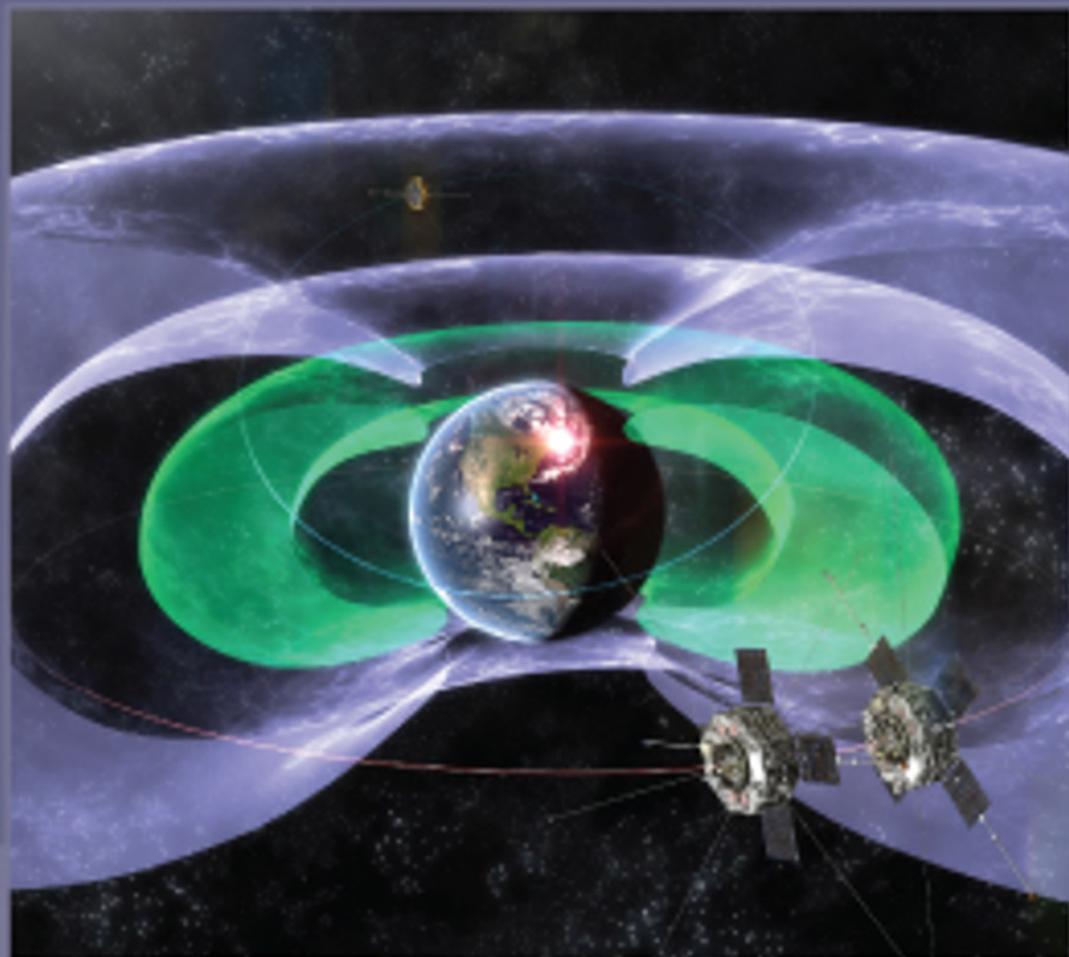


*Dynamics of the Earth's
Radiation Belts and Inner
Magnetosphere*



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

netically 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

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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	Mcllwain 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- <i>Radiation Belts: Models and Standards</i>
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)		

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.

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.

A particularly valuable source of radiation belt data is the Combined Release and Radiation Effects Satellite (CRRES), which was launched on 25 July 1990 and functioned until 12 October 1991 [Johnson and Kierein, 1992]. The spacecraft had a geosynchronous transfer orbit, namely, an elliptical orbit with a perigee of $1.05 R_E$ and apogee of $6.26 R_E$, with respect to the Earth's center, with an inclination of 18.15° . The outermost L shell reached by CRRES was about $L = 8$. The orbital period was about 9 h 55 min, and the apogee precessed from 10:00 magnetic local time (MLT) to 14:00 MLT through midnight before the mission ended. The satellite was, thus, able to provide excellent coverage of the radiation belts for nearly 15 months since it traversed the inner magnetosphere on average about 5 times per day. The CRRES particle, field, and wave data remain a valuable (and still not fully mined) radiation belt resource today.

In 1992, NASA launched the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) satellite with a nearly circular, low-Earth (600 km), high-inclination (82°) orbit with a period of about 100 min [Baker et al., 1993]. While the primary mission of SAMPEX was to measure cosmic rays and solar energetic particle enhancements, the spacecraft also carried highly sensitive electron detectors. The latter instruments served to reveal new insights into radiation belt dynamics and to provide monitoring of the radiation belts on a continuous basis. SAMPEX has, in fact, proved to be one of the best NASA radiation belt missions. The SAMPEX spacecraft is scheduled to end its mission and reenter the Earth's atmosphere by December 2012. The contribution of SAMPEX to our knowledge of the radiation belts

over its 20 year mission is the subject of an article by Baker and Blake [this volume].

The NASA spacecraft Polar, carrying charged particle, field and electromagnetic wave instruments, was launched in 1996 and primarily designed to study the polar magnetosphere and aurora [Acuña et al., 1995]. Polar was placed in a highly elliptical orbit with perigee $1.8 R_E$ and apogee $9.0 R_E$, with an inclination of 86° , and a period of about 17.5 h. Notwithstanding its primary mission, as its orbit precessed over time, Polar made valuable observations of the Earth's radiation belts and equatorial inner magnetosphere. The Polar mission was terminated in April 2008.

The NASA twin-spacecraft Radiation Belt Storm Probes (RBSP) mission, successfully launched in August 2012, should provide the most complete measurements hitherto made of the charged particles, fields, and waves in the Earth's radiation belts. The overall objective of RBSP is to provide understanding, ideally to the point of predictability, of the dynamics of radiation belt particles in response to variable energy inputs from the Sun. Equivalently, this will require a complete understanding of the energization, transport, and loss processes of radiation belt particles in time and space. The RBSP spacecraft will have 600 km perigee, $5.8 R_E$ geocentric apogee, and will traverse both inner and outer radiation belts twice per 9 h orbit. The low-inclination (10°) orbit will permit RBSP to access essentially all magnetically trapped particles. The sunward oriented spin axis will permit full particle pitch angle distribution sampling twice per 12 s spin and ensure accurate measurements of the dominant dawn-to-dusk electric field component. The identically instrumented spacecraft will carry five suites of instruments: Energetic Particle Composition and Thermal Plasma Suite (ECT), Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS), Electric Field and Waves (EFW) Instrument, Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE), and Proton Spectrometer Belt Research (PSBR). Collaborations are planned for RBSP with the Time History of Events and Macroscale Interactions during Substorms (THEMIS) and Balloon Array for Radiation belt Relativistic Electron Losses (BARREL) missions. Details of the mission design, instruments, and science questions related to RBSP are given in an article by Kessel [this volume].

