at the time of writing, promises to provide unprecedented measurements of the particles, electric and magnetic fields, and plasma waves in the Earth's radiation belts.

This volume provides a timely state-of-the-art account of radiation belt science prior to the start of the RBSP era.

The discovery by James Van Allen in 1958 of the Earth's radiation belts (now "Van Allen belts"), using Explorer 1 data [*Van Allen et al.*, 1958], was a momentous event in space physics. The intense radiation environment around the Earth has since attracted much scientific interest. Here we recount some important developments in radiation belt research, a selection of which we include in Table 1. The late 1950s and 1960s heralded the birth of the space age. Sputnik 1, launched on 4 October 1957 by the Soviet Union, was the first successful Earth-orbiting satellite. The first commercial telecommunications satellite Telstar-1, launched on 10 July 1962, carried a set of solid-state detectors to characterize the radiation environment that the vehicle would encounter. A day before the launch of Telstar, the Starfish high-altitude nuclear explosion greatly enhanced the trapped electron fluxes, thereby creating an artificial radiation belt in the vicinity of Telstar's orbit. The radiation environment was further enhanced by a Soviet nuclear test in October 1962. The resulting intense radiation caused the premature demise of Telstar-1 in February 1963. The detectors onboard Telstar were able to monitor the artificial radiation belt and record its degradation via particle precipitation losses attributed to natural wave-particle interactions. Much theoretical work has since been carried out to evaluate wave-particle interaction processes in the Earth's (natural) radiation belts. It is interesting to note that prior to the discovery of the natural radiation belts by Van Allen, the U.S. Air Force was preparing to carry out an experiment, code-named Argus, to study the trapping of energetic particles by the Earth's magnetic field. It was actually suggested during the planning sessions for Argus that a natural radiation belt might exist around the Earth. Then, immediately following Van Allen's discovery of the

Earth's radiation belts, the U.S. Air Force exploded the Argus high-altitude nuclear bombs in order to create artificial radiation belts. These artificial belts were studied by the satellite Explorer 4, built for this purpose by Van Allen and his group.

Table 1. Developments in Radiation Belt Science

Satellites and Observations		Theory and Modeling	
Timeline	Event	Timeline	Description
1958	Discovery of the Earth's radiation belts by James Van Allen using Explorer 1	1907, 1933, 1955	Stormer: motion of a charged particle in a dipole magnetic field
1958	Creation of artificial radiation belts by Argus high-altitude nuclear bombs	1960s	Development of fundamental radiation belt theory (particle sources, losses, transport, diffusion)
1958	Sputnik 3 confirms the existence of the Earth's radiation belts	1960s	Development of AE, AP models of radiation belt electron, proton environment
1960s	Polar Operational Environmental Satellites (POES) program of polar orbiting satellites begins	1961	McIlwain *L* shell parameter
1962	Starfish high-altitude nuclear explosion: artificial radiation belt produced	1963	Northrop: adiabatic invariants
1962–1963	Telstar-1	1964	Andronov and Trakhtengerts: kinetic instability of the outer radiation belt
1966	Launch of (geosynchronous) Applications Technology Satellite-1	1965	Falthammar: radial diffusion produced by time-varying electric field
1970s–1980s–1990s	Radiation belts observed at Jupiter, Saturn, Uranus, Neptune (Pioneer 11, Voyagers 1, 2)	1966	Kennel-Petschek theory
1975	Launch of GOES geostationary satellites begin	1970	Roederer *L** parameter
1976	Los Alamos National Laboratory geosynchronous satellite energetic particle measurements begin	1974	Schulz and Lanzerotti monograph on radiation belt particle diffusion
1990–1991	CRRES	1981	Gendrin: wave-particle interactions
1992	Launch of Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX)	1991	Vette AE-8 model of trapped electron environment
1994	Term "killer electrons" coined	1996	AGU Geophysical Monograph-*Radiation Belts: Models and Standards*
1996–2008	Polar	2000s	Resurgence of radiation belt studies
2000s	Coming of age of space weather science	2011	AGU Chapman Conference: Dynamics of the Earth's Radiation Belts and Inner Magnetosphere, St. John's, Canada
2012	Launch of Radiation Belt Storm Probes (RBSP)		

The Soviet spacecraft Sputniks 2 and 3 also contributed to the early measurements of the Earth's radiation belts. An experiment by S. N. Vernov et al. on board Sputnik 2, launched on 3 November 1957 before Explorer 1, might have discovered the radiation belts, but the orbit was in far northern latitudes. It was thus beneath most of the outer radiation belt when it was monitored in the USSR. Moreover, published data from Sputnik 2, which showed increased detector count rates above the USSR, were not reported as unusual, nor interpreted as geomagnetically trapped particles [*Vernov et al.*, 1959]. Subsequently, Sputnik 3 confirmed the existence of the Earth's inner and outer radiation belts, which had already been found and documented by Van Allen.

With the launches of Syncom 3 in 1964 and Intelsat 1 in 1966, geosynchronous orbit (GEO) soon became the preferred orbit for commercial communications and television broadcasts. NASA launched the Applications Technology Satellite (ATS-1) in December 1966. In addition to its communications experiments, ATS-1 carried three separate charged particle instrument suites designed to characterize the GEO radiation environment. These instruments provided new and fundamental information on the dynamics of the radiation belts that would impact commercial and government space systems at GEO, including the discovery of the dramatic changes that can occur during geomagnetic storms (both the intense particle enhancements and depletions) and the rapid access of solar energetic particles to GEO.

Early in the space program, the charged particle data being gathered by numerous satellites circling the Earth (such as Interplanetary Monitoring Platforms (IMPs), Explorers (especially Explorer 26), Orbiting Geophysical Observatories (OGOs), International Sun-Earth Explorer (ISEE) 1, 2) were incorporated into the so-called AE, AP models of the radiation belt electron and proton environment. The NOAA Polar Operational Environmental Satellites (POES) program began in the 1960s, while the Geostationary Operational Environmental Satellites (GOES) program began in 1975. Los Alamos National Laboratory (LANL) geosynchronous satellite energetic particle measurements began in 1976. The POES, GOES, and LANL satellites continue to monitor the radiation environment today.