

# History and Science Motivation for the Van Allen Probes Mission

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## ABSTRACT

The NASA Van Allen Probes (previously known as Radiation Belt Storm Probes, or RBSP) mission addresses how populations of high-energy charged particles are created, vary, and evolve in space environments, specifically within Earth's magnetically trapped radiation belts. The Probes were launched 30 August 2012 and comprise two spacecraft making in situ measurements for the past several years in nearly the same highly elliptical, low inclination orbits ( $1.1 \times 5.8 R_E$ ,  $10^\circ$ ). The initial orbits are slightly different so that one spacecraft laps the other spacecraft about every 67 days, allowing separation of spatial from temporal effects over spatial scales ranging from  $\sim 0.1$  to  $5 R_E$ . The uniquely comprehensive suite of instruments, identical on the two spacecraft, measures all of the particles (electrons, ions, ion composition), fields (E and B), and wave distributions (dE and dB) needed to resolve the most critical science questions. Summarized in this article are the high-level science objectives for the Probes mission, examples of the radiation belts' most compelling scientific mysteries that motivated the mission, and the mission design that targets these mysteries and objectives. The instruments that are now working to deliver these measurements are also addressed.

## INTRODUCTION

It has now been more than 50 years since observations from the first spacecraft in the late 1950s were used to discover the radiation belts and reveal their basic configuration.<sup>1,2</sup> Those discoveries led to an explosion of investigations into the nature of the belts over the next two decades, including studies of the behavior of the transient belts created artificially with nuclear explosions.<sup>1,3,4</sup> Textbooks like those written by Hess,<sup>5</sup> Roederer,<sup>6</sup> and Schulz and Lanzerotti<sup>7</sup> captured the fundamental physics of the radiation belts discovered during the first decade of study. By the mid-1970s, interest in studying the radiation belts had dwindled, and those who continued to work on the belts shifted their focus

to characterizing their properties for engineering and space environment applications. The belts are known to be highly hazardous to satellites and astronauts.

In the early 1990s, several observations revealed that the behavior of Earth's radiation belts was far more dynamic and interesting than previously thought. Specifically, the observations of the Air Force Combined Release and Radiation Effects Satellite (CRRES) mission, flying in a highly elliptical geosynchronous transfer orbit, revealed the sudden creation of a brand-new radiation belt that filled the electron slot region (Fig. 1; Ref. 8), caused by a coronal mass ejection from the Sun. Also in the early 1990s, NASA's Solar, Anomalous, and

Magnetospheric Particle Explorer (SAMPEX) mission launched into a low-altitude polar orbit with the science goals of studying cosmic rays, radiation belts, and other energetic particles.<sup>9</sup> The extended SAMPEX mission, two decades long and still ongoing, has enabled studies of the dynamics of the low-altitude, high-latitude extensions of Earth's radiation belts. SAMPEX revealed that the radiation belts change dramatically over multiple timescales for reasons that are not always readily apparent.

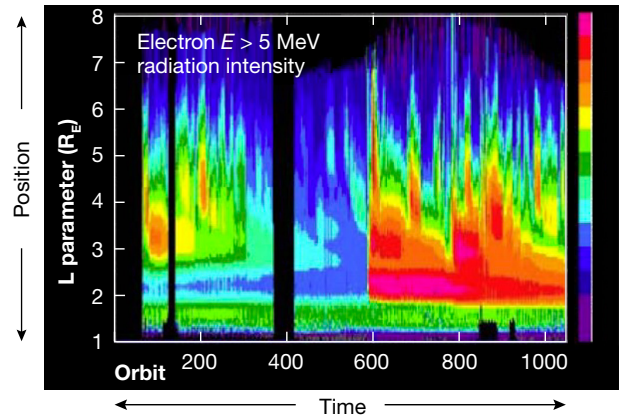
These scientific findings and uncertainties, and the fact that Earth's radiation belts pose such a serious threat to satellites and astronauts, led NASA, as a part of its Living With a Star (LWS) program, to develop the concept of the science mission originally called the Radiation Belt Storm Probes (RBSP). After launch in 2012, the name of the mission was changed to the Van Allen Probes to honor a key individual responsible for the discovery of the radiation belts.