In the right-hand side of Table 1, selected developments in radiation belt theory and modeling are listed. We comment here, briefly, on some of these developments.

C. Stormer was the first to calculate the different types of trajectory of a charged particle moving in a dipole magnetic field [Stormer, 1907, 1933, 1955]. His landmark work, which was carried out before the discovery of the Earth's radiation belts, is still relevant today. Stormer determined

“allowed regions” and “forbidden regions” in the vicinity of the Earth that can or cannot be reached by a charged particle traveling toward the Earth. Calculation of such regions is relevant to determining the regions near the Earth that can be accessed by solar energetic particles (SEP) and galactic cosmic rays (GCR) and can be applied to the problem of creating a “magnetic shield” around a spacecraft to protect it from highly energetic particles. It is clearly of interest to determine the extent to which Stormer’s theory is applicable to a time-dependent geomagnetic field. For instance, *Kress et al.* [2005] show that a generalization of Stormer’s theory, to a time dependently perturbed dipole magnetic field, is relevant to SEP geomagnetic trapping

The fundamental physics of the radiation belts was developed in the 1960s in parallel with the early radiation belt particle observations. The main topics addressed then were precisely those with which we are concerned today, namely, radiation belt particle sources and losses, transport, and diffusion. *Andronov and Trakhtengerts* [1964] and *Kennel and Petschek* [1966] showed that radiation belt particle distributions can be unstable to the generation of plasma waves. Thus, there was early recognition of the importance of wave-particle interactions and, in particular, of particle precipitation resulting from resonant pitch angle scattering by electromagnetic waves. Seminal approaches to radiation belt modeling were established by *Northrop* [1963], who showed that radiation belt particle dynamics could be described in terms of three adiabatic invariants, and *Fälthammar* [1965], who developed a radial diffusion equation. Subsequently, *Schulz and Lanzerotti* [1974] published a comprehensive account of what might be called the classical theory of particle diffusion in the radiation belts. The framework of radiation belt dynamics was simplified by the introduction of the magnetic shell parameter L by *McIlwain* [1961] and, later, the (adiabatically invariant) generalized L shell parameter L^* by *Roederer* [1970]. A synthesis of the early literature on radiation belt studies, both theoretical and experimental, is provided by *Hess* [1968]. *Gendrin* [1981] devised a method for treating wave-particle interactions by evaluating wave growth and particle diffusion in terms of the relative configuration of specified curves in the particle velocity space. *Van Allen* [1983] provides a retrospective view of the discovery of Earth’s radiation belts and the early developments in magnetospheric physics.

The 1970s to the 1980s was largely a period of stagnation in studies of the Earth’s radiation belts. The prevailing sentiments were that the radiation belts were static, the necessary theory had been developed, and that the radiation belts were well understood. A dramatic change in thinking in the radiation belt science community occurred in the 1990s as a result of observations by the CRRES and SAMPEX satel-

lites. The new radiation belt of highly relativistic electrons created in minutes by the March 1991 shock injection, observed by CRRES, was without precedent. The complexity of radiation belt dynamics revealed by the CRRES particle and wave instruments was unexpected. Moreover, SAMPEX provided a totally new insight into how the radiation belts evolve in time with respect to solar events, geomagnetic storms, and over the solar cycle. The 1990s, and especially the 2000s, saw an intensification of radiation belt studies, with attempts to create realistic models of the dynamical radiation belts that were now known to change over many time scales. The AGU volume edited by *Lemaire et al.* [1996] provides a useful account of radiation belt modeling at that time.

The resurgence in radiation belt studies, continuing today, is partly the result of the emergence of space weather science. Increasing human reliance on spacecraft technology has caused an increased need to protect spacecraft against such space weather hazards as “killer electrons,” the highly energetic (\sim MeV) electrons that can be generated in the outer radiation belt during geomagnetic storms (the evocative term “killer electrons” was coined in an article by *Graham* [1994]). Understanding exactly how, and under what circumstances, killer electrons are generated remains a great challenge in radiation belt physics. As well, notwithstanding considerable efforts over the last decade, radiation belt modeling attempts face significant difficulties, e.g., multidimensional, time-dependent models are required but lack global spatiotemporal information on the various plasma wave modes that control radiation belt particle dynamics, reliable magnetic field models that are valid under disturbed conditions are unavailable, classical radial diffusion theory may not be as widely applicable as previously thought, and quasi-linear theory of wave-particle interactions may need to be augmented or replaced by nonlinear theories. Further, radiation belt dynamics couples with the ring current, plasmasphere, and ionosphere, so realistic radiation belt models should incorporate such coupling. The papers in this volume speak to these challenges in radiation belt modeling, as well as providing a current state-of-the-art account of radiation belt science.

The contents of this monograph are as follows.

As a historical prelude, *Lanzerotti* [this volume] describes in a narrative style the development of technologies on the Earth and in space and how the space environment around the Earth has affected their design and operation. Lanzerotti’s article is written partly with reference to Newfoundland, Canada, the location of the Chapman Conference from which this book derives. Newfoundland played key roles in world communication “firsts,” including the landing of the first trans-Atlantic telegraph and telecommunications cables, and

the first reception of trans-Atlantic wireless signals at Signal Hill in St. John's.

The second section addresses our current state of knowledge of the Earth's radiation belts. At the approach to sunspot minimum, recurrent solar wind streams typically cause geomagnetic storms and enhanced relativistic electrons in the outer radiation belt. On the other hand, strong magnetic storms associated with aperiodic coronal mass ejections occur most frequently around sunspot maximum. Such disturbances can also cause significant radiation belt enhancements. *Baker and Blake* [this volume] illustrate these phenomena by using SAMPEX particle data to characterize the differences in radiation belt behavior over the course of the 11 year solar activity cycle. The remaining papers in the second section relate to particular types of plasma wave in the inner magnetosphere that are considered to be instrumental in controlling radiation belt particle dynamics. *Cattell et al.* [this volume] review measurements from the STEREO and Wind Waves waveform capture instruments of large-amplitude whistler mode waves. These waves, which are different from whistler mode chorus, are shown by simulations to result in rapid electron energization by many MeV as a result of nonlinear processes including phase trapping. A key implication of the work of Cattell et al. is that quasilinear treatments of electron energization and scattering may not be adequate for understanding radiation belt dynamics. *Fraser et al.* [this volume] use GOES data to classify various types of electromagnetic ion cyclotron (EMIC) waves at geosynchronous orbit ($L = 6.6$). EMIC wave scattering is thought to contribute significantly to radiation belt MeV electron losses and localized ring current ion decay. *Mann et al.* [this volume] present an overview of the role of ULF waves in radiation belt dynamics. These authors characterize ULF waves around electron drift orbits on a mesoscale and global scale by using the ground-based magnetometer arrays CARISMA and THEMIS GMAG. ULF waves are highlighted for their role in influencing a wide range of radiation belt acceleration, transport, and loss processes, including cross-energy coupling of the radiation belts with the ring current and plasmasphere.