The science objectives for the mission were first articulated by the NASA-sponsored Geospace Mission Definition Team (GMDT) report published in 2002.<sup>10</sup> They were refined in the payload announcement of opportunity issued in 2005. They were finalized in the RBSP program-level (level 1) requirements document signed by NASA's associate administrator for science in 2008. The fundamental objective of the mission is to provide understanding, ideally to the point of predictability, of how populations of relativistic electrons and penetrating ions in space form or change in response to variable inputs of energy from the Sun. The principal concern regards those particles that can penetrate the walls of spacecraft and other vehicles in Earth's space environment.

This broad objective is parsed into three overarching science questions:

1. Which physical processes produce radiation belt enhancements?
2. What are the dominant mechanisms for relativistic electron loss?
3. How do ring current and other geomagnetic processes affect radiation belt behavior?

The Van Allen Probes have now been in orbit for more than 3 years and are making great progress in answering these questions.<sup>11</sup> The purpose of this article is to provide the background and context for these overarching questions and to reveal the most compelling scientific issues regarding the behavior of the radiation belts. We describe how these questions motivated the development of the Van Allen Probes and how the characteristics and capabilities of the Probes enable the resolution of the outstanding issues. A much more extensive exposition of these materials is provided by Mauk et al.<sup>12</sup>



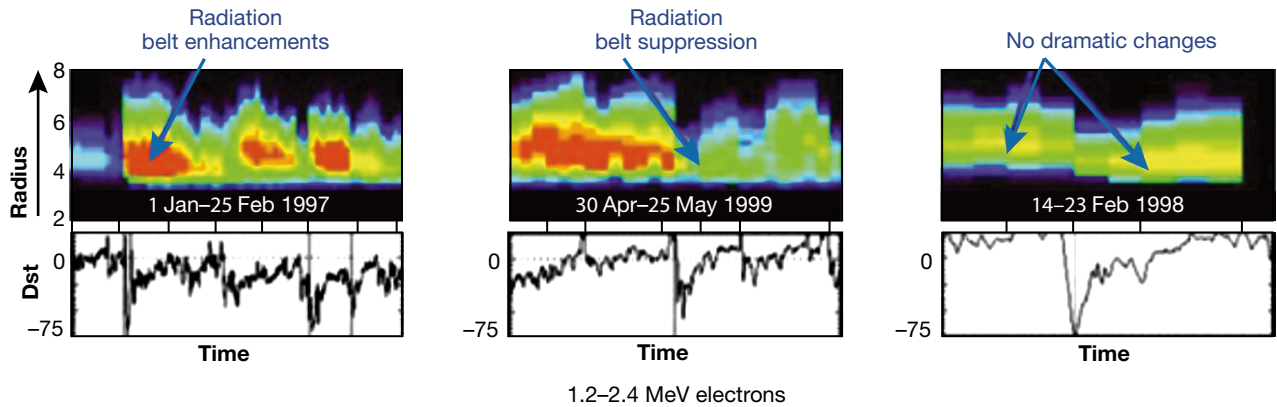
**Figure 1.** CRRES spacecraft observation of the creation of a new electron radiation belt that filled the slot region between 2 and 3  $R_E$  (Ref. 8; figure discussed by Hudson et al.<sup>13</sup>). The new belt (bright red) is thought to be the result of an interplanetary shock wave impinging on Earth's magnetosphere.

## RADIATION BELT SCIENCE MYSTERIES

After more than 50 years of study, we know a lot about Earth's radiation belts. Many of the fundamental processes that control radiation belt behaviors have been studied both observationally and theoretically. However, we are still far from having a predictive understanding of the radiation belts. We do not fully understand the complexity of how the various processes combine to produce different radiation belt configurations or the characteristics and complex behaviors of some of the specific mechanisms. In this article we provide some illustrative examples of selected scientific mysteries regarding the behaviors of Earth's radiation belts.