The third section addresses satellite missions that will probe the Earth's radiation belts and inner magnetosphere, specifically NASA's RBSP mission, the Japanese Energization and Radiation in Geospace (ERG) project, and the Russian RESONANCE mission. We have already provided information on the RBSP mission in the Preface and earlier in the Introduction. *Kessel* tracks the progress of RBSP from formulation and development of the science objectives through instrument selection to mission design, integration, and testing, with an emphasis on how the chosen measurements address the science objectives. Following the success-

ful launch of RBSP on 30 August 2012 (see Figure 1), commissioning of the instruments will take place during September and October in 2012, with the start of normal operations scheduled for 1 November 2012. While the initial period of operation of RBSP will be 2 years, both RBSP spacecraft carry sufficient propellant for up to 5.5 years of normal operations. *Miyoshi et al.* [this volume] describe the ERG mission, which is a science satellite program of the Institute of Space and Astronautical Science (ISAS)/Japan Aerospace Exploration Agency (JAXA). The ERG satellite will explore how relativistic electrons in the radiation belts are generated during space storms. ERG will measure the plasma distribution function, electric and magnetic fields, and plasma waves. A new and innovative technique will be used for wave-particle interactions that directly measures the energy exchange process between particles and waves. ERG has been approved for implementation with a nominal launch date of December 2015. *Mogilevsky et al.* [this volume] provide an overview of the current state of the Russian RESONANCE project. RESONANCE is a four-satellite mission designed to investigate wave processes in the inner magnetosphere related to resonant wave-particle interactions. A characteristic feature of this mission is that the four satellites will make long-term simultaneous measurements of electromagnetic fields and particle fluxes at different locations in the same magnetic flux tube. The RESONANCE spacecraft will be launched in two steps. The first pair of satellites is due to be launched at the end of 2014; the launch of the second pair is planned for March–April 2015.

In the fourth section, the modeling of radiation belt electron dynamics using global MHD simulations is addressed. *Elkington et al.* [this volume] analyze the azimuthal mode structure of ULF waves during the 24–26 September 1998 geomagnetic storm and find that the bulk power in the fluctuating electric and magnetic field components can be described by low ($m < 3$) mode numbers during the storm recovery phase, but that there was significant power in the higher mode numbers ($m > 3$) during the main phase. These results have implications for the commonly made assumption $m = 1$ used in studies of the interaction of radiation belt particles with global ULF waves. *Ozeke et al.* [this volume] employ ULF wave-driven radial diffusion simulations of outer radiation belt electrons and demonstrate that the radial diffusion coefficients hitherto typically used in such models may not actually be correct. Ozeke et al. rederive the radial diffusion coefficient as the sum of a term due to electric field fluctuations and a term due to magnetic field fluctuations. They then show that corresponding electron flux enhancements at lower L shells can be several orders lower than the flux enhancements obtained using the commonly employed diffusion coefficients. In the final paper of the fourth section,

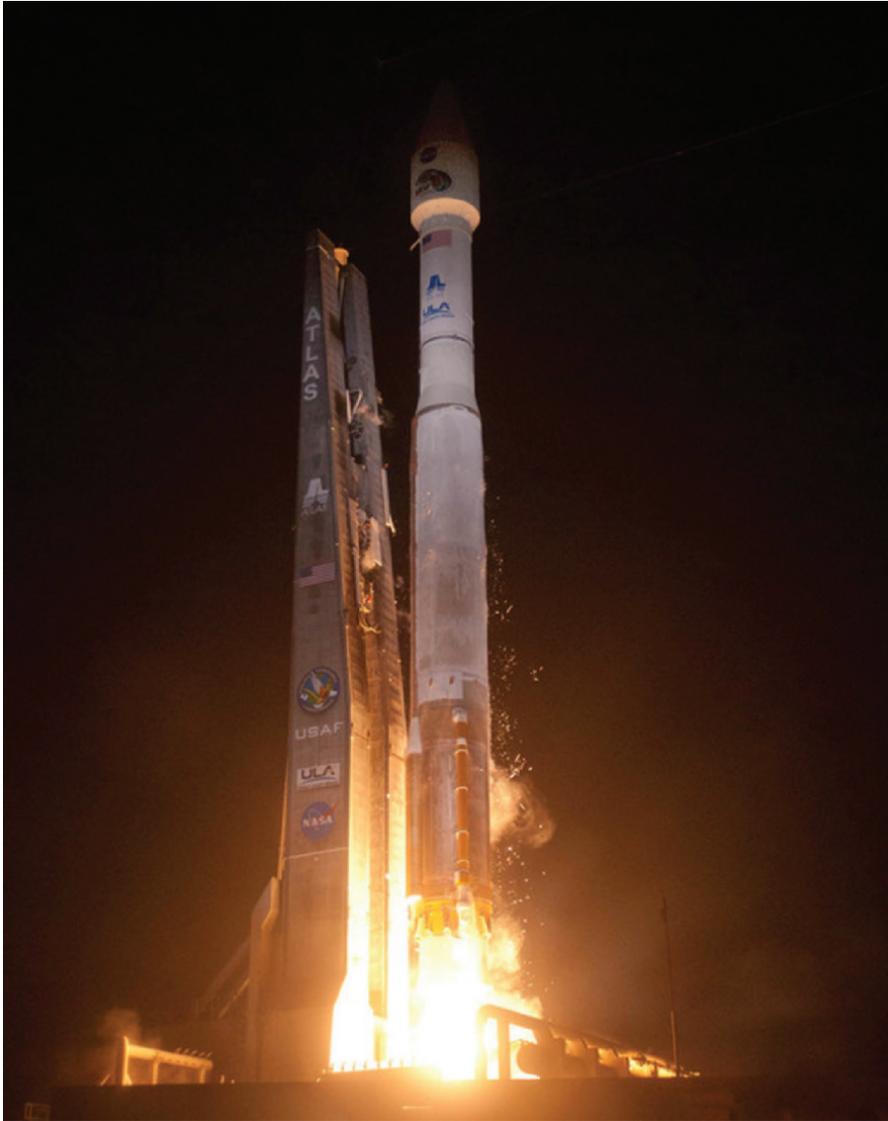


Figure 1. Launch of the United Launch Alliance Atlas V 401 rocket carrying the NASA Radiation Belt Storm Probes at Cape Canaveral Air Force Station on 30 August 2012. Photo credit: Pat Corkery, United Launch Alliance.