As to the continuing mysteries of radiation belt dynamics, it has long been conventional wisdom that the radiation belts dramatically intensify in association with geomagnetic storms. Such storms are often created by the impact of solar coronal mass ejections with Earth's magnetosphere and also the passage of high-speed solar wind streams. The north-south orientation of the interplanetary magnetic field also plays an important role. Storms last for one to several days, occur roughly a dozen times a year, and cause dramatic increases in the flux of hot ion populations at geocentric distances between 2 and 6  $R_E$ . Currents associated with these "ring current" ion populations distort inner magnetospheric magnetic fields and depress equatorial magnetic fields on Earth's surface. The storm time disturbance (Dst) index, a measure of these magnetic field depressions, is generally taken to provide a direct measurement of the ring current energy content according to the Dessler-Parker-Sckopke relationship;<sup>14,15</sup> however, there are caveats.<sup>16</sup>

Reeves et al.<sup>17</sup> published a now classic paper that showed that radiation belt responses to storms can contradict conventional wisdom. At times Earth's outer radiation belt populations do increase during mag-



**Figure 2.** Variable responses of Earth's outer electron belt (top of each panel) to magnetospheric storms as diagnosed with the Dst parameter (bottom). (Adapted from Ref. 17.)

netic storms (accompanied by decreases in Dst), but at other times they remain largely unchanged by magnetic storms or even decrease dramatically (Fig. 2). We do not know why the outer electron belt responds so differently during individual magnetic storm events, and these results highlight our lack of predictive understanding about radiation belts.

The work performed in conjunction with and after the CRRES and SAMPEX missions convinced the scientific community that it is far from having a predictive understanding of the behavior of Earth's radiation belts.

### Energization (Quasi-Linear and Nonlinear)

Radiation belt particles have higher energy than they "should" have. For example, in Earth's magnetic field environment, the magnetosphere reconfigures constantly with different solar wind drivers. Simplistically, a particle contained within the magnetosphere would vary in energy predictably in relation to the particle's surrounding magnetic field (i.e., in a magnetically regulated fashion referred to as energization via adiabatic invariants). However, the particle behaves in a much more complicated fashion.

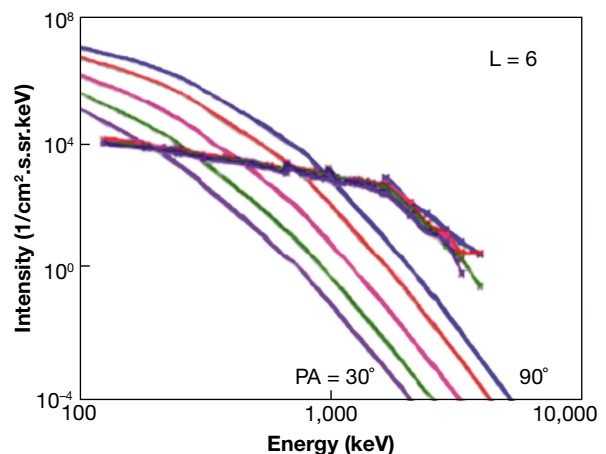
One might assume that Earth's radiation belts result from the transport of electrons that populate Earth's comet-like magnetic tail into the inner magnetosphere in a fashion that conserves the first and possibly the second adiabatic invariants, those associated with gyration and bounce motion. Conservation of the first adiabatic invariant requires the energies of core and tail populations to increase by a factor of perhaps 40 as particles are transported Earthward from regions in the magnetotail where magnetic field strengths are on the order of 5 nT to regions of the inner magnetosphere where field strengths are on the order of 200 nT.