Kress et al. [this volume] call into question the modeling of the radial transport of radiation belt electrons by the very process of electron diffusion. *Kress et al.* compare radial diffusion with transport modeled by computing electron-guiding center trajectories in MHD magnetospheric model fields and claim that the radial transport of MeV outer radiation belt electrons due to moderate solar wind fluctuations is not well modeled by a diffusion equation.

The fifth section mainly addresses the topics of localized radiation belt particle injection and radiation belt flux “drop-outs.” Aside from the artificial injection of energetic electrons into the radiation belts by such means as high-altitude

nuclear explosions and relativistic electron beam injections from a satellite, there are two main forms of radiation belt particle injection. These are particle injection from the magnetotail and rapid particle energization by a shock front passing through the inner magnetosphere. *Liemohn et al.* [this volume] analyze time scales for localized particle injections to spread into a thin shell and find, for instance, that at $L = 2.8$ (in the slot region) during quiet driving conditions, it takes 4–6 h for a narrow MLT initial distribution of 3 MeV electrons to transform into a uniformly distributed ring. This result implies that the common assumption of instant symmetrization with respect to MLT of a localized injection of

~MeV electrons is incorrect and clearly has ramifications for radiation belt modeling. Using particle observations from the spacecraft Akebono, *Nagai* [this volume] reports a rapid storm time rebuilding of the central part of the outer radiation belt over a timescale of a few hours. Since this rebuilding coincides with a large-scale dipolarization of the magnetic field caused by storm time substorms, it is likely that electrons are transported from the magnetotail by an intense substorm-associated electric field. *Blake* [this volume] presents hitherto unreported CRRES data on the well-known shock injection of 24 March 1991, that produced a new radiation belt in the slot region. It is hoped that analysis of these unpublished CRRES observational details of the first minutes of the rapid injection may prove useful in the analysis of data from the RBSP mission. *Turner et al.* [this volume] provide a current understanding of the sudden depletion of the outer radiation belt electron fluxes known as a flux dropout. Dropouts are characterized by the depletion of electron fluxes by up to several orders of magnitude over a broad range of L shells, energies, and equatorial pitch angles in just a few hours. *Hendry et al.* [this volume] emphasize the importance of energetic electron precipitation in flux dropouts occurring during high-speed solar wind stream-driven storms. In the final paper of this section, *Thomson* [this volume] analyzes the background variability of the equatorial magnetosphere as inferred from a long time series of GOES data and suggests that the dominant component of the variability in the solar wind, the driver of the magnetosphere, comes from the discrete normal modes of the Sun.

Whistler mode chorus waves are known to play an important role in controlling radiation belt dynamics. In the sixth section, on wave-particle interactions, *Omura et al.* [this volume] discuss the generation processes of chorus emissions and summarize the current status of nonlinear wave growth theory. The generation mechanisms of chorus involve the nonlinear dynamics of resonant electrons and the formation of electromagnetic “holes” or “hills” that result in resonant currents generating rising-tone emissions or falling-tone emissions, respectively. *Summers et al.* [this volume] analyze the generation of a whistler mode rising-tone chorus element and are able to construct complete time-profiles for the wave amplitude that smoothly match at the interface of the linear and nonlinear growth phases. *Albert et al.* [this volume] analyze nonlinear, test-particle behavior under the action of a coherent quasimonochromatic wave using a Hamiltonian approach, with a view toward practical long-term modeling of nonlinear wave-particle interactions in the radiation belts. *Ripoll and Mourenas* [this volume] adopt quasilinear diffusion theory and, by using effective analytical approximations, determine precipitation lifetimes for radiation belt electrons due to resonant scattering by whistler

mode hiss waves. *Ni and Thorne* [this volume] discuss how wave-particle interactions, specifically resonant electron interactions with whistler mode chorus and electrostatic electron cyclotron harmonic waves, play a dominant role in the scattering of injected plasma sheet electrons leading to diffuse auroral precipitation.

The seventh section relates to how cross-energy coupling of the particle populations of the radiation belts, ring current, plasmasphere, and ionosphere influences the dynamics of the inner magnetosphere. Using numerical modeling, *Jordanova* [this volume] finds that storm time development of the ring current affects radiation belt dynamics in three ways: it depresses the background magnetic field on the nightside, provides a low-energy seed population for the radiation belts, and generates electromagnetic wave modes that scatter radiation belt particles. *Siscoe and Fok* [this volume] analyze the recently formulated Love-Gannon relation connecting the storm time ring current to the dawn-dusk asymmetry in the geomagnetic field observations on the ground at low latitudes. The (possibly controversial) relation, which states that the dawn-dusk asymmetry is proportional to the Dst index, may cause a revision of some classical ideas of magnetospheric dynamics and magnetosphere-ionosphere coupling.

Moldwin and Zou [this volume] argue that the plasma-pause, which acts as a separator between different wave and particle environments in the inner magnetosphere, should be considered the plasmasphere boundary layer (PBL). The PBL concept captures the complexity and local dynamics of the plasmopause with respect to both L shell and azimuth. The PBL modulates ULF and plasma waves, which in turn modulate the higher-energy particle populations in the inner magnetosphere.

It is accepted that ion outflow from the polar ionosphere is a significant supplier of plasma to the terrestrial plasma sheet and ring current. *Yau et al.* [this volume] model the transit of polar wind oxygen O^+ ions to the storm time inner magnetosphere and find that such outflow could explain the prompt presence of energetic O^+ ions in the plasma sheet and ring current at the storm onset. *Haaland et al.* [this volume] use measurements from the Cluster mission to quantify the amount of cold plasma supplied to the magnetosphere from the polar ionosphere for various geomagnetic disturbance levels and solar wind conditions.

Reversal of the geomagnetic field polarity has dramatic effects on the radiation belts and ring current, as well as on the access to the magnetosphere of GCR and SEP. *Lemaire and Singer* [this volume] use an adaptation of Stormer's theory to determine the depletion, rebuilding, and characteristic properties of the radiation belts over the course of a geomagnetic field reversal. These results may provide insight, for instance, on the role of the northward/southward turning of

the interplanetary magnetic field on the dynamics of today's inner magnetosphere as well as in paleomagnetospheres.

In the penultimate section, three papers discuss particular issues related to space weather and the radiation belts. O'Brien *et al.* [this volume] provide details of the various types of space weather hazards from energetic electron and ion populations that affect spacecraft and describe the type of information that the satellite design community needs from the radiation belt science community. In general, the satellite design community needs worst case and mean radiation environment specifications. O'Brien *et al.* make recommendations on how the science community can improve the quality and quantity of knowledge transfer to the satellite designers. Fennel *et al.* [this volume] examine energetic electron responses to storms that occurred during 1998–2008 in the inner magnetosphere, $2 \leq L \leq 4$, using HEO3 data. They conclude that a definitive explanation of the electron flux response to storms, namely, “flux increase,” “no response,” or “flux decrease” requires a better combination (than is currently available) of electron observations and supporting information on plasma waves, plasmopause position, magnetopause position, and ring current penetration. Li *et al.* [this volume] describe the space weather mission CSSWE, which was launched on 13 September 2012. The science objectives of CSSWE are twofold: to determine the precipitation loss and evolution of the energy spectrum of radiation belt electrons, and to investigate the relationship of solar flare properties to the timing, duration, and energy spectrum of SEPs reaching the Earth. This NSF-funded Cubesat mission will not only provide valuable space weather data but also provide training for the next generation of engineers and scientists.