However, recent results indicate that adiabatic energization of plasma populations is not sufficient to account for the >1 MeV component of Earth's outer electron radiation belt (see Fig. 3 and Ref. 18). We have

also learned that at least some of that unaccounted-for energization occurs within the regions of the radiation belts themselves.<sup>19</sup>

And so the question remains: how does that additional energization of the radiation belt populations come about?

One possibility is that the particles gain energy by interacting with plasma waves in the magnetosphere. Quasi-linear interactions with whistler mode plasma waves may provide the additional energization, effectively by transferring energy from low- to high-energy electrons.<sup>20-22</sup> Whistler waves that propagate parallel to the magnetic field establish a cyclotron resonance with



**Figure 3.** Comparison between CRRES-measured electron spectra during a very strong magnetic storm with the maximized expectations from the most intense spectra observed within the magnetotail ( $R = 11 R_E$ ) after transporting the magnetotail spectra adiabatically to the measurement position by conserving the adiabatic invariants of gyration and bounce. The different-colored lines refer to different initial pitch angles (angles of the particle velocity vectors with respect to the local magnetic field). The adiabatically transported spectra cannot explain the >1 MeV portion of the spectra measured within the inner magnetosphere. (Reproduced from Ref. 18.)

gyrating electrons. This process represents a quasi-linear mechanism of transporting energy from low- to high-energy particles.<sup>23</sup> The timescale for high-energy particle energization via this mechanism has been modeled and compared with observed energization timescales, and a reasonable match has been achieved.<sup>22</sup> However, this and other hypotheses need further testing. In view of recent observations (Ref. 24) and theoretical studies (Refs. 25 and 26), the role of large amplitude waves interacting in a highly nonlinear fashion with the particles must be considered. Theoretical modeling indicates that other wave modes, for example the so-called fast magnetosonic waves,<sup>27</sup> must also be considered. Figure 4 shows the regions in which the various proposed wave interactions are thought to occur.<sup>28</sup> Understanding how and when particles are locally accelerated is very important for understanding how the radiation belts are formed and maintained.

The ultimate sources of radiation belt electrons are the ionosphere and the solar wind. Ionospheric electron temperatures are less than 0.1 eV. Temperatures of the core population in the solar wind are on the order of 10 eV, whereas temperatures of the halo (heated) population in the solar wind are on the order of 60 eV.<sup>29,30</sup> Auroral and related magnetospheric interaction processes extract and energize ionospheric electrons, providing them to the outer magnetosphere (generally at distances beyond  $9 R_E$ ) at energies ranging from one to tens of kilo-electronvolts. Processes occurring at Earth's bow shock and magnetopause both energize and transport electrons into the magnetosphere. Processes occurring within Earth's magnetic tail may then accelerate

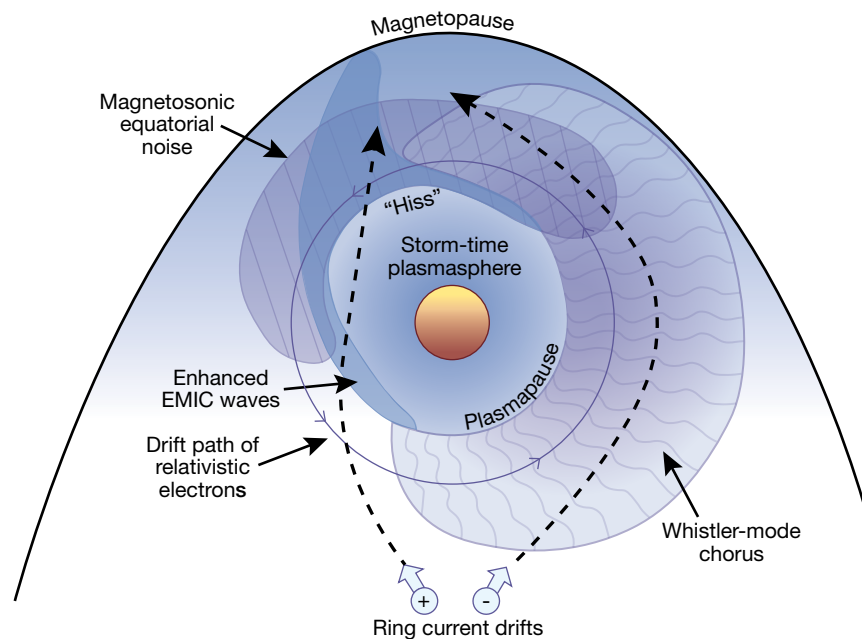
electrons of both ionospheric and solar wind origins still further. One such process, called magnetic reconnection, is thought to occur when magnetic field lines connected to both Earth and the solar wind “break” and become connected only to Earth. The resulting plasma sheet populations have temperatures of order 5 keV but often exhibit very substantial high-energy tails in their energy distribution.<sup>31</sup>