Finally, in the last section, we examine radiation belts beyond the Earth. All the strongly magnetized planets of the solar system have robust radiation belts extending to relativistic energies. It is natural to ask what we have learned about the Earth's radiation belts that can immediately carry over to the other planetary radiation belts, and what lessons can be learned about the Earth's radiation belts from a comparative study of solar system radiation belts. Mauk [this volume] uses the Kennel-Petschek differential flux limit to compare the radiation belts at Earth, Jupiter, Saturn, Uranus, and Neptune and further provides a cautionary tale about attempts to apply radiation belt physics to hyperenergetic radiation regions outside the solar system.

Plasma wave emissions have been detected at all of the planets that have been visited by spacecraft equipped with plasma wave instruments. Wave-particle interactions involving whistler mode chorus, hiss, equatorial noise, and electron cyclotron harmonic waves are implicated in the acceleration and loss of radiation belt particles and are expected to play a

major role in radiation belt dynamics throughout the solar system. Hospodarsky *et al.* [this volume] summarize the properties of these wave modes and discuss the similarities and differences of the plasma waves detected at the Earth, Jupiter, and Saturn.

To conclude, we thank all the authors for their stimulating contributions and hope that this volume will prove to be a valuable resource for experienced researchers and beginning graduate students alike.

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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Space Weather: Affecting Technologies on Earth and in Space

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Beginning with the era of development of electrical telegraph systems in the early nineteenth century, the space environment around Earth has influenced the design and operations of ever-increasing and sophisticated technical systems, both on the ground and now in space. Newfoundland had key roles in important first events in communications, including the landing of the first working telegraph cable in Heart's Content (1866), the first reception of trans-Atlantic wireless signals at Signal Hill in St. John's (1901), and the North American location of the first trans-Atlantic telecommunications cable in Clarendville (1956). All of the systems represented by these "firsts" suffered from effects of space weather. This paper reviews some of the historical effects of space weather on technologies from the telegraph to the present, describing several events that impacted communications and electrical power systems in Canada. History shows that as electrical technologies changed in nature and complexity over the decades, including their interconnectedness and interoperability, many important ones continue to be susceptible to space weather effects. The effects of space weather on contemporary technical systems are described.

1. INTRODUCTION

The aurora has been observed and marveled at for as long as humans have existed. The aurora has been viewed with awe not only in polar regions but also has been visible at various times at low geomagnetic latitudes such as Hawaii, Cuba, Rome, and Bombay. An understanding of the origins of the aurora only began to become scientifically rigorous in the late nineteenth century. Slowly, the aurora became to be understood as somehow related to the Sun, and therefore, solar activity might influence the Earth. That is, the Sun could influence the space environment around the Earth [Chapman and Bartels, 1940; Soon and Yaskell, 2003]. The Sun, in fact, does influence the "weather" in the space environment around the Earth, although the terminology of

"space weather" did not become commonly employed until near the end of the twentieth century.

Any noticeable effects of the Sun and the Earth's space environment on human technologies had to wait until the first large-scale electrical technologies began to be deployed and used. This first large-scale technology was the electrical telegraph, first put into use some 160 or so years ago, several generations ago, and yet short in the course of human existence. W. H. Barlow, the company engineer for the Midland Railroad in England reported "spontaneous deflections" of the needles of the telegraph lines running aside the railroad tracks [Barlow, 1849]. Barlow's data for the Derby to Birmingham line is shown in Figure 1 for about 2 weeks of measurements in May 1847. The hourly variations in the "deflections" are clearly evident, as is an approximately daily variation throughout the interval. Barlow [1849, p. 66] further noted that "... in every case that [came under his] observation, the telegraph needles [were] deflected whenever aurora [were] visible."

Less than two decades after Barlow's observations, the white light solar flare observed by Carrington [1863] on 1 September 1959, ejected what we now know to be a coronal

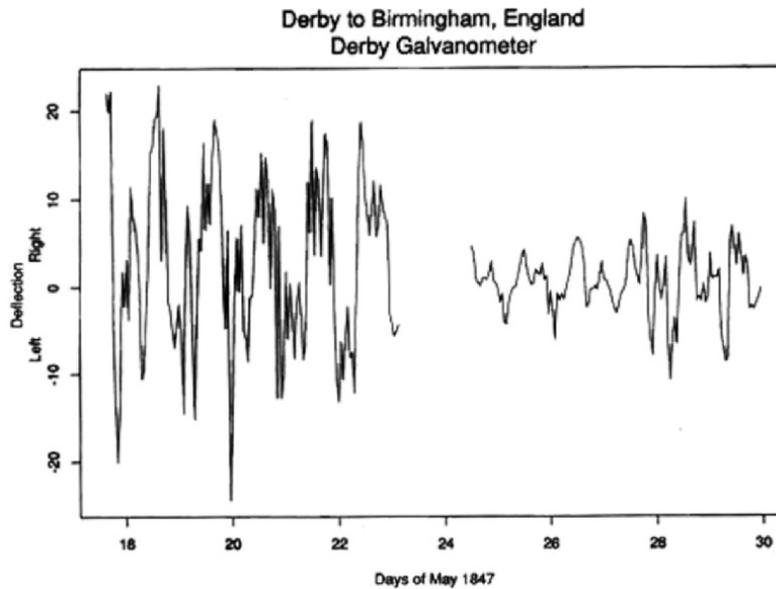


Figure 1. Galvanometer deflections on the telegraph cable along the Midland Railroad line from Derby to Birmingham for a 2 week interval in May 1847.

mass ejection (CME) into the interplanetary medium. Less than 20 h later, the Earth’s space environment was struck. Huge changes in the geomagnetic field were observed wherever measurements were being made: “During the great auroral display . . . disturbances of the magnetic needle [at] Toronto, in Canada, the declination of the needle changed nearly four degrees in half an hour” [Loomis, 1869, p. 12]. Auroras were observed on Earth from the north to as low latitude as Hawaii.

In the years since Barlow, the telegraph made large strides in its development and deployment across many locales on Earth, greatly enabling faster communications across large distances. Carrington’s solar event produced greater disturbances in telegraph systems than Barlow had experienced. As reported by Prescott [1875, p. 322], on the telegraph line from Boston to Portland (Maine) on Friday, 2 September 1859, “. . . the line was worked [without batteries] more than two hours when, the aurora having subsided, the batteries were resumed.” Between South Braintree and Fall River (Massachusetts; a distance of about 40 miles) “such was the state of the line . . . when for more than an hour [the operators] held communication over the wire with the aid of the celestial batteries alone.”

Prescott [1875], in his treatise on the electric telegraph, records the observations and experiences of many eastern U.S. telegraph operators during the Carrington event (as well as observations of effects on telegraphs from other auroral events in Europe and the United States). Prescott subtitles one section of his chapter on “Terrestrial Magnetism” as

“Working Telegraph Lines with Auroral Magnetism.” Shea and Smart [2006] published a compendium of eight contemporary, published U.S. articles attributed to, or written by, Elias Loomis (Professor at Yale) related to the aurora and magnetic observations during the Carrington event.

The decades following the Carrington event found much work by electrical and telegraph engineers in attempts to understand the origins of the “spontaneous” electrical currents in their systems and to mitigate against them. In parallel, scientists worked to attempt to understand how an event on the Sun, such as the one Carrington reported, could affect the Earth so far away.

Newfoundland in the late nineteenth and early twentieth century was the site of many firsts in electrical communications technologies. The first trans-Atlantic telegraph cable from Valencia, Ireland, to Bull Arm (Trinity Bay) failed after 1 month. Cyrus Field, using the huge *Great Eastern* ship, was successful in establishing the first operating cable from Valencia, landing it in Heart’s Content (Trinity Bay) in 1868 (Figure 2). This cable was operational for a century, until 1965. Each year, a celebration is held in the small village of Heart’s Content on the anniversary day of the landing, 27 July. The 145th anniversary party occurred the week following the 2011 Chapman Conference on Dynamics of the Earth’s Radiation Belts and Inner Magnetosphere in St. John’s (Figure 3). As recounted by Rowe [2009, p. 45], “. . . the beginning of cable service was far from reliable . . . Earth’s magnetic currents, lightning, the aurora borealis . . . sent the [galvanometer] into wild and rapid gyrations.” The “Earth’s



Figure 2. Still existent trans-Atlantic telegraph cables landing from Trinity Bay, Newfoundland, with Heart's Content cable station (original station in red) in the background. The station is now a Canadian Provincial Historical Site.

magnetic currents” and the aurora borealis were evidence of “space weather,” although not known to be such at the time.

The year 1956 saw the inaugural call on the first trans-Atlantic voice telephone cable (TAT-1) across the Atlantic. The cable, from Oban, Scotland, was landed in Clarenville, Newfoundland (Trinity Bay), and saw service until 1978. TAT-2, from Penmarch, France, to Clarenville, was placed in service in 1959 and was retired in 1982. The large magnetic storm of February 1958 produced havoc on TAT-1. As John Brooks wrote in the *New Yorker* magazine “At almost the exact moment when the magnetograph traces leaped and the aurora flared up, huge currents in the earth . . . manifested themselves not only in power lines in Canada but in cables under the north Atlantic” [Brooks, 1959, p. 56].

Axe [1968] reported that an induced voltage swing larger than ~ 1.5 kV was measured at Oban, Scotland, during the most intense portion of the geomagnetic storm that affected TAT-1. Voltage excursions larger than 1 kV were measured

on the telephone cable from Clarenville to Sydney Mines, Nova Scotia, at the peak of the storm [Winckler *et al.*, 1959].

2. ADVANCES IN ELECTRICAL TECHNOLOGIES

Over the following century and a half, to today, as humans continued to develop electrical technologies for communications, electric power, and other uses, the effects of the Sun and the Earth’s space environment continued to be felt and had to be dealt with. Engineers and scientists did not understand solar-terrestrial phenomena, or believe, until the early twentieth century, that the Sun could actually disturb the Earth in the ways that were implied by the coincidences observed between solar activity and geomagnetic storms, aurora, and disturbances on electrical systems.

In 1885, Guglielmo Marconi began experimental studies of wireless transmissions on his father’s estate near Bologna, Italy. This work evolved into extensive experiments on land, shore-to-sea, and between-ship transmissions, much carried out in England. In 1901, Marconi established transmitting stations at Poldhu and The Lizard in Cornwall, and receiving stations at Wellfleet on Cape Cod, Massachusetts, and on Signal Hill, St. John’s in Newfoundland (there are many books and articles relating to Marconi’s life and work, e.g., the work of *Bussey* [2001]). He encountered many hurdles, including wind damage and destruction of transmission and receiving towers, in his attempts to cross the Atlantic with a radio wave.

On 12 December 1901, Marconi had success, receiving the Morris Code letter “S” at Signal Hill (Figure 4) as transmitted from Poldhu. For this, he was awarded, with Karl Braun of Germany, the Nobel Prize in Physics for 1909. The beginnings of communications through the “air” had begun. Such communications had the potential to provide more bandwidth, did not require the laying of long cables across a deep ocean, and could evade the pesky “spontaneous” currents in the telegraph cables.

The Marconi Company established a wireless station at Cape Race, Newfoundland, in 1904 (Figure 5). It was at this station that the distress signals from the Titanic were received on 14 April 1912.

While the anomalous (and often large) electrical currents experienced in the telegraph wires were avoided by Marconi’s wireless innovation, the solar-terrestrial environment had surprises for the new electrical technology. As *Marconi* [1928] himself wrote

“ . . . times of bad fading [of the wireless signals] always coincide with the appearance of large sun-spots and intense aurora-boreali usually accompanied by magnetic storms. . . .” These are “ . . . the same periods when cables and land lines experience difficulties or are thrown out of action.”



Figure 3. Celebration cake for the 145th year of landing of the first successful trans-Atlantic telegraph cable, 27 July 2011.



Figure 4. Cabot Tower, Signal Hill, St. John's, Newfoundland, August 2011, a Canadian National Historic Site.



Figure 5. Cape Race, Newfoundland, on the Avalon Peninsula, the site of the Marconi Company wireless station established in 1904.

In the early days of wireless, and as the understanding of the relationship of solar activity to successful operations of the technology increased, the need for better understanding of the causes of wireless “fading” and other anomalies became more important. In fact, the data shown in Figure 6 (reproduced from the work of *Lanzerotti*

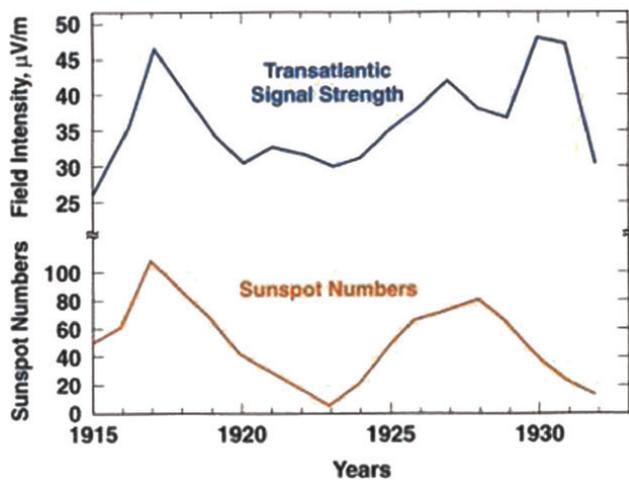


Figure 6. Trans-Atlantic daylight wireless transmission signal levels (15–23 kHz) measured by the AT&T Company during sunspot cycles 15 and 16.

[2004]) of the relationship between daylight trans-Atlantic signal strength (15–23 kHz) and sunspot numbers shortly after the AT&T company began trans-Atlantic transmissions represent one of the earlier efforts at what might today be called “space weather predictions.” It is clear that the field strength of the signal appears to be “correlated” with sunspot number, with higher strength when there was more solar activity during these two solar cycles (numbers 15 and 16).

The experience of “unexpected” effects of the Earth’s space environment on new electrical technologies (such as cable and then wireless) is a theme that persists to the current day. As new technologies are introduced, their successful operations can often be impeded by surprises from the solar-terrestrial environment. The characteristics of the environment must often be used in the making of design decisions. Since some of the most intense space environmental changes occur infrequently, past events of operational failure can be forgotten; design and operation decisions might then be made on the basis of more benign assumptions as to possible space environmental impacts. The fact that the most intense space environmental effects occur so infrequently also means that design decisions have to be made on imperfect knowledge of the solar-terrestrial environment [e.g., *Riley*, 2012]. All of these types of considerations have been operative throughout the twentieth

century as one after the other of electrical technologies have been introduced and employed, for civilian and for national defense purposes.

While not recognized until their discovery by James Van Allen in 1958, the trapped radiation belt particles are centrally involved in producing many of the foregoing historical impacts on electrical technologies. In particular, the depletion of the trapped radiation under geomagnetic storm conditions greatly increases the conductivity of the ionosphere at the foot points of the magnetic field flux tubes that contained the formerly trapped particles. These changes in ionosphere conductivity, and the spatial differences in the conductivity that are produced because of different intensities of trapped particle loss, are responsible for large changes in magnetic fields at the Earth's surface. These Earth surface magnetic field changes are those that give rise to the telluric currents that flow in and disrupt long conductor systems. The enhanced ionosphere conductivities also produce the anomalous propagation conditions for wireless signal transmissions.

3. CONTEMPORARY SPACE WEATHER EFFECTS

Table 1 (adapted from the work of *Lanzerotti* [2004]) lists a majority of the solar terrestrial processes that are

understood today that can affect contemporary technical systems. These processes, and some of the impacted technologies, are illustrated in Figure 7. Many of these physical processes are coupled. For example, the magnetic field variations as measured on the Earth's surface that can affect systems consisting of long conductors (such as the first telegraph cables and contemporary electric power grids and transocean cables) are produced by variations in the electrical currents flowing in the ionosphere. This, in fact, is the physical basis behind the observation made by Marconi in the quote above from one of his publications. Different types of ionosphere disturbances (such as the "plasma bubbles" in Figure 7), and confined principally to some regions on the Earth such as near the equator and in the auroral zones, are the source of disturbances (signal fading and signal scintillations) on other "wireless" signals such as modern-day navigation and satellite-to-ground signals.

3.1. Magnetic Field Variations

The magnetic field variations in Table 1 that produce electrical currents in the Earth that can affect electricity grids, long communications cables, and pipelines primarily result from geomagnetic storms. The largest of these storms, those most likely to produce the largest currents in the Earth,

Table 1. Solar-Terrestrial Processes and Their Consequences^a

Solar-Terrestrial Process	Impact	Technologies Affected
Magnetic field variations	induction of electrical currents in the Earth	power distribution systems long communications cables pipelines
	directional variations	spacecraft attitude control compasses
Ionosphere variations	reflection, propagation attenuation interference, scintillation	wireless communication systems communication satellites geophysical prospecting
Solar radio bursts	excess radio noise	wireless systems radar systems GPS transmissions
Particle radiation	solar cell damage	spacecraft power
	semiconductor damage/failure	spacecraft control
	faulty operation of semiconductor devices	spacecraft attitude control
	charging of surface and interior materials	spacecraft electronics
	human radiation exposure	astronauts Airline passengers
Micrometeoroids and artificial space debris	physical damage	Solar cells
		Orbiting mirrors, surfaces, materials Entire vehicles
Atmosphere	increased drag	Low altitude satellites
	attenuation/scatter of wireless signals	Wireless communication systems

^aAdapted from *Lanzerotti* [2004].

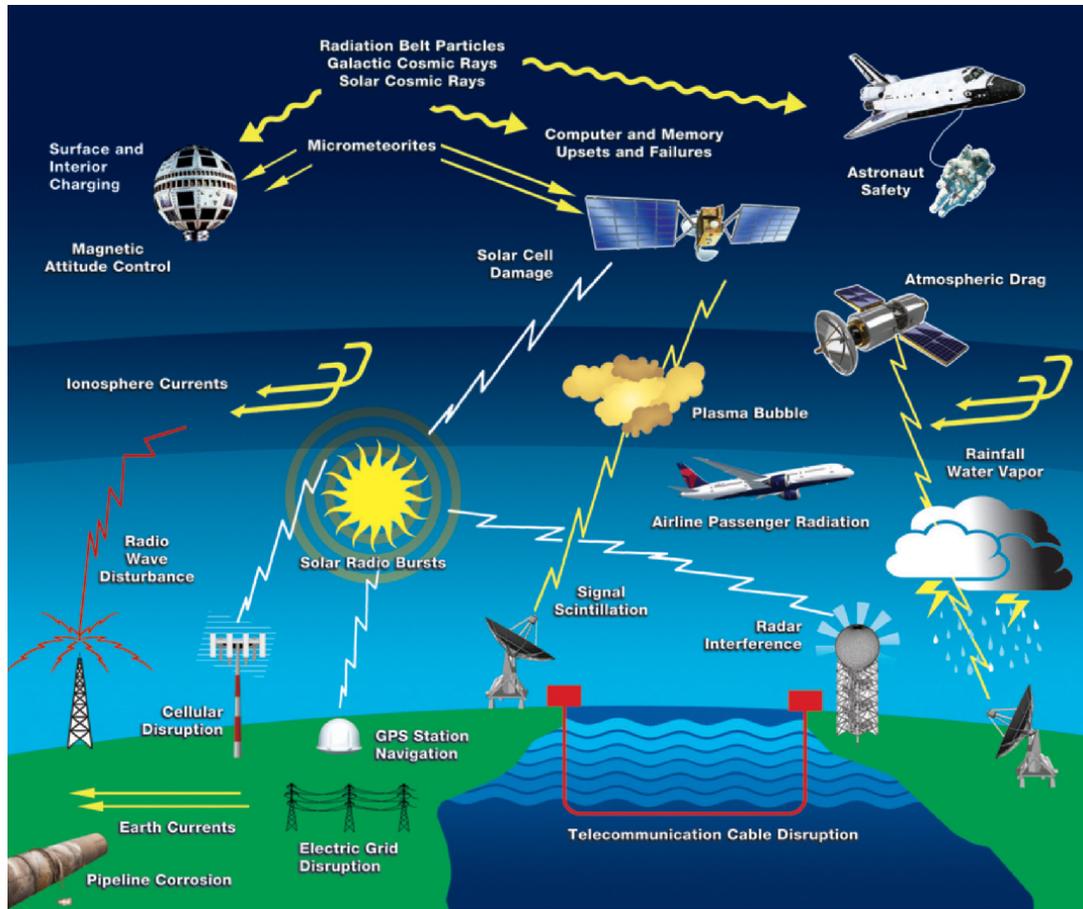


Figure 7. Illustration of many space weather effects and some of the modern-day electrical technologies and systems that can be adversely affected by them.