The purpose of these examples is to specifically confront the long-standing notion that developing a predictive understanding of Earth's radiation belts is simply one of characterization or modeling. On <1-h timescales, dynamic events called substorm injections are thought to only modestly perturb the distribution of mega-electronvolt-class electrons in the outer radiation belts. Substorms are transient releases of magnetic energy that occur on timescales much shorter than (hour) those associated with magnetic storms (day). Their importance has traditionally been viewed as helping in the transport of the source populations, specifically by providing a “seed” population for the subsequent transport and energization that occurs during the generation of the radiation belts.<sup>32–34</sup>

Evidence suggests that substorms are critical to the fundamental processes that energize radiation belt electrons.<sup>35</sup> Substorms may even increase radiation belt intensities while storms reduce intensities.<sup>36</sup> Substorm injections disturb the structure of medium-energy electron pitch angle distributions, making them highly conducive to the generation of strong whistler/chorus mode emissions. The waves in turn can accelerate the higher-energy electrons in the manner described in the

discussion above. The evidence in favor of this scenario is based on observed correlations between magnetic storms and substorms as diagnosed with magnetic indices (Dst, Kp, Ap, etc.), observations of whistler/chorus mode emissions, and observations of radiation belt intensities over a wide range of energies and extended periods of time. It is of interest that a similar scenario has been proposed for Jupiter's dramatic radiation belt.<sup>27</sup>

Because we are so uncertain about the role of substorms in the processes of transporting particles from the magnetotail to the middle and inner magnetosphere, much work remains to be done in testing the ideas discussed above and in generally understanding the role of substorms in the generation of Earth's radiation belts.



**Figure 4.** A now standard schematic of the regions of the influence of plasma waves on the radiation belts. (Reproduced from Ref. 28.)

## Loss

What causes the dramatic, sudden, large-scale dropout of radiation belt particles as near to Earth as  $L = 4 R_E$ ? These losses are distinct from the losses associated with the so-called slot region that occurs closer to Earth ( $2.5 R_E$ ).

Closely related to the issue of the variable responses of the radiation belts to magnetic storms are the surprising observations of very sudden dropouts of particle fluxes in the outer electron radiation belt for  $L$  values as close to Earth as  $4 R_E$ . Su et al.<sup>37</sup> have modeled several particular dropouts as amalgamations of multiple processes acting simultaneously, all making significant contributions. The processes included are magnetopause shadowing, adiabatic transport, radial diffusion, and wave-particle scattering losses associated with the so-called plasmaspheric plumes (comprising losses due to electromagnetic ion cyclotron waves and whistler hiss waves). Multiple processes (magnetopause shadowing and wave scattering) were also invoked by Millan et al.<sup>38</sup> to explain a similar depletion; such was the basis of the Balloon Array for RBS-P Relativistic Electron Losses (BARREL) arctic balloon campaign<sup>39</sup> to be selected and integrated into the Van Allen Probes mission.

For another observed depletion, Turner et al.<sup>40</sup> invoked magnetopause shadowing followed by modeled outward radiation diffusion. A common element in all of the most recent proposed ideas is the robust partici-

pation of magnetopause shadowing, whereby initially closed magnetic drift paths encounter the magnetopause because of changes in the global magnetic field configuration. Ukhorskiy et al.<sup>41</sup> have shown that the partial ring current can distort trajectories in the middle magnetosphere to a greater extent than previously appreciated, even to the extent of generating isolated drift path islands (Fig. 5). These strong distortions can substantially enhance the magnetopause shadowing losses. This idea remains highly controversial, and it and other ideas need to be tested with a mission like Probes that can separate spatial from temporal processes.

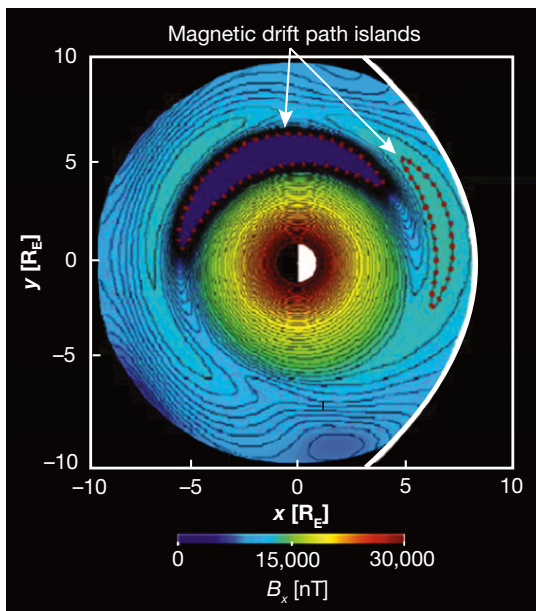
Although they were seemingly dismissed in the previous discussions, major storm and substorm reconfiguration with its attendant acceleration or deceleration is extremely important in distributing energetic particles within (and without) Earth's magnetosphere.

The uncertainties about the configuration of the global electric field configuration, and whether or not enhanced global electric fields move magnetotail plasma sheet particles Earthward during geomagnetic storms, raised the importance of establishing the fundamental role that substorm injections may play in the transport of particles to the middle and inner magnetosphere. The relative importance of that role needed to be explored and resolved.

## SCIENCE PLAN/SUMMARY

The high-level objectives of the Probes mission articulated above are specific enough to invite the generation of testable hypotheses. The Probes mission design has many of the capabilities needed to discriminate between and test these hypotheses. Most critical is the Probes' ability to perform simultaneous multipoint sampling over a broad spectrum of spatial and temporal scales, combined with extremely capable and highly coordinated instrumentation. These capabilities will enable researchers to discriminate between time and space variations. Key elements of the Van Allen Probes design are as follows:

- It comprises two identically instrumented spacecraft.
- The two spacecraft are in nearly identical orbits with perigee of  $\sim 600$  km altitude, apogee of  $5.8 R_E$  geocentric, and inclination of  $10^\circ$ . These orbits allow the Probes to access all of the most critical regions of the radiation belts.
- The lines of apogee for the two spacecraft precess in local time at a rate of about  $220^\circ$  per year in the clockwise direction (looking down from the north). The 2-year nominal mission lifetime ( $\sim 4$  more years of expendables are available) allows all local times to be studied. By starting the mission with lines of apogee at dawn (a program-level mission require-



**Figure 5.** A model of magnetic configurations that accompany the evacuation of the outer radiation belts based on partial ring currents that are stronger than anticipated. The partial ring current is strong enough to generate topological changes in the electron drift orbits. The contours show drift orbits and the colors indicate perturbations in the night-day component of the magnetic field ( $B_x$ ). (Reproduced from Ref. 41.)

ment), the nightside hemisphere will be accessed twice within the nominal 2-year mission lifetime.