usually result from CME events striking the Earth's magnetosphere. These geomagnetic storms produce large changes in the electrical currents in the ionosphere. These fluctuating ionosphere currents produce fluctuating magnetic fields at the Earth's surface, which in turn cause electric currents to flow in the Earth's crust. These "telluric currents" seek the highest conductivity paths in which to flow, and long grounded conductors such as power grids, communications cables, and pipelines provide such paths [e.g., *Lanzerotti and Gregori, 1986*].

The magnitude and locations of the flowing telluric currents depend very much on the locations of the currents in the ionosphere and the conductivity of the underlying Earth. The ionosphere currents vary in location from geomagnetic storm to geomagnetic storm; current models of geomagnetic activity cannot predict these locations very precisely. The conductivity profile of the Earth is not known well in many locales. A given ionosphere current variation (if there was a "standard" variation) could pro-

duce very different telluric currents in regions that had different Earth conductivities.

The telluric currents that flow in the long conductors can produce damage, and even failure, of power system transformers, overwhelm constant current powering systems on long communication cables, and render inoperative pipeline corrosion protection circuits. Mitigation procedures depend upon the particular technical system and are implemented in some systems. There are costs for mitigation, and business decisions are made as to the cost/benefit results that might be achieved by implementations.

Some spacecraft use the Earth's magnetic field for orientation and guidance. A very intense solar wind shock wave, as from a strong CME event, can push the Earth's magnetopause inside geosynchronous orbit. The magnetic field just outside the magnetopause is of opposite polarity to that inside; a magnetically oriented spacecraft that crosses the magnetopause will thus suddenly be misoriented, and operators will likely have to intervene.

3.2. Ionosphere Fluctuations

The fluctuating ionosphere currents can cause havoc in the propagation of radio signals over a wide bandwidth. At HF and VHF frequencies, frequencies used, for example, by civil emergency agencies and by commercial airlines flying over the north polar region, signals transmitted from a location on the Earth can be absorbed or reflected anomalously from the ionosphere and, thus, not reach their destinations. At higher frequencies, such as those used for satellite-to-ground (and ground-to-satellite) transmissions and for GPS navigation signals, the radio waves can be severely distorted in phase and amplitude, affecting severely communications and navigation.

3.3. Solar Radio Noise

A scientific area that has become of more importance in recent years is that of the effects of solar radio noise on navigation technologies in the form of GPS. Solar radio bursts produced by solar flares were discovered in 1942 when British radars were rendered inoperable by jamming signals. These radars were being used to warn of enemy aircraft launched from continental Europe. The initial thinking was that the enemy was purposefully jamming the radars. J. S. Hay, a British scientist, identified the source as actually coming from the Sun, and not from across the English Channel [e.g., *Hey*, 1975].

While radars are still susceptible to solar radio noise, the vast proliferation of technologies that operate in the near-GHz and GHz frequency ranges, such as GPS and cell phones, means that this aspect of solar phenomena becomes of more significance in terms of its influence on technical systems [e.g., *Cerruti et al.*, 2006, 2008]. Solar radio noise, as well as bursts of solar X-rays, arrives at the Earth at the speed of light. Thus, there is no warning of their occurrence as there is for a possible encounter of a CME with the Earth to produce a magnetic storm. Accurate predictions of solar flares are still rather rudimentary, and predictions of how intense a radio burst or (an X-ray burst) might be are non-existent. Radio noise and bursts, and X-rays are produced by electrons trapped and propagating in the Sun's magnetic fields. Until the intensities of the trapped electrons and of the magnetic fields can be readily measured and/or predicted, the forecast of the occurrence and intensity of solar radio and X-ray events remains a major unsolved problem.

3.4. Particle Radiation

When Sir Arthur Clark and John Pierce proposed Earth-orbiting communications satellites (at geosynchronous and

low Earth-orbiting altitudes, respectively), they did not anticipate that the space environment around the Earth was not benign. However, the charged particle environment in space determines the design of space systems in many important ways. These charged particles are those trapped in the Earth's magnetosphere (the radiation belts), solar energetic particles outside the magnetosphere and those that penetrate into the magnetosphere, and galactic cosmic rays.

Even though the spatial extent and intensities of the trapped radiation were not delineated for a number of years following Van Allen's discovery in 1958, it was, nevertheless, recognized that the radiation presented a formidable environmental constraint to system designs and to human occupation of space. The design and build of the first active telecommunications satellite Telstar 1, conceived and promoted by John Pierce of Bell Laboratories, could not provide substantial shielding for many reasons, including the launch vehicle available (a Delta), and the size and weight of the small spacecraft (about 77 kg; 87.6 cm in diameter).

Telstar 1 was built at Bell Laboratories of largely discrete components including transistors (no integrated circuits or microprocessors available in those days), paid for by AT&T, including the launch costs reimbursed to NASA. The spacecraft carried several transistor solid-state detectors with different front aperture thicknesses to measure the radiation environment encountered by the satellite. Telstar was launched on 10 July 1962 into a low Earth orbit (perigee 952 km; apogee 5933 km). On the prior day, the United States had conducted the Starfish Prime high-latitude nuclear test over the Pacific. In addition to large disturbances in the electric grids in Hawaii and New Zealand, the test injected into the low-altitude magnetosphere fluxes of electrons more than 100 times the natural background radiation. Less than 8 months after launch, Telstar succumbed to the radiation environment. The electron data obtained from the radiation detectors on Telstar are still referenced today for the information obtained on electron lifetimes at those altitudes.

The radiation environment at geosynchronous altitude was unknown at the time of launch (July 1963) of the first operational satellite at that location, Syncom 2. The NASA Applications Technology Satellite ATS-1, launched to geosynchronous orbit in December 1966, carried particle detector instruments from three U.S. institutions: Aerospace Corporation, University of Minnesota, and Bell Laboratories. Discovery data from these instruments showed that the radiation environment at this altitude, where almost all communications satellites reside today, is highly variable in time and location along the orbit. These data also provided the first evidence that in some solar-produced events, the magnetopause can be pushed inside geosynchronous, exposing space assets to the interplanetary environment.