- Slightly different (~100 km) orbital apogees cause one spacecraft to lap the other every ~67 days, corresponding to about twice for every quadrant of the magnetosphere visit during the 2-year mission.
- Because the spacecraft lap each other, their radial spacing varies periodically between ~100 km and ~5  $R_E$ , and resampling times for specific positions vary from minutes to 4.5 h.
- The orbital cadence (9-h periods; an average of 4.5 h between inbound and outbound sampling for each spacecraft) is faster than the relevant magnetic storm timescales (day).
- The low inclination (10°) allows for the measurements of most of the magnetically trapped particles, while the precession of the line of apogee and the tilt of the Earth's magnetic axis enable nominal sampling to magnetic latitudes of  $0 \pm 21^\circ$ .

With all of these capabilities, one may compare the timescales for the generation of local particle acceleration features with the theoretical expectations based on the measurements of the static and dynamic fields. With such capabilities, one may measure, rather than just infer, the gradients that generate currents and the gradients that reveal electric potential distributions. With the capabilities of the Probes' instrumentation, one may determine the detailed characteristics of resonant interactions between particles and waves.

An important element in achieving some of the science objectives is the use of sophisticated models and simulations to place the Probes' multipoint measurements into the broader 3-D picture. Strong coordination among data analysts and model builders is described in each of the investigation reports in a special volume of *Space Science Reviews* (volume 179, 2013).

The papers cited in the special volume describe the instrument investigations for the Energetic Particle, Composition, and Thermal Plasma suite (ECT); the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS); the Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE); the Electric Field and Waves Instrument (EFW); and the Relativistic Proton Spectrometer (RPS) investigations. These instruments cover enormous parameter ranges. These papers describe in various degrees the science objectives of the individual team investigations; the science teams involved; the data processing, analysis, and archiving plans; the role of theory and modeling in resolving the targeted science issues; and the role of modeling in synthesizing the two point measure-

ments that are made possible by the Probes' instrument investigations.

As the reader can fully assess, the discovery and subsequent research of Earth's radiation belts produced both understanding and more mysteries. As one may suspect, such a dangerous environment has hitherto been observed minimally, but it is important because it impacts electronics, as well as the longevity and performance of vital platforms. The important mysteries involve the radiation belt's intensity, location, and dynamics. These parameters are known only climatically with sporadic and far-too-averaged input.

The common theme in all precedents, publications, books, and journals concentrates on the dynamics and absolute levels of the belts in all aspects—size, location, intensity energy content, radiation equivalent, dosage, acceleration, and losses. Awareness about radiation began with its discovery by James Van Allen with Explorer 1 in 1958, but also with nuclear explosion tests that produced long-living, artificially created radiation belts (e.g., Starfish in July 1962). The most noticeable U.S. experiment, because of the power of the weapon and the altitude at which it was exploded, was the Starfish Prime experiment, which led to the formation of enhanced flux zones in the inner belt between 400 and 1600 km and beyond. The USSR experiments are not well documented, but it is believed that they contributed to flux enhancements in the outer belt. These modified fluxes finally extended in all the radiation belt regions and were detectable as late as the early 1970s. In some zones of the inner electron belt, fluxes increased by a factor of 100. Electrons from the Starfish blast dominated the inner belt fluxes for 5 years. These artificial fluxes delayed the study of representative natural radiation belt models, and Starfish artifacts are present in some zones of the AE8 and AP8 models in use today.

The Van Allen Probes have achieved their 2-year baseline mission and have been extended into the declining phase of the present solar cycle; the declining phase very often results in increased geomagnetic activity. The Probes' high-resolution and comprehensive instrumentation will continue to unravel the mysteries of Earth's radiation belts. The Van Allen Probes mission is concentrating on a limited but universal region of Earth's magnetosphere. Our solar system, our galaxy, and all galaxy systems have mysterious physical processes that escape our current understanding. Improving this understanding is critically important to the advancement of science but also to the ultimate goal of being able to predict the space environment and conditions.

